2021 RAPID PRODUCT DEVELOPMENT ASSOCIATION OF SOUTH AFRICA - ROBOTICS AND MECHATRONICS - PATTERN RECOGNITION ASSOCIATION OF SOUTH AFRICA

(RAPDASA-RobMech-PRASA)

DIGITAL MANUFACTURING: INDUSTRIALISING AFRICA

THE 22ND ANNUAL INTERNATIONAL RAPDASA CONFERENCE

3 - 5 NOVEMBER 2021

AT THE INTERNATIONAL CONVENTION CENTRE CSIR PRETORIA

Hosted by the CSIR National Laser Centre

ISBN 978-0-6397-0111-0
2021 RAPID PRODUCT DEVELOPMENT ASSOCIATION OF SOUTH AFRICA - ROBOTICS AND MECHATRONICS - PATTERN RECOGNITION ASSOCIATION OF SOUTH AFRICA

DIGITAL MANUFACTURING: INDUSTRIALISING AFRICA

3 - 5 NOVEMBER 2021

AT THE
INTERNATIONAL CONVENTION CENTRE
CSIR
PRETORIA

Hosted by the CSIR National Laser Centre

ISBN 978-0-6397-0111-0
2021 CONFERENCE HOST

CSIR National Laser Centre
https://www.csir.co.za/
TABLE OF CONTENTS

COPYRIGHT

2021 CONFERENCE HOST

2021 CONFERENCE SPONSORS

TECHNICAL COMMITTEE

FOREWORD

REVIEW PROCESS

KEYNOTE AND INVITED SPEAKERS

PRE-CONFERENCE PROGRAMME

CONFERENCE PROGRAMME

PAPERS

Pre-conference Seminar: Design and Additive Manufacturing of Titanium Parts

1. Direct Metal Laser Sintering Production of Ti6Al4V Parts from a Purely Elemental Powder Blend, Lekhetho Ramosena, Thywill Dzogbewu and Willie Du Preez
2. Examining Various Mixing Techniques and their Effect on the Uniform Dispersion of Carbon Nanotubes in a Ti6Al4V (ELI) Matrix, Mpho Mashabela, Maina Maringa and Thywill Dzogbewu
3. Comparative Analysis of the High Velocity Impact Behaviour of Wrought Ti6Al4V and Stress Relieved DMLS Ti6Al4V (ELI), Teboho Moleko, Maina Maringa and Willie Du Preez

Additive Manufacturing Material Development

4. Characterization of Polypropylene Powder Produced by Precipitation for Powder Bed Fusion Additive Manufacturing, Joseph Nsengimana, Jacobus G van der Walt, Ernst H G Langner and Deon J de Beer
5. Parameters Affecting the Mixing of Powders and the Results of Mixing SiC and Ti6Al4V(ELI) Powders, Masenate Thamae, Maina Maringa and Willie du Preez
6. Laser Metal Deposition of TiB2/TiC/Ti6Al4V Composites, Nomahlubi Thunyiswa, Chris Theron, Paul Lekoadi and Bathusile Masina
Additive Manufacturing Process Development

7. A Risk Based Classification Method for Powder Bed Defects, Francois Du Rand, Malan van Tonder and Andre van der Merwe
8. Laser Optimised Process Parameters for Suppressing Columnar Phase and Nb Segregation in IN718 Clad, Bathusile Masina, Khoro Malabi, Samuel Skhosane, Sisa Pityana and Monnamme Tlotleng

Additive Manufacturing Part Characterisation

10. Fractography of Polypropylene Laser Sintered Tensile Test Specimens, Fredrick M Mwania, Maina Maringa and Jacobus G van der Walt
12. Investigation of Microstructure and Hardness Properties of in-situ TiB/Ti6Al4V ELI Composite Manufactured by Laser Metal Deposition, Paul Lekoadi, Monnamme Tlotleng and Bathusile Masina

Rapid Sand Casting

15. Assessment of Moulding Properties of Local Chromite Sand for Rapid Sand Casting Applications, Julieth Langutani Chauke, Kasongo Didier Nyembwe and PJM van Tonder
16. Assessment and Comparison of Local Silica Sands for Three Dimensional Printing Applications, Oyombo Dady, Didier Kasongo Nyembwe and Malan van Tonder

Additive Manufacturing Post Processing and Qualification

17. Dimensional Error Testing of 3D Printed Samples after Sterilization for Orthopedic Surgery, Leon Kotze, Johan van der Merwe and Rudolph Grobler Venter
18. Importance of Characterizing the Variability for Batch Production using Laser Powder Bed Fusion, Cindy Sithole, Ian Gibson and Sipke Hoekstra
19. Industry’s Adoption of Additive Manufacturing of Spare Parts, Duwan Bester and Lerato Tshabalala
Product Development


21. Directed Energy Deposition of a Cemented Tungsten Carbide Rotary Burr Prototype, Emma Molobi, Natasha Sacks and Maritha Theron

22. Combined Implicit and Explicit Techniques to Create a Bespoke Optimized 3D Printed Lattice Socket for a Prosthetic Hand, Jode Fourie, Clive Hands, William Rall and Riaan Stopforth


25. An AM Solution to a Golfing Predicament - a Bespoke Golf Putter Head and Hosel with Multiple Configuration Options for Personalized Club Fitment, Wian van Aswegen, Clive Hands, William Rall and Riaan Stopforth
2021 CONFERENCE PLATINUM SPONSOR

Department of Science and Innovation
www.dst.gov.za
2021 CONFERENCE
SILVER SPONSORS

Central University of Technology,
Free State, Bloemfontein
www.cut.ac.za

Vaal University of Technology,
Vanderbijlpark, Gauteng
www.vut.ac.za

EOS
www.eos.info

CSIR National Laser Centre
www.csir.co.za

3D Printing Systems South Africa
www.3dprintingsystems.co.za

Simteq
https://simteq.co.za/
TECHNICAL COMMITTEE

Prof Willie du Preez
RAPDASA Editor and Chairperson of Technical Committee

Dr Kobus van der Walt
(Track director for pre-conference seminar on design and additive manufacturing of titanium parts)

Dr Thywill Dzogbewu
(Track director for additive manufacturing material development)

Prof Elisha Markus
(Track director for robotics and mechatronics)

Dr Ritesh Ajoodha
(Track director for pattern recognition)

Prof Thorsten Becker
(Track director for additive manufacturing process development)

Dr Lerato Tshabalala
(Track director for additive manufacturing part characterisation)

Dr Ntombi Mathe
(Track director for additive manufacturing post processing and qualification)

Mr Francois Du Rand
(Track director for product development)

Dr Hein Möller
(Track director for rapid sand casting)
The 22nd Annual International RAPDASA Conference

Digital Manufacturing: Industrialising Africa

TECHNICAL COMMITTEE

REVIEWERS

Prof I Campbell
Mr David Mauchline
Dr Malika Khodja
Mr Heinrich van der Merwe
Prof Riaan Stopforth
Prof Deborah Blaine
Mr Daniel Kirkman
Mr Duncan Gibbons
Prof Lesley Cornish
Dr Maina Maringa
Dr David Prawel
Kyla Purdon
Dr Hossein Ramezani-Dana
Prof Allan Rennie
Alfred Sidambe
Dr Judit Svidró
Prof André van der Merwe
Daniel Withey
Prof Sanat Agrawal
Prof Olaf Diegel
Mncedisi Dewa
Prof Rangith Kuriakose
Prof Philip Hackney
Ms Belinda Matebese
Dr Babatunde Obadele
Samuel Ogunniyi
Daniel Oladele
Dr Dean Kouprianoff
Prof George Rading

Dr Gerrit ter Haar
Mr Danie Louw
Dr Chris Aggenbacht
Dr Silethelwe Chikosha
Prof Eyitayo Olatunde
Olakanmi
Prof Eujin Pei
Mr Wynand Roux
Dr Pratik Shukla
Mr Dinesh Sundaram
Prof József Svidró
Lintle Tsiu
Dean Van Aswegan
Devon Hagedorn-Hansen
Dr Ulyate Curle
Dr Sylvester Bolokang
John Fernandes
Prof Vijay Gautam
Chioniso Kuchwa-Dube
Prof Tolulope Loto
Mr Lebohang Loto
Mr Joseph Moema
Viwe Mqaqa
Dr Lameck Mugwagwa
Mr Teboho Ntsinyi
Dr Enoch Ogunmuyiwa
Dr Vincent Ojijo
Mr Preyin Govender
Dr Emad Uheida
FOREWORD

Message by the Chairperson of the RAPDASA 2021 Conference
Mr Marius Vermeulen

The first RAPDASA international conference was held here at the CSIR in November 2000, and today, we are celebrating our 22nd annual conference. Being back here, where we started, allows a glance into history to see how the world around us has been changing and adapting over two decades.

During the last two years we have been faced by many challenges and digital solutions have become an everyday solution. This impacted in many ways, from the way we interact in the workplace, to the way we do our shopping. This step-change in our realm, however, seems to reflect what has been happening in industry over the last two decades.

In a world where manufacturing is moving into a digital realm, rapid product development is now the norm, rather than the exception. To keep up with an ever-changing world, product development is not just about the physical object anymore, but on how the product relates, communicates and interacts with its user and environment. The designer is, more than ever, faced with a multi-disciplinary environment and solutions require collaborative approaches. As always, it is the responsibility of our scientists, engineers and captains of industry to not only adapt to this change, but to drive innovation for tomorrow.

The Rapid Product Development Association of South Africa (RAPDASA) have a proud history of fostering product development in the country. By bringing stakeholders together, we have been creating a platform for collaborative innovation for over two decades. This year, we are honoured to take hands with IEEE and to be joined by RobMech for their 14th conference on ‘Robotics and Mechatronics’, as well as PRASA for the 32nd ‘Pattern Recognition Association of South Africa’ conference.

I’m excited about the new possibilities when we bring together our gurus in Additive Manufacturing, Robotics, Mechatronics, Pattern Recognition and Artificial Intelligence. Collaboration, across disciplines, is one of the essential tools we need to adopt when carving our future. Our conference theme for the year ‘Digital Manufacturing: Industrialising Africa’ is about us taking charge of our own future in a world where the pace of innovation is increasing. This is only possible by taking hands and innovating together.
I would like to take this opportunity to congratulate the organisers of the RAPDASA/RobMech/PRASA conference of 2021! You have risen to the challenges and created a conference within a set of unprecedented limitations. Not only have you succeeded but you excelled.

I want to thank our sponsors who continually support us and make RAPDASA possible, with a special thanks to the CSIR, our conference host. I also wish to thank our exhibitors who trust in us and adds tremendous value to the conference and to our delegates. We also appreciate the involvement of our speakers and international guests and thank you for sharing your experience.

To our delegates: the students, scientists, makers, engineers, policy makers, funders, innovators and industrialists of Africa and abroad. We thank you for your contribution and I challenge you to reach out, network, take hands and develop the solutions of our future together. I’m excited to be able to look back again a decade from now and to see how you changed our world again.

Mr Marius Vermeulen
REVIEW PROCESS

A formal “Call for papers” for the 2021 Rapid Product Development Association of South Africa - Robotics and Mechatronics - Pattern Recognition Association of South Africa (RAPDASA-RobMech-PRASA) Conference was issued in May 2021 to submit an ‘Extended Abstract’ within the identified conference themes. Extended Abstract submissions were subjected to an internal reviewing process, whereby successful submissions were notified and invited for presentation to the conference. Authors were subsequently invited to submit an optional ‘Full Paper’, which was intended for publication in the conference proceedings. Both the Extended Abstracts and Full Papers were submitted online through the EasyChair conferencing system whereafter acknowledgement of receipt was sent to authors through the system. Authors were informed that a double-blind review process would be applied to Full Paper submissions.

The following dates were set by the Technical Committee:

• Deadline for submission of abstracts: 4 June 2021
• Extended deadline for submission of abstracts: 30 June 2021
• Notification of acceptance of abstracts: 26 July 2021
• Deadline for submission of full papers: 16 August 2021
• Feedback on paper reviews: 27 September 2021
• Deadline for final revised paper submission: 8 October 2021

Extended Abstracts were required to be a maximum length of 2 pages. Full Papers were required to comply with the Author Guidelines and template provided on the conference website.

A double-blind peer review process was used for the Full Paper submissions. The authors’ identities were concealed from the reviewers and the reviewers’ identities were concealed from the authors, throughout the review process. Each Full Paper submission was sent to a minimum of two reviewers, with a third reviewer being requested in case of lack of consensus between the first two reviewers. The reviews were performed by national and international academics, and other experts in the respective fields, listed on the Technical Committee page.

For this conference 62 papers were submitted for review and more than 90 local and international reviewers participated in the review process. Reviewers were asked to review submissions according to the following criteria and were encouraged to provide recommendations and suggestions.

• Does the title reflect the contents of the paper?
• Does the paper relate to what has already been written in the field?
• Do you deem the paper to be proof of thorough research and knowledge of the most recent literature in the field of study?
• Is the paper clearly structured, easy to read and with a logical flow of thought?
• Are the arguments employed valid and supported by the evidence presented?
• Are the conclusions clear and valid?
• Does the paper conform to accepted standards of language and style?
• Any other recommendation(s)?
• Select reviewer recommendation: ‘Accept Submission’, ‘Revision Required’, or ‘Decline Submission’.

Reviewer feedback was saved on the EasyChair submission system, from where acceptance emails together with review comments were sent to the authors, allowing them to revise the submission. The authors were given about 2 weeks to incorporate changes, after which the final document was submitted for approval and publication in the conference proceedings.

Based on the outcome of the double-blind peer review process and the recommendations of the reviewers, eight papers were selected from the papers submitted to the conference and were submitted to the South African Journal of Industrial Engineering (SAJIE) to be considered for publication as journal articles. The editor of SAJIE accepted six of the submitted papers for publication in the journal. These papers were not included in the conference proceedings and were subjected to SAJIE’s editorial process.
KEYNOTE AND INVITED SPEAKERS

Prof Ian Campbell
Emeritus Professor at Loughborough University

Prof Paulo Bartolo
Executive Director, Singapore Centre for 3D Printing

Markus Glasser
Senior Vice President EMEA, EOS GmbH

Dr Karsten Heuser
VP Additive Manufacturing, Siemens Digital Industries

Prof Alessandro Fortunato
Associate Professor at the University of Bologna

Prof Med Dr Mashudu Tshifularo
ENT specialist, University of Pretoria, Steve Biko Academic Hospital

Dr Terry Wohlers
Dr Terry Wohlers, President of Wohlers Associates, Inc., U.S.A

Johan Pretorius
Aerosud Group IT Leader, Leader and Strategist at OCTi Agile Consulting and MWorx™

Prof Olaf Diegel
Professor of Additive Manufacturing, University of Auckland, New Zealand

Prof Joel Vasco
Polytechnic of Leiria, Institute for Polymers and Composites, Portugal

Stefan Ritt
SPEE3D GmbH
After graduating from the Special Engineering Programme at Brunel University in 1985, Ian Campbell worked as a design engineer, first in Ford Motor Company, and later in the Rover Group. In 1989, he was appointed as a Senior Teaching Fellow for CAD/CAM at the University of Warwick. This gave him the opportunity to raise his awareness of CAD/CAM technology and practices. He remained in this position for four years, during which time, he undertook a part-time MSc degree by research. In 1993, he obtained a lectureship at the University of Nottingham and gained his PhD, again through part-time study, in 1998. He moved to Loughborough University in October 2000, where he was appointed as a senior lecturer and then promoted to reader in 2006. He became Professor of Computer Aided Product Design in the School of Design and Creative Arts in 2017. He is currently supervising several research projects, mainly in the area of design interaction and 3D printing technologies. Prof Campbell is a Fellow of the Institution of Mechanical Engineers and was Editor-in-Chief of the Rapid Prototyping Journal from 1995 to 2020. He is now an Emeritus Professor at Loughborough University.

ABSTRACT

How a Collaborative International Partnership is Driving the DiCoMI Project Forward

Many research projects require an interdisciplinary approach that brings together the best minds and best facilities from different subject areas. Finding the appropriate combination of partners within a single institution, or even a single country, is often difficult and sometimes impossible. The European Commission’s programme entitled Research and Innovation Staff Exchange Evaluations (RISE) is designed to overcome these issues. This presentation describes Loughborough University’s experience in developing, submitting and running the DiCoMI project under the auspices of the RISE programme. It explains the importance of finding the right partners, writing a strong bid,
and managing a project effectively. The results of the DiCoMI project are presented, both in terms of technological advancements, but also the human development aspect. Important lessons that have been learned will be shared to help future applicants to this and other programmes. The outcomes should be of particular interest to South African researchers since the Vaal University of Technology is a DiCoMI partner.
Prof Paulo Bartolo
Executive Director, Singapore Centre for 3D Printing

Paulo Bartolo holds a PhD from the University of Reading (2001), an MSC in Mechanical Engineering (1996) and a first degree (Licenciatura – five year programme) in Mechanical Engineering (1993) both from the University of Lisbon (Portugal). Since August 2021, Paulo Bartolo is Professor at the School of Mechanical and Aerospace Engineering (MAE), Nanyang Technological University (NTU), Executive Director of Singapore Centre for 3D Printing (SC3DP) and Director of the National Additive Manufacturing Innovation Cluster (NAMIC) hub at NTU. Since 2014 he served the University of Manchester as Chair Professor on Advanced Manufacturing. At the University of Manchester, he was the Head of the Manufacturing Group, the Industry 4.0 Academic Lead; member of the Advanced Manufacturing Strategic Oversight Group; member of the Management Board of the EPSRC & MRC Centre for Doctoral Training in Regenerative Medicine; and theme leader of the “Industry 5.0” Societal Challenge area within the Digital Futures. Between 1994 and 2014, Paulo Bartolo served the Polytechnic Institute of Leiria (Portugal) as Lecturer, Assistant Professor and Coordinator Professor. At the Polytechnic Institute of Leiria, he was the founder and Director of the Centre for Rapid and Sustainable Product Development (2007-2013); Head of the Mechanical Engineering Department (2001-2009); President of the Research Assessment Commission (2009-2013); President of the Scientific Council for Research, Development and Advanced Studies (2009-2013); and Member of the Academic Council and Senate of the Polytechnic Institute of Leiria (2009-2013).

Paulo Bartolo authored/co-authored more than 600 publications in journal papers, book chapters and conference proceedings, co-edited 22 books and holds 16 patents. He has been engaged in around 100 research projects funded by EPSRC, Innovate UK, Bill and Melinda Gates Foundation, the Royal Society, the Portuguese Foundation for Science and Technology, the Portuguese Agency for Innovation, the European Commission, and Industry representing around £45 million.

Public recognition for outstanding contributions: Commendation and public recognition from the Portuguese Government, published in the Portuguese Government’s Law
Journal (Diário da Republica), for the outstanding work as advisor of the Portuguese Government in the area of Research and Innovation; Commendation from the Polytechnic Institute of Leiria, published in the Portuguese Government Journal, for the outstanding work carried out (2014); Council award Afonso Lopes Vieira in the area of Innovation, Leiria Town Council, Portugal (2009). Microsoft Academic ranked Paulo Bartolo as the most salient author worldwide on the biomanufacturing field and among the top 100 most salient author worldwide on the field of tissue engineering.

**ABSTRACT**

**Advances in Additive Manufacturing: a journey from Manchester to Singapore**

Additive manufacturing is a disruptive technology being one of the key technological pillars of the fourth industrial revolution allowing to increase labour and resource productivity, strengthening supply chains and creating new value streams, reduce cost of quality and inventory, enabling manufacturing close to point of use. Through the last two decades we have contributed to the development of this field in multiple ways. This keynote summarises our most recent contributions in terms of advanced materials and novel fabrication strategies. Examples related to the construction, marine, agriculture and medical sectors will be provided.
As the Senior Vice President EMEA since January 2020, Markus is responsible for EOS’s business in Europe, Middle East, Africa and also South America. Since joining EOS in 1998, Markus has held various sales-related roles in the export region. Over the years, he established EOS subsidiaries in UK and Nordics, introduced distribution partners in many other countries in his region and significantly grew the business by expanding into new markets and industries.

Prior to joining EOS, Markus was the Area Manager for Europe and Asia at Kettner, an equipment manufacturer in the packaging industry. Markus has a Dipl. Ing. degree in Production Engineering.

ABSTRACT

BRINGING INDUSTRIAL 3D PRINTING OF SERIAL PRODUCTION PARTS TOGETHER WITH RESPONSIBLE MANUFACTURING

EOS provides responsible manufacturing solutions via industrial 3D printing technology to manufacturers around the world. We are deeply committed to fulfilling customer needs while acting responsibly for the planet. To emphasize our commitment, EOS is introducing a holistic sustainability approach that extends the boundaries of industrial 3D printing to ensure that future production is less harmful for the planet. What that means in detail and how this supports the success of our customers, I will present in my presentation.
Dr Karsten Heuser  
VP Additive Manufacturing, Siemens Digital Industries

Dr Heuser has been with Siemens for nearly 20 years in various management positions within Siemens businesses including Corporate Technology, Energy and is now the VP of Additive Manufacturing and is located in Erlangen next to the AMEC which is one of the AM Competence Center in Siemens.

Dr Heuser has a Ph.D. in solid state physics from the University Augsburg, as well as a Postgraduate Diploma in Advanced Management from ESMT.

ABSTRACT

MANUFACTURING REINVENTED WITH ROBOT-BASED ADDITIVE MANUFACTURING

Additive Manufacturing transforms the everyday with unlimited opportunities. May it be performance improved designs, enabling personalized products, supporting more efficient and flexible manufacturing, or unleashing new business models like spare parts on demand. However, the technology is still at the verge of being industrialized for serial production. It’s all about efficiency, reliability and affordability while scaling 3D printing.

Within my keynote at this years RAPDASA hybrid conference, I would like to take the chance to present out of our Additive Manufacturing Experience Center in Germany. We will dive into the technology of transforming a robot system into a high precision, free-form Additive Manufacturing machine. Based on our CAD-CAM integrated software solutions and the Sinumerik controller nearly unlimited opportunities become possible, may it be composite or metal free form printing.
Prof Alessandro Fortunato
Associate Professor at the University of Bologna

Allessandro Fortunato is an Associate Professor in Manufacturing Technologies at the University of Bologna. He obtained his PhD in Mechanics of Materials and Production Technologies at the same university in 2006 with a thesis on numerical modelling of laser processes.

ABSTRACT

SELECTIVE LASER MELTING IN ENDOPROSTHESES FABRICATION: OPPORTUNITIES AND CHALLENGES

Joint replacement is the surgical treatment that allows to preserve joint motion in case of osteoarthritis and the use of patient-specific prostheses is a current challenge. The present research aims at investigating the use of Laser Powder-Bed Fusion to produce innovative CoCrMo endoprostheses. This process allows geometrical customization of prosthesis design to fit the patient anatomy and it enables the production of functionally graded (FG) bone-to-implant surface for failure reduction. This study involves process optimization, mechanical and kinematic characterization of both full density and FG structures and biological tests for the validation of innovative prostheses.
The road from herdsman to ground-breaking ear, nose and throat (ENT) surgeon is one that Professor Mashudu Tshifularo has walked with determination, skill and dignity. Born in poverty in Thohoyandou to a large family, Prof Tshifularo tended his family’s livestock as a boy and attended school under a tree. He knew, however, from a young age that his future lay in medicine and his career has been one of many firsts: he was the first black ENT specialist in South Africa and one of the youngest appointed to Medunsa’s Department of Otorhinolaryngology. More importantly, he made world headlines earlier this year when he performed the first transplant surgery of the hammer, anvil, stirrup and the ossicles – that make up the middle ear – using 3-dimensional printed inner ear bones.

Today, Prof Tshifularo is Head of the Department of Otorhinolaryngology at the University of Pretoria and Steve Biko Academic Hospital. Like many black children at the time, Tshifularo was affected by financial challenges in furthering his education after he passed matric. But today he has several degrees to his name. He is currently busy with his second PhD degree at the University of Pretoria. He holds a number of patents for middle ear implants and has published extensively in a number of leading peer-reviewed journals. He has dedicated himself to the training of students from disadvantaged groups and has been instrumental in training more black ENT specialists than any other institution.
ABSTRACT

The role of 3D technology in medicine prosthesis (personal experience)

The 4IR technology has changed the way we practice medicine. The advances in 3D technology have allowed us to do prosthesis as a possible to normal part which is defective, because of advances.

I will present my experience on 3D middle total ossicle replacement and the outcome. The case report of this technique brings about possibility of middle ear transplant pioneering idea research.
Dr Terry Wohlers
President of Wohlers Associates, Inc., U.S.A

Terry Wohlers is principal consultant and president of Wohlers Associates, Inc., an independent consulting firm he founded 35 years ago. Through Wohlers Associates, he has provided consulting assistance to more than 280 organizations in 27 countries, as well as to nearly 200 companies in the investment community. He has authored 440 books, articles, and technical papers and has given 170 keynote presentations on six continents. Wohlers served as a featured speaker in events at the White House in 2012 and 2014 and has appeared on many television and radio news programs. He is a principal author of the Wohlers Report, the undisputed industry-leading report on additive manufacturing and 3D printing worldwide for 26 consecutive years. Many refer to it as the “bible” of 3D printing. In 2004, Wohlers received an Honorary Doctoral Degree of Mechanical Engineering from Central University of Technology in Bloemfontein, South Africa.

ABSTRACT

A Maturing Industry Advancing to the Next Level

The additive manufacturing industry is 32 years of age. Many AM applications are nothing short of astounding, both from technical and business points of view. Investment in the development and adoption of AM is at a pace not seen in the past. This activity is helping companies to scale and focus on complete end-to-end solutions. Sales of machines, materials, software, and services are strong, even in a pandemic. The industry faces a myriad of challenges and obstacles, yet it is on track to exceed $100 billion in less than 10 years. This will be supported by strong returns on investment, coupled with countless stakeholders determined to take AM to the next level.
Johan Pretorius is the Aerosud Group IT Leader and Business Strategist with 25+ years of information and communication technology experience. He has an in-depth understanding of Business and Digital Transformation in the manufacturing industry and the approach needed to unlock business value. He is a committed change agent and business agility coach.

**ABSTRACT**

*Stabilise, Automate, Innovate and Accelerate:*

Speed and agility in a rapidly changing world have become the new benchmark for businesses. Any business successfully achieving this will gain the competitive edge. This is the journey of how we re-imagined and transformed the legacy Aerosud business and how it shaped our current and future business strategies.
Olaf is both an educator and a practitioner of additive manufacturing (AM) and product development with an excellent track record of developing innovative solutions to engineering problems. In his role as professor of additive manufacturing, at the University of Auckland, in New Zealand, he is involved in all aspects of AM and is one of the principal authors of the annual Wohlers Report, considered by many to be the bible of AM. His current main area of research expertise is in design for AM. In his consulting practice he develops a wide range of products for companies around the world. Over the past three decades he has developed over 100 commercialized new products including innovative new theatre lighting products, security and marine products and several home health monitoring products and, for this work, has received numerous product development awards.

Over the last 30 years, Olaf has become a passionate follower of AM. He believes it is one of the technologies that has been a real godsend to innovation as it allows designers and inventors to instantly test out ideas to see if they work. It also removes the traditional manufacturing constraints that have become a barrier to creativity and allows us to get real products to market without the normally high costs that can become a barrier to innovation. In 2012, Olaf started manufacturing a range of 3D printed guitars that has developed into a successful little side-business.
ABSTRACT

Design for additive manufacturing and design automation: A perfect synergy

Many industries approach additive manufacturing (AM) as a drop-in replacement for conventional manufacturing technologies. This approach, however, does not fully utilize the unique possibilities that additive processes offer and their potential to be a catalyst for innovation. For over thirty years, AM has been extensively used as a rapid prototyping technology. When using the technologies for manufacturing, however, it should be noted that AM does not remove all manufacturing restrictions. It, instead, replaces them with a different set of design considerations that designers must take into account if they wish to successfully use the technologies to add value to their products. Otherwise AM can easily become a slow and uneconomical way of manufacturing products or parts.

The recent advent of automated design software technologies has also allowed the ability to almost completely automate the design of complex products that are perfectly suited to the complexity that AM offers. If these software technologies are combined with good design for AM practices, it can become a tremendous catalyst for increased innovation. This talk attempts to impart some practical guidance on how to design parts and use automated design software to gain the maximum benefit from what AM can offer.
Prof Joel Vasco  
Polytechnic of Leiria, Institute for Polymers and Composites, Portugal

Joel Vasco has been lecturing at the School of Technology and Management in Leiria since November 2001, as a member of the Mechanical Engineering Department, lecturing classes in areas such as Industrial Production Processes, Mould Design, Advanced Manufacturing Processes, Direct Digital Manufacturing Technologies, among others. He is currently the coordinator of the Master of Engineering for Direct Digital Manufacturing since December 2018 for the Polytechnic of Leiria and the vice-director of the PhD in Direct Digital Manufacturing for the polymers and moulds industries for the University of Minho, recently approved.

He also performs research at the Institute of Polymers and Composites at the University of Minho, focusing his areas of interest on subtractive, formative and additive manufacturing processes, micro technologies and direct digital manufacturing. The results of the research have been published in international indexed scientific journals, book chapters and in renowned international conferences, with scientific peer review.
ABSTRACT

Presentation Title: The adoption of AM by the Automotive industry

Automotive industry is a very competitive industry, where new market and design trends emerge continuously, requiring new manufacturing approaches to comply with the market requests. Additive manufacturing (AM) rises up in this context as a key-enabling technology to provide flexibility on production and bringing an important competitive edge to this industrial domain.

The use of AM on soft assembly tools or specialized tools to produce vehicle components is powered by the freeform of design that AM has to offer. It enables the design and direct production of optimized automotive components, incorporating lightweight structures, focused on vehicle’s performance as well as customised assembly tools to enhance productivity. Finally, AM is the key-enabling technology for mass customization, providing the means for collaborative development of products between designers, engineers, regulators and end-users to co-create new products within the AM ecosystem.
After earning his engineering degree in technical physics from the University of Applied Science in Lübeck, Germany, Stefan Ritt started his career in RP/AM in 1985 when running a prototype lab in the R&D arm of a coffee and vending machine company. After that, he held positions in QA and product management for mid-sized Dutch and Danish companies. In 1998, Stefan took on international sales and marketing of RP tooling products for a UK/German joint venture. In this capacity, he was successful in international markets with the development and support of the transition of RPT and metal AM equipment into production equipment. Stefan has also worked for SLM Solutions where he continued his efforts to grow the metal AM market internationally. There he managed to bring the first powder-bed Laser metal printer on display at an AMUG-conference to the US. He now works for SPEE3D from Melbourne-Australia, which brings another new metal AM technology for production into the market, as their European managing director. He is a part-time lecturer for supply chain management at the technical university of Lübeck and guest lecturer for international business communication in marketing at the Technical University in Hamburg. He was also head of the DIN standardization group “additive manufacturing in aerospace” for 4 years and helped to develop the first international AM-standards for certification in that industry. In 2011, he was appointed as the European liaison officer and global ambassador for AMUG. As he travels around the world, he spreads the news about AMUG activities to expand the awareness of the users group in global markets. In 2015 he was awarded the AMUG-DINO for his continuous support and involvement for the user group and industry. Every year he brings the latest news, trends and future outlooks of the AM industry from around the world to the audience at the AMUG conference. Stefan is also part of the EPMA AM-steering committee to help our association to focus on the additive manufacturing industry for our members.
ABSTRACT

Additive manufacturing for metals is now established in more and more industries

Due to the high flexibility and just-in-time as well as on-demand manufacturing possibilities, this technology is also predestined for expeditionary and defense applications. However, many systems on the market are technically very sensitive and complex and therefore stand in the way of use “in the wild”.

Several field tests have already been successfully carried out with cold spray technology. The presentation will report on this and thus also show possible future application concepts such as offshore wind farms, oil and gas industry applications and expeditionary environments such as in Central Africa or Asia.

Because cold spray technology does not completely melt the material, the process is tens of orders of magnitude faster and handling much easier. The number of usable metal powders is constantly increasing, opening up more and more areas of application.

The Australian Defence Force has already been using the technology for several years to support field repair and spare parts procurement problems. Other industrial applications such as mould making and the production of unavailable spare parts have also been developed.

These attributes make the potential use of cold spray technology in the environmental conditions of the African continent particularly interesting and the presentation is intended to stimulate discussion on this.
PROGRAMME

PRE-CONFERENCE SEMINAR

Tuesday, 02 November 2021
Pre-Conference Seminar on Design and Additive Manufacturing of Titanium Parts

08:30  Registration
09:00  Welcoming Address - Dr Kobus van der Walt, CUT
09:10  Opening Address - Ms Mmamose Seloane, Director: Technology Localisation, DSI
09:30  Direct metal laser sintering production of Ti6Al4V parts from a purely elemental powder blend - LA Ramosena, TC Dzogbewu and WB du Preez
09:50  Surface morphology of LPBF manufactured Ti6Al4V processed by centrifugal barrel finishing - NW Makoana, I Mathoho, L Tshabalala and I Yadroistev
10:10  Examining various mixing techniques and their effect on the uniform dispersion of carbon nanotubes within a Ti6Al4V (ELI) matrix - M Mashabela, M Maringa and TC Dzogbewu

10:30  TEA
11:00  Investigation of acoustic emission signal during laser powder bed fusion at different operating modes - D Kouprianoff
11:20  Comparative analysis of the high velocity impact behaviour of wrought and stress relieved DMLS Ti6AL4V (ELI) - TC Moleko, M Maringa and WB du Preez
11:40  Effect of varying energy density on the microstructure of TIC/TI-6AL-4V metal composite - P. Ramasobane, P. Lekoadi, PM Mashinini and B Masina
12:00  Additive Manufacturing: Looking Beyond Prototyping - I Adam
12:20  Closure - Dr Kobus van der Walt
12:30  Lunch

Hosted by Central University of Technology, Free State (CUT)
Supported by the Department of Science and Innovation (DSI)
PROGRAMME

DAY 1

Wednesday, 03 November 2021
The 22nd Annual International RAPDASA Conference
Digital Manufacturing: Industrialising Africa

BREAKAWAY SESSIONS
ROOM 1  ROOM 2  ROOM 3
ZOOM Room 1  ZOOM Room 2  ZOOM Room 3

Links and passwords to the online Zoom sessions will be distributed via email to registered conference attendees. For additional information, visit: https://rapdasa.org/annual-conference/

Wednesday, 03 November 2021

09:00 Opening and Welcome: Chairperson RAPDASA 2020 conference organizing committee - Dr Hencharl Strauss

09:15 Welcoming by CSIR management: Dr Thulani Dlamini, President and CEO of CSIR

09:30 Opening Address: Mr Beeuwen Gerryts, Chief Director: Technology localisation, beneficiation and advanced manufacturing, Department of Science and Innovation

PLENARY SESSIONS
Chair: Prof Deon de Beer

10:00 Keynote Address: Prof Ian Campbell, Emeritus Professor at Loughborough University: How a Collaborative International Partnership is Driving the DiCoMI Project Forward

10:30 TEA/COFFEE BREAK

10:50 Prof Paulo Bartolo, Executive Director, Singapore Centre for 3D Printing: Advances in Additive Manufacturing: a journey from Manchester to Singapore

11:20 Questions and answers
## TECHNICAL PRESENTATIONS

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Title</th>
<th>Speaker(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:30</td>
<td>Influence of powder characteristics on the spreadability of pre-alloyed WC-CO</td>
<td>Preyin Govender (1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:50</td>
<td>Development of a multipurpose, outdoor autonomous ground vehicle for agricultural inspection</td>
<td>Willis de Ronde (12)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:10</td>
<td>Characterization of polypropylene powder produced by precipitation for powder bed fusion additive manufacturing</td>
<td>Joseph Nsengimana (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:30</td>
<td>Parameters affecting the mixing of powders for additive manufacturing and the results of mixing SiC and Ti6Al4V powders</td>
<td>Mamphutlane Seleso (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13:00</td>
<td>Laser metal deposition of TiB2/TiC/Ti6Al4V composites</td>
<td>Athernia Thunyiswa (4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>An Octomap-based 3D costmap</td>
<td>Daniel Withey (14)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Development of a graphical user interface as a learning tool for artificial intelligence</td>
<td>Natasha Botha (26)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ground Robot Path Planning on 3D Mesh Surfaces Using Local Regions</td>
<td>Cebisile Mthabela (15)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A comparative study towards particle identification employing semi-automated image processing in experimental SEM images</td>
<td>Beatrice van Eden (27)</td>
</tr>
</tbody>
</table>

**Breakaway Sessions**

<table>
<thead>
<tr>
<th>Room</th>
<th>Session Title</th>
<th>Session Chair</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROOM 1</td>
<td>Additive Manufacturing</td>
<td>Hardus Greyling</td>
</tr>
<tr>
<td>ROOM 2</td>
<td>RobMech</td>
<td>Prof Elisha Markus</td>
</tr>
<tr>
<td>ROOM 3</td>
<td>PRASA</td>
<td>Imdaadulah Adam</td>
</tr>
</tbody>
</table>

**Themes:**

- **AM Material Development**
- **Robotics and Mechatronics**
- **Pattern Recognition**
The 22nd Annual International RAPDASA Conference

**Digital Manufacturing: Industrialising Africa**

**BREAKAWAY SESSIONS**

<table>
<thead>
<tr>
<th>ROOM 1</th>
<th>ROOM 2</th>
<th>ROOM 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive Manufacturing</td>
<td>RobMech</td>
<td>PRASA</td>
</tr>
<tr>
<td>Session Chair: Prof Sisa Pityana</td>
<td>Session Chair: Duwan Bester</td>
<td>Session Chair: Dr Lethu Chikosha</td>
</tr>
</tbody>
</table>

**Theme: AM Material Development**

**14:00**

Development of novel bioinks for bioprinting and tissue engineering by **Jaundrie Fourie (5)**

Evaluation of visual odometry method in 3D LIDAR based mapping by **Samuel Ogunniyi (16)**

One-Class Support Vector Machines for Boat Detection using Fully Polarimetric Radar by **Thabang Matladi (28)**

**Theme: AM Process Development**

**14:20**

Risk based classification of powder bed defects by **Francois Du Rand (6)**

Manufacturing and Evaluation of the Open-Source AR3 Robot Arm for Educational Uses by **Kyla Purdon (17)**

Framework for cemented tungsten carbide drill bit prototype fabrication using laser engineered net shaping by **Natasha Sacks (29)**

**14:40**

Efficiency evaluation of a high-temperature preheating system for additive manufacturing by **Rabelani Ramulifho (7)**

Development of a platform for the freeform extrusion of a continuous glass fiber reinforced photopolymers by **Daniel Kirkman (18)**

Direct energy deposition of a cemented tungsten carbide rotary burr prototype by **Emma Molobi (30)**

**15:00**

Effect of particle size distribution on the resulting part density and mechanical properties in selectively laser melted cobalt chrome by **Stuart Papworth (8)**

Core functional MES with machine monitoring using open-source software by **Kshir Ramruthan (19)**

The role of AM polymers to improve the OEE of operations by **Henk Harmse (31)**

**15:20**

Validation and investigation of deformation prediction and deformation compensation for additive manufacturing by **Benic van Wyk (9)**

PID Control for a collaborative humanoid robot by **Teboho Ntsinyi (20)**

Combined implicit and explicit techniques to create a bespoke optimized 3D printed lattice socket for a prosthetic hand by **Jode Fourie (32)**
<table>
<thead>
<tr>
<th>TIME</th>
<th>SESSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:40</td>
<td>TEA/COFFEE BREAK</td>
</tr>
<tr>
<td>16:00</td>
<td><strong>Room 1</strong>&lt;br&gt;<strong>Additive Manufacturing</strong>&lt;br&gt;<strong>Session Chair:</strong> Dr Wayne Koen</td>
</tr>
<tr>
<td>16:00</td>
<td><strong>Room 2</strong>&lt;br&gt;<strong>RobMech</strong>&lt;br&gt;<strong>Session Chair:</strong> Dr Hein Möller</td>
</tr>
<tr>
<td>16:00</td>
<td><strong>Room 3</strong>&lt;br&gt;<strong>Additive Manufacturing</strong>&lt;br&gt;<strong>Session Chair:</strong> Duncan Gibbons</td>
</tr>
</tbody>
</table>

### BREAKAWAY SESSIONS

#### Room 1: Additive Manufacturing
- **Theme:** AM Process Development
  - **16:00** Effect of Stress-relief anneal time on residual stress of Co-Cr-Mo parts manufactured with selective laser melting<br>Genevieve Rousseau (10)
  - **16:20** Prediction of inter-layer adhesion in polymer additive manufacturing<br>Tobias Ott (11)
  - **16:40** Assessment of the financial feasibility of rapid sand-casting process using the payback period method<br>Anazo Msani (23)

#### Room 2: RobMech
- **Theme:** Robotics and Mechatronics
  - **16:00** Design and manufacturing of an aggregate abrasion test device for testing in high acceleration field<br>Sipho Xungu (21)
  - **16:20** Elimination of shrinkage porosity in low alloy steel using MAGMASOFT simulation software<br>Jonathan Kabasele (22)
  - **16:40** Medical product development for animals using AM and digital manufacturing<br>Philip van der Walt (34)

#### Room 3: Additive Manufacturing
- **Theme:** Product Development
  - **16:00** A mobile and portable pre-ICU AM-produced BI-PAP ventilator system in response to COVID19 challenges<br>Zaahid Imran (33)

### 17:00 CLOSURE
Dimitri Dimitrov Scholarship
In honour of Dimitri Dimitrov

Enabling student participation
Financial aid for postgraduate students to attend and present at the annual RAPDASA conference
Make your donation to grow the number of students attending future conferences and ensure sustainability via the Snapscan QR code.

For more information, visit
www.rapdasa.org
PROGRAMME

DAY 2

Thursday, 04 November 2021
Thursday, 04 November 2021

08:00 Opening and Welcome: Chairperson RAPDASA 2020 conference organizing committee - Dr Hencharl Strauss

PLENARY SESSIONS
Chair: Dr Ntombi Mathe

08:10 Markus Glasser, Senior Vice President EMEA, EOS: Bringing industrial 3D printing of serial production parts together with responsible manufacturing

08:40 Dr Karsten Heuser, VP Additive Manufacturing, Siemens Digital Industries: Manufacturing reinvented with robot-based additive manufacturing

09:10 Prof Alessandro Fortunato, Associate Professor, University of Bologna: Selective laser melting in endoprostheses fabrication: opportunities and challenges

09:40 Prof Mashudu Tshifularo, ENT specialist, University of Pretoria, Steve Biko Academic Hospital: The role of 3D technology in medicine prosthesis (personal experience)

10:10 Questions and answers

10:20 TEA/COFFEE BREAK
## TECHNICAL PRESENTATIONS

### BREAKAWAY SESSIONS

<table>
<thead>
<tr>
<th>ROOM 1</th>
<th>ROOM 2</th>
<th>ROOM 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive Manufacturing</td>
<td>RobMech</td>
<td>Additive Manufacturing</td>
</tr>
<tr>
<td>Session Chair: Prof Thorsten Becker</td>
<td>Session Chair: Prof Didier Nyembwe</td>
<td>Session Chair: CP Kloppers</td>
</tr>
</tbody>
</table>

### Theme: AM Process Development

<table>
<thead>
<tr>
<th>10:40</th>
<th>Cold spray technology for metal 3D printing in rough environments and offshore applications</th>
<th>Characterization of waste sand generated during the Voxeljet rapid sand casting process</th>
<th>Topology Optimisation for Mass Reduction in Additively Manufactured Rocket Engine Propellant Pumps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Invited speaker: Stefan Ritt (35)</td>
<td>Accolade Motlabane (46)</td>
<td>Byron Blakey-Milner (56)</td>
</tr>
</tbody>
</table>

### Theme: Rapid Sand Casting

<table>
<thead>
<tr>
<th>11:00</th>
<th>Heat Treatment Development for Residual Stress Reduction in SLM Manufactured CoCr Components</th>
<th>Pre-optimisation of a resin coated chromite sand for rapid sand casting applications</th>
<th>Geographical education of the visually impaired using Braille system on physical models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Juan Du Plessis (36)</td>
<td>Neo Tshabalala (47)</td>
<td>Sanat Agrawal (57)</td>
</tr>
</tbody>
</table>

### Theme: Product Development

<table>
<thead>
<tr>
<th>11:20</th>
<th>Laser optimized process parameters for suppressing columnar phase and Nb segregation in IN718 clad IN718 clad</th>
<th>Suitability of Local Chromite Sand for use in Rapid sand casting</th>
<th>An AM solution to a golfing predicament – a bespoke golf putter head and hosel with multiple configuration options for personalized club fitment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bathusile Masina (37)</td>
<td>Julieth Langutani Chauke (48)</td>
<td>Wian van Aswegen (58)</td>
</tr>
</tbody>
</table>

<p>| 11:40 | Assessment of Consol silica sand for three dimensional printing applications |                                                                   |                                                                                                  |
|-------|--------------------------------------------------------------------------------|                                                                   |                                                                                                 |
|       | Oyombo Dady (49)                                                              |                                                                   |                                                                                                  |</p>
<table>
<thead>
<tr>
<th>Time</th>
<th>Theme: AM Part Characterisation</th>
<th>Theme: AM Post Processing and Qualification</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:00</td>
<td>Qualitative measurement rubric for internal cranial prostheses STL evaluation by Henra Muller (38)</td>
<td>Dimensional error testing of 3D printed samples and sterilisation techniques for orthopedic surgery by Leon Kotze (50)</td>
</tr>
<tr>
<td>12:20</td>
<td>Investigation of the properties of direct energy deposition additive manufactured 304 stainless steel by Shaik Ebrahim Hoosain (39)</td>
<td>High cycle fatigue performance of Ti6Al4V (ELI) parts produced with inherent direct metal laser sintering surface roughness by Hlakae Miya (51)</td>
</tr>
<tr>
<td>12:40</td>
<td>Influence of Ti and Cu on the Corrosion Properties of Laser-Deposited High Entropy Alloys in NaOH solution by Modupeola Dada (40)</td>
<td>Understanding the effect of characterising variability for batch production using laser powder bed fusion by Cindy Sithole (52)</td>
</tr>
</tbody>
</table>

13:00 LUNCH BREAK

**BREAKAWAY SESSIONS**

<table>
<thead>
<tr>
<th>ROOM 1</th>
<th>ROOM 2</th>
<th>ROOM 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive Manufacturing</td>
<td>Additive Manufacturing</td>
<td>Industry Presentations</td>
</tr>
<tr>
<td>Session Chair: Dr Lerato Tshabalala</td>
<td>Session Chair: Dr Ntombi Mathe</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Theme: AM Part Characterisation</th>
<th>Theme: AM Post Processing and Qualification</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00</td>
<td>An overview of the latest additive manufacturing research in the 3D Innovation group at Stellenbosch University by Anton Du Plessis (41)</td>
</tr>
</tbody>
</table>
## Digital Manufacturing: Industrialising Africa

### 14:20

**Using the Vickers indentation method to measure surface residual stress in SLM IN718 specimens**  
**Barend Coetsee Stander**  
*(42)*

**Industry taking up on-demand Additive Manufacturing of spare parts**  
**Duwan Bester**  
*(54)*

### 14:40

**Fractography of polypropylene laser sintered tensile test specimens**  
**Fredrick Mwania**  
*(43)*

**Qualification and certification for fatigue life in additive manufacturing**  
**Nic Macallister**  
*(55)*

### 15:00

**Residual stress, porosity and surface roughness measurements for laser powder bed fusion manufactured Ti6Al4V at high laser powers**  
**Nkutwane Washington Makoana**  
*(44)*

### 15:20

**The efficacy of the inherent strain method in determining residual stress in IN718 SLM specimen**  
**Herculaas Botha**  
*(45)*

### 15:40 TEA/COFFEE BREAK

## PLENDARY SESSION

**Chair: Prof Ian Campbell**

16:00 **Keynote Address: Dr Terry Wohlers,** President of Wohlers Associates, Inc.: A Maturing Industry Advancing to the Next Level

16:30 Questions and answers

16:40 **CLOSURE**

17:00 **RAPDASA ANNUAL GENERAL MEETING**

19:00 **GALA DINNER**
2021 CONFERENCE SILVER SPONSORS

Central University of Technology, Free State, Bloemfontein
www.cut.ac.za

Vaal University of Technology,
Vanderbijlpark, Gauteng
www.vut.ac.za

EOS
www.eos.info

Simteq
https://simteq.co.za/

3D Printing Systems South Africa
www.3dprintingsystems.co.za
Dimitri Dimitrov Scholarship
In honour of Dimitri Dimitrov

Enabling student participation
Financial aid for postgraduate students to attend and present at the annual RAPDASA conference
Make your donation to grow the number of students attending future conferences and ensure sustainability via the Snapscan QR code.

For more information, visit www.rapdasa.org
PROGRAMME

DAY 3

Friday, 05 November 2021
Friday, 05 November 2021

08:00  Opening and Welcome: Chairperson RAPDASA 2020 conference organizing committee - Dr Hencharl Strauss

PLENARY SESSIONS
Chair: Prof André van der Merwe

08:15  Mr Johan Pretorius, Aerosud Group IT Leader, Leader and Strategist at OCTi Agile Consulting and MWorx™: Stabilise, Automate, Innovate and Accelerate

08:45  Prof Olaf Diegel, Professor of Additive Manufacturing, University of Auckland, New Zealand: Design for additive manufacturing and design automation: A perfect synergy

09:15  Prof Joel Vasco, Polytechnic of Leiria, Institute for Polymers and Composites, Portugal: The adoption of AM by the Automotive industry

09:45  Questions and answers

10:30  TEA BREAK – Sponsors live sessions
## TECHNICAL PRESENTATIONS

<table>
<thead>
<tr>
<th>BREAKAWAY SESSIONS</th>
<th>ROOM 1</th>
<th>ROOM 2</th>
<th>ROOM 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive Manufacturing</td>
<td><strong>SESSION CHAIR:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dr Monnamme Tlotleng</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Theme: AM Part Characterisation

<table>
<thead>
<tr>
<th>Time</th>
<th>Presentation Title</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:50</td>
<td>An overview of the latest Analysis of corrosion and mechanical properties of DMLS manufactured Ti6Al4V parts</td>
<td>Kabelo Raselabe (59)</td>
</tr>
<tr>
<td>11:10</td>
<td>Investigation of microstructure and hardness properties of in-situ TiB/Ti6Al4V ELI composite manufactured by laser metal deposition</td>
<td>Paul Lekoadi (60)</td>
</tr>
<tr>
<td>11:30</td>
<td>Microstructure and tensile properties of 3D printed Ti-48Al-2Nb-2Cr alloy manufactured by direct laser metal deposition</td>
<td>Sisa Pityana (61)</td>
</tr>
</tbody>
</table>

**11:50 ACKNOWLEDGEMENTS:** Chairperson of RAPDASA 2021 - Mr Marius Vermeulen

12:00 CLOSING

12:00 LUNCH
## AUTHOR INDEX

<table>
<thead>
<tr>
<th>Author Name</th>
<th>Author Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accolade Motlhabeane</td>
<td>Leon Kotze</td>
</tr>
<tr>
<td>Anazo Msani</td>
<td>Lerato Tshabalala</td>
</tr>
<tr>
<td>André Broekman</td>
<td>Maina Maringa</td>
</tr>
<tr>
<td>André van der Merwe</td>
<td>Malan van Tonder</td>
</tr>
<tr>
<td>Annikie Matjila</td>
<td>Maritha Theron</td>
</tr>
<tr>
<td>Anton du Plessis</td>
<td>Martin Mgangira</td>
</tr>
<tr>
<td>Bathusile Masina</td>
<td>Masenate Thamae</td>
</tr>
<tr>
<td>Beatrice van Eden</td>
<td>Modupeola Dada</td>
</tr>
<tr>
<td>Brandon Davoren</td>
<td>Monnabwa Tiotleng</td>
</tr>
<tr>
<td>B T Matebese</td>
<td>Mpho Mashabela</td>
</tr>
<tr>
<td>Cebisile Mthabela</td>
<td>Natasha Botha</td>
</tr>
<tr>
<td>Chioniso Kuchwa-Dube</td>
<td>Natasha Sacks</td>
</tr>
<tr>
<td>Chris Theron</td>
<td>Nicolene Botha</td>
</tr>
<tr>
<td>Cindy Sithole</td>
<td>Nkutwane Washington Makoana</td>
</tr>
<tr>
<td>Clive Hands</td>
<td>Nomahlubi Thunylswa</td>
</tr>
<tr>
<td>Daniel Kirkman</td>
<td>Ntombi Mathe</td>
</tr>
<tr>
<td>Daniel Withey</td>
<td>Olufemi Aramide</td>
</tr>
<tr>
<td>Deon J de Beer</td>
<td>Oyombo Dady</td>
</tr>
<tr>
<td>Didier Kasongo Nyembwe</td>
<td>Paul Lekoadi</td>
</tr>
<tr>
<td>Duncan W Gibbons</td>
<td>Patricia Popoola</td>
</tr>
<tr>
<td>Duwan Bester</td>
<td>Riaan Stopforth</td>
</tr>
<tr>
<td>Elisha Didam Markus</td>
<td>Rudolph Grobler Venter</td>
</tr>
<tr>
<td>Emma Molobi</td>
<td>Samson Adeosun</td>
</tr>
<tr>
<td>Ernst H G Langner</td>
<td>Samuel Ogunniyi</td>
</tr>
<tr>
<td>Francois Du Rand</td>
<td>Samuel Skhosane</td>
</tr>
<tr>
<td>Fredrick M Mwania</td>
<td>Sanat Agrawal</td>
</tr>
<tr>
<td>Gert Wessels</td>
<td>Sipho Xungu</td>
</tr>
<tr>
<td>Ian Campbell</td>
<td>Sipke Hoekstra</td>
</tr>
<tr>
<td>Ian Gibson</td>
<td>Sisa Pityana</td>
</tr>
<tr>
<td>Ina Yadroitsava</td>
<td>Stephen Marais</td>
</tr>
<tr>
<td>Igor Yadroitsev</td>
<td>Teboho Moleko</td>
</tr>
<tr>
<td>Jacobus G van der Walt</td>
<td>Teboho Ntsinyi</td>
</tr>
<tr>
<td>Jode Fourie</td>
<td>Thembisile Dlamini</td>
</tr>
<tr>
<td>Johan van der Merwe</td>
<td>Thywill Dzogbewu</td>
</tr>
<tr>
<td>John Dickens</td>
<td>Tiro Setati</td>
</tr>
<tr>
<td>John Giani</td>
<td>Wian van Aswegen</td>
</tr>
<tr>
<td>Joseph Nsengimana</td>
<td>William Rall</td>
</tr>
<tr>
<td>Julieth Langutani Chauke</td>
<td>Willie du Preez</td>
</tr>
<tr>
<td>Jurie Du Toit</td>
<td>Willis de Ronde</td>
</tr>
<tr>
<td>Khoroe Malabi</td>
<td>Wynand Steyn</td>
</tr>
<tr>
<td>Kshir Ramruthan</td>
<td>Vikas Khoj</td>
</tr>
<tr>
<td>Kyla Purdon</td>
<td>Yurisha Goorun</td>
</tr>
<tr>
<td>Lebohang Masheane</td>
<td>Zaahid Imran</td>
</tr>
<tr>
<td>Lekhetho Ramosena</td>
<td></td>
</tr>
</tbody>
</table>
PAPERS
Pre-conference Seminar: Design and Additive Manufacturing of Titanium Parts
Direct Metal Laser Sintering Production of Ti6Al4V Parts from a Purely Elemental Powder Blend

Lekhetho Ramosena  
Department of Mechanical and Mechatronics Engineering  
Central University of Technology, Free State  
Bloemfontein, Free State  
iramosen@cut.ac.za

Thywill Dzogbewu  
Department of Mechanical and Mechatronics Engineering  
Central University of Technology, Free State  
Bloemfontein, Free State  
tdzogbewu@cut.ac.za

Wille du Preez  
Centre for Rapid Prototyping and Manufacturing, Faculty of Engineering, Built Environment and Information Technology  
Central University of Technology, Free State  
Bloemfontein, Free State  
wdupreez@cut.ac.za

Abstract—Additive manufacturing processes have been successfully used to produce Ti6Al4V alloy parts from pre-alloyed Ti6Al4V powders. The produced parts were defect free and had properties that are comparable to wrought Ti6Al4V parts. Although the efficacy of this method has been scientifically proven, the high-cost production of the pre-alloyed parts can be used to produce this alloy. The purpose of this paper is to demonstrate the results obtained from an attempt to produce the Ti6Al4V alloy from a purely elemental powder blend using the Direct Metal Laser Sintering process. For this investigation, single tracks followed by single and double layers were produced and analysed. Since single tracks are considered as the building blocks of sintered parts, this investigation began with the production and analysis of single tracks. The process parameters that produced optimum single tracks were identified and used to produce the subsequent layers. Two sets of process parameters that could potentially be used to produce 3D parts were found to be laser powers of 200 and 250 W at the corresponding scanning speed of 0.6 m/s.

Keywords—Additive manufacturing, pre-alloyed, powder blend, process parameters, single track, energy density.

I. INTRODUCTION

Additive Manufacturing (AM), formerly known as Rapid Prototyping (RP), is a manufacturing technology that has revolutionised the manufacturing industry since it was first developed about three decades ago [1]. AM is a tool-less manufacturing technology capable of producing customized and complex geometry parts that would have been near impossible to produce using the conventional subtractive manufacturing methods [2]. According to the American Society for Testing and Materials (ASTM), AM can be defined as “the process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [3]. ASTM F2792-12a classifies AM processes into seven distinct categories, namely: Binder Jetting, Directed Energy Deposition (DED), Material Extrusion, Material Jetting, Powder Bed Fusion (PBF), Sheet Lamination and Vat Photopolymerization. The Direct Metal Laser Sintering (DMLS) process is a constituent of the PBF category.

There has been an increased demand for additively manufactured parts that are intended for use in common engineering applications and industries [1]. However, AM parts are known for their high cost that is usually associated with the price of the production machine or of the starting feedstock material [4]. For this reason, it is imperative that new AM methods and materials are developed in order to broaden the application of this disruptive technology so that it is able to reach the less critical industries that cannot currently afford to employ it [1,2]. As a starting point, AM machine manufacturers have developed affordable desktop printers such as the ReaLizer SLM 50 [5] in an attempt to bridge the gap between the industries that are already taking advantage of this AM technology and those that are interested in the technology but cannot afford to purchase the full-scale AM machines. The task now remains for researchers to match the efforts made by the AM machine manufacturers by investigating and developing new and more cost effective materials that can be used to produce AM parts. The study of the new AM materials would warrant the development of new process parameters that are suitable for that particular material and a thorough analysis of the microstructure and properties of the produced parts. A comparison of the microstructure and properties of these parts will then be done against the parts produced by the conventional AM materials and the relevant standards. The development of new AM materials has the potential to open a new avenue in the AM industry which could in turn potentially open up new opportunities for the development of the AM industry [1,2,4,6].

The Ti6Al4V alloy is the most common and widely used titanium alloy. Ti6Al4V has a combination of properties and characteristics such as high strength, lightweight, formability and corrosion resistance, which make it a desirable material for applications in many industries [7]. However, this alloy is mostly used for applications in industries such as the aerospace, motorsports and medical industries where its good properties and characteristics justify its high price [8]. This alloy is normally used to produce parts for these industries using pre-alloyed (PA) powders of Ti6Al4V as feedstock in the DMLS and other AM processes. The production of these PA powders involves cost-intensive thermo-mechanical processes that result in a costly starting material, therefore resulting in costly Ti6Al4V parts [9]. In order to introduce new and less critical applications for this alloy, different methods of production need to be explored in an attempt to produce more affordable powder feedstock, thereby expanding the range of powder materials that can be employed to produce this alloy [6,9]. As an alternative to the PA Ti6Al4V powder feedstock, a powder blend of elemental Ti, Al and V powders that have been mixed in the ratio of 90:6:4 - Ti-Al-V, respectively, can be used as feedstock in the AM processes. This blended elemental (BE) powder route
has the potential to lower the cost of the Ti6Al4V parts by virtue of the lower cost of the starting elemental feedstock [9]. Therefore, the purpose of this study is to determine the optimum process parameters that can be employed to produce the Ti6Al4V alloy from blended elemental powders of Ti, Al and V. The process parameters that were investigated for the purpose of this study were laser power, scanning speed and hatch distance, while maintaining a constant powder layer thickness.

II. METHODOLOGY

A. Employed powder materials

An EOSINT M280 machine was used to produce single tracks and single and double layers from a powder blend consisting of elemental Ti (Grade 1), Al and V powders that have been blended to the ratio of Ti6Al4V. The commercially pure (CP) Ti and Al powders were argon gas atomized, while the V powder was produced by an aluminothermic smelting process followed by ball milling. Therefore, the Ti and Al powders were completely spherical, while the V powder was irregularly shaped as confirmed through scanning electron microscopy (SEM) (see Fig. 1). Inductively coupled plasma optical emission spectroscopy (ICP-OES) analyses were conducted on the powders to determine the elemental composition of the feedstock powders.

![Fig. 1. SEM secondary electron micrograph of the elemental powder blend](image)

B. DMLS production of experimental specimens

The process parameter matrix employed for the production of the specimens is shown in Table I. Single tracks were deposited on a 3 mm thick Ti6Al4V substrate using laser powers ranging from 100 to 300 W and a scanning speed range of 0.4 to 1.8 m/s. Three single tracks of 30 mm lengths were produced for each combination of laser power and scanning speed. A total of 42 process parameters were used to produce a total of 126 single tracks for analysis. Single and double layers were produced on two 3 mm Ti6Al4V substrates using a process parameter set that was identified as optimum from the single track analyses. Single and double layers were produced on two 3 mm Ti6Al4V substrates using a process parameter set that was identified as optimum from the single track analyses. The first substrate contained a total of three single layers and three double layers that were produced at varied hatch distances of 80, 90 and 100 µm for each process parameter set. On the second substrate, three single layers and three double layers at hatch distances of 80, 90 and 100 µm were produced by using the rescanning strategy for each of the two process parameters that were determined from the single track analysis.

<table>
<thead>
<tr>
<th>Laser Power (W)</th>
<th>Scanning speed range (m/s)</th>
<th>Speed increments (m/s)</th>
<th>No. of tracks per increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.4 – 1.0</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td>150</td>
<td>0.6 – 1.8</td>
<td>0.2</td>
<td>3</td>
</tr>
<tr>
<td>170</td>
<td>0.6 – 1.8</td>
<td>0.2</td>
<td>3</td>
</tr>
<tr>
<td>200</td>
<td>0.6 – 1.8</td>
<td>0.2</td>
<td>3</td>
</tr>
<tr>
<td>250</td>
<td>0.6 – 1.8</td>
<td>0.2</td>
<td>3</td>
</tr>
<tr>
<td>300</td>
<td>0.6 – 1.8</td>
<td>0.2</td>
<td>3</td>
</tr>
</tbody>
</table>

C. Specimen preparation

The specimens were cut in order to prepare them for their respective analyses. The single tracks and single and double layers were cross-sectioned across their lengths in order to prepare them for their respective cross-sectional analyses. A wire electrical discharge machine (EDM) produced by AccuteX was used to cross-section the single tracks and the single and double layers specimens. This machine is a computer numerical control (CNC) machine that uses a 0.25 mm thick electrically charged wire to remove material from a workpiece.

The specimens were prepared for analysis by mounting and polishing them with the Struers CitoPress-15 and the Tegramin-30 grinding and polishing machines, respectively. After grinding and mirror-polishing, the samples were etched with Kroll’s reagent in a ductless fume cabinet to reveal their surface structure. [10]. The etchant was applied to the specimens for an exposure period of 5 to 10 seconds until effervescent bubbles started to nucleate on the surface of the specimens. The specimens were then immediately cleaned with ethanol to stop the etching process and dried.

A Zeiss-Axio Scope.A1 optical microscope was used to analyse the surface morphology and the microstructure of the samples during their respective analyses. The elemental homogeneity of the produced layers was investigated using backscattered electron (BSE) imaging in a JEOL JSM-7800F scanning electron microscope (SEM).
C. Track and layer analysis

1) Single tracks: The single track analysis was conducted in two phases. In the first phase, optical microscopy was used to observe the top views of the single tracks and identify continuous and non-continuous single tracks. In the second phase, continuous single tracks were analysed on the cross-sectioned specimens to observe their substrate penetration shape and depth together with the track height, width and angle of contact between the single track and the substrate surface, as illustrated in Fig. 2. The cross-section of an optimum single track should exhibit sufficient (not too deep) penetration into the substrate with a semi-circular U-shape penetration. A good penetration depth is usually equal to half the width of the single track. The track height of the single track should be high enough to ensure the fast and economical build of parts. The width of the single track that penetrated the substrate should be equal to that of the visible single track surface. Lastly, the angle of contact between the track and the substrate should be greater than 90° to ensure adequate bonding with the next track [12]. This two-phase analysis led to the identification of process parameters that enabled the production of optimum single tracks from an elemental powder blend.

2) Single and double layers: The morphology and homogeneity of the produced layers were assessed before and after the rescanning strategy was applied. The bonding relationship between the superpositioned tracks, together with the intra-layer bonding relationship between two layers were determined from the cross-sectioned specimens.

III. RESULTS
The chemical composition of the starting raw material plays a vital role in the chemical composition of the final part, especially in in-situ alloying [9]. It is therefore imperative that the composition of the starting raw material is analysed and documented. The ICP-OES analyses revealed that the chemical composition of the Ti powder was 99.9 wt% Ti, while the Al and V had compositions of 99.2 wt% Al and 99.0 wt% V.

A. Single track analysis
Laser powers of 100, 150, 170, 200, 250 and 300 W together with scanning speeds ranging from 0.4 to 1.8 m/s were used for the production of the single tracks. The top view of an optimum single track should be continuous with no evident defects and irregularities such as a varied track width or broken sections along the length of the track (balling). Examples of continuous, non-continuous and non-optimum single tracks that exhibited bead formation and the balling effect are given in Fig. 3a, b and c respectively.

From the top view analysis, the process parameters that produced continuous and non-continuous single tracks were identified and displayed in Table 1. The green blocks represent the continuous single tracks while the yellow blocks represent the single tracks that were continuous however with non-optimum track irregularities such as varied track width and irregular track morphology. The red blocks represent the non-continuous single tracks that exhibited irregularities such as broken-sections caused by the balling phenomenon.

<table>
<thead>
<tr>
<th>Laser Power [W]</th>
<th>100</th>
<th>150</th>
<th>170</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speeds [m/s]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>0.5</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>0.6</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.7</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>0.8</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>0.9</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>1.0</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The continuity of the single tracks produced at the 100 W laser power ranged between scanning speeds of 0.4 to 0.5 m/s (Error! Reference source not found.a). At 0.6 m/s, the produced tracks were continuous however, their morphology was irregular and not satisfactory (Error! Reference source not found.b). The morphology of the single track affects the morphology of the layer and ultimately the properties of the final part, it is therefore imperative that the morphology of the single track is taken into consideration when conducting single track parameter investigations [13]. For scanning speeds above 0.6 m/s, the single tracks were not continuous (Error! Reference source not found.c). For the laser powers of 150, 170 and 300 W, the single tracks were continuous for scanning speeds between 0.6 and 0.8 m/s. At the scanning speed range between 1 and 1.2 m/s, the single tracks were continuous however with the irregularities shown in Error! Reference source not found.b. Scanning speeds above 1.2 m/s produced single tracks that had irregular track widths which indicated the effect of surface tension and the pre-balling phenomenon [12]. At 200 and 250W, the continuity of the single tracks ranged between 0.6 and 0.8 m/s.
optimum single tracks were formed at scanning speeds of 1-1.4 m/s for the 250 W laser power. Scanning speeds of 1-1.8 m/s and 1.6-1.8 m/s for the laser powers of 200 and 250 W respectively yielded non-continuous single tracks.

It was observed that the width of the produced tracks decreased with increasing scanning speed (Fig. 4), this observation has also been reported in other single track studies [14–16]. This occurrence is due to the relationship between the energy density (power per selected speed) and the surface tension. The surface tension is a temperature-dependent property between the melt pool and the substrate that tends to decrease the surface area of the melt pool [17]. At a lower scanning speed for any particular laser power, the energy density is high therefore resulting in more heat energy being transferred onto the metallic powder and the substrate. The surface tension on the substrate will thus be lower due to the thermal conduction from the heat energy source therefore allowing the resulting melt pool to flow freely thus forming a continuous stream that will solidify into a single track. As the scanning speed increases gradually, the heat energy decreases therefore increasing the surface tension between the melt pool and the substrate resulting in a reduction in the surface area of the melt pool and ultimately a thin solidified single track. In extreme high scanning speed cases, the surface tension will tend to break the melt pool into segments resulting in thin cylindrical beads that can be further reduced to a series of round individual balls. This is a result of the balling phenomenon [18,19].

The effect of the energy density can also be seen in the cross-section of the deposited single tracks (Fig. 5). At an excessively high scanning speed, the penetration of the single track into the substrate can take up a shape that resembles a keyhole (Fig. 5a.). At a high energy density, the dynamic viscosity of the melt pool is low therefore a thermocapillary recirculating flow is set up in the melt pool due to the change in the surface tension between the melt pool and the substrate [20]. This recirculating flow results in the subsequent accelerated penetration of the melt pool into the substrate [20]. Since the temperature of the melt pool is highest at the center and lower at the edges of the melt pool, the shape of the penetration thus resembles a keyhole shape with the deepest penetration at the center. The keyhole penetration is undesired in the DMLS production of parts because it can lead to pore formation in the final produced component when the vapour pockets formed in the deeply penetrated melt pool collapse [12,21]. At an adequate energy density, the penetration shape of the single track into the substrate can resemble a semi-circular U-shape which signposts a good combination of laser power and scanning speed (Fig. 5b). This kind of penetration occurs when the energy density is sufficient to allow the heat transfer within the powder bed to occur through normal absorption, conduction and convection heat transfer methods without any boiling or vaporization of the melt pool [22]. This type of conductive mode is highly desired in the DMLS process as it results in adequate bonding between the track and the substrate. A low energy density will not be sufficient to melt the metal powders and weld them into the substrate, thus resulting in a single track that has poor or no penetration into the substrate (Fig. 5c.).

The results of the cross-sectional analysis that was conducted on the single tracks that were considered to be optimum in

Table 1 are presented in Table 2. As in

Table 1, the process parameters highlighted in green were considered to be optimum while those in red were considered as non-optimum and consequently disqualified. At 100 W and scanning speeds between 0.4 and 0.5 m/s, the single tracks had an optimum U-shape penetration however, the penetration depth was not satisfactory. The track height and angle of contact of these tracks were satisfactory. At 150 W and corresponding scanning speeds of 0.6 and 0.8 m/s, the single tracks exhibited a keyhole (0.6 m/s) and semi-keyhole (0.8 m/s) penetration into the substrate. The penetration depth of the single track produced at 0.6 m/s was excessive, typical of this kind of penetration [14] and the track height was poor, owing to the excessive penetration of this single track into the substrate. The single track produced at 0.8 m/s had a fairly good penetration depth and track height despite the formation of the semi-keyhole penetration shape. The angle of contact of the single tracks produced at 150 W 0.6-0.8 m/s was greater than 90. The continuous single tracks produced at 170 W and corresponding scanning speeds of 0.6 and 0.8 m/s exhibited a keyhole penetration shape with an excessive substrate penetration depth and poor track height. The angle of contact was however greater than 90. The cross-sections of the single tracks produced at 200 and 250 W and corresponding scanning speeds of 0.6 and 0.8 m/s exhibited an optimum semi-circular U-shape penetration with a good penetration depth and track height. The single tracks produced at these process parameters had an optimum contact angle greater than 90. At 300 W and corresponding scanning speeds of 0.6 and 0.8 m/s, the single tracks had an optimum semi-circular U-shape penetration. The penetration depth of the single track produced at the corresponding scanning speed of 0.6 m/s was good and that of the single track produced at 0.8 m/s was not satisfactory. The track height and angles of contact for the single tracks produced at both the process parameters were greater than 90°.
TABLE II. SUMMARY OF THE SINGLE TRACK CROSS-SECTIONAL ANALYSIS

<table>
<thead>
<tr>
<th>Process parameter</th>
<th>Penetration shape</th>
<th>Penetration depth (µm)</th>
<th>Track height (Good)</th>
<th>Contact angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 W; 0.4 m/s</td>
<td>Semi-circular</td>
<td>21 (Poor)</td>
<td>35 (Good)</td>
<td>≤90</td>
</tr>
<tr>
<td>100 W; 0.5 m/s</td>
<td>Semi-circular</td>
<td>19 (Poor)</td>
<td>35 (Good)</td>
<td>≤90</td>
</tr>
<tr>
<td>150 W; 0.6 m/s</td>
<td>Keyhole</td>
<td>74 (Excessive)</td>
<td>26 (Poor)</td>
<td>≤90</td>
</tr>
<tr>
<td>150 W; 0.8 m/s</td>
<td>Semi-</td>
<td>38 (Good)</td>
<td>36 (Good)</td>
<td>≤90</td>
</tr>
<tr>
<td>170 W; 0.6 m/s</td>
<td>Keyhole</td>
<td>111 (Excessive)</td>
<td>30 (Poor)</td>
<td>≤90</td>
</tr>
<tr>
<td>170 W; 0.8 m/s</td>
<td>Keyhole</td>
<td>83 (Excessive)</td>
<td>29 (Poor)</td>
<td>≤90</td>
</tr>
<tr>
<td>200 W; 0.6 m/s</td>
<td>Semi-circular</td>
<td>54 (Good)</td>
<td>45 (Good)</td>
<td>≤90</td>
</tr>
<tr>
<td>200 W; 0.8 m/s</td>
<td>Semi-circular</td>
<td>52 (Good)</td>
<td>30 (Poor)</td>
<td>≤90</td>
</tr>
<tr>
<td>250 W; 0.6 m/s</td>
<td>Semi-circular</td>
<td>35 (Good)</td>
<td>36 (Good)</td>
<td>≤90</td>
</tr>
<tr>
<td>250 W; 0.8 m/s</td>
<td>Semi-circular</td>
<td>31 (Good)</td>
<td>30 (Poor)</td>
<td>≤90</td>
</tr>
<tr>
<td>300 W; 0.6 m/s</td>
<td>Semi-circular</td>
<td>39 (Good)</td>
<td>44 (Good)</td>
<td>≤90</td>
</tr>
<tr>
<td>300 W; 0.8 m/s</td>
<td>Semi-circular</td>
<td>30 (Good)</td>
<td>35 (Good)</td>
<td>≤90</td>
</tr>
</tbody>
</table>

From the single track analyses, process parameters that produced single tracks that exhibited an optimum combination of track continuity and the required cross-sectional characteristics were identified at laser powers of 200, 250 and 300 W at the corresponding scanning speed of 0.6 m/s. However, a light halo can be seen on the etched cross-section of the single track produced at 300 W and 0.6 m/s (Error! Reference source not found.). This halo is a heat affected zone, and it is an indication of the excessive energy density that the powder and substrate were exposed to during the production of the single track [15,23].

Since the elemental powder blend used in this study consists of elemental Al powders, the chosen process parameters need to give off minimum heat energy while also not compromising the quality of the produced single track. The excessive heat energy given off by the 300 W and 0.6 m/s process parameter could potentially cause an accelerated evaporation of the low melting point Al powder. For this reason, this process parameter was disqualified from the analysis. Therefore, the process parameters that were considered as optimum from the analysed results are 200 and 250 W at the corresponding scanning speed of 0.6 m/s. It is anticipated that the 200 W; 0.6 m/s process parameter will result in a better conservation of the elemental Al powder due to its lower heat energy compared to that of the 250 W; 0.6 m/s process parameter set. The top and cross-sectional views of these single tracks are presented in Fig. 7; these process parameters were used to produce single and double layers.

B. Single and double layer analysis

The morphology of the produced layers that was achieved before and after the rescanning strategy is presented in Fig. 8. The morphology of the single layers was identical to that of the double layers. Additionally, a much more clear indication of the morphology, homogeneity and bonding relationship of the layers can be obtained from multiple layers as opposed to a single layer. Therefore, the results presented will be based on the production of the double layers.

The single-scanned double layers exhibited satellite particles at the edges of the super-positioned single tracks. Krakmalev [24], reported that the satellite particles formed on the surface of the layers increased with the increasing hatch distance. This can be clearly seen in Fig. 8. There were more satellite particles formed on the surface of the layers produced at a hatch distance of 100 µm as compared to those formed on the surface of the 80 µm hatch distance. These satellite particles are essentially just imperfectly melted powder that formed on the periphery of the single tracks [12,20]. During single track production, the uneven distribution of the laser beam radiates more energy at the centre of the single track than at the edge of the single track [25,26]. Therefore the powder at the edge of the single track will not be exposed to the same amount of energy as the powder at the centre [26], thus resulting in imperfectly melted powder at the edge of the track that becomes spheroidized due to the effect of the surface tension. Since the morphology of the layers is dependent on the morphology of the single tracks [12], the produced layers will exhibit satellite particles at the edge of the super-positioned single tracks. The rescanning
strategy was able to re-melt these satellite particles thus redistributing them into the bulk of the layer material.

The effect of the varied hatch distance on the bonding and overlapping of the single tracks can be seen from the edges of the super positioned single tracks in Fig. 9. At the hatch distance of 80 µm, the overlapping of the single tracks is much greater than that of the 100 µm hatch distance. Yadroitsev [28], stated that the value of the hatch distance should not be greater than the average width of the produced single track in order to obtain sufficient bonding between the single tracks. However, one should be careful not to select a hatch distance that is a great fraction smaller than the track width as the amount of melted powder decreases as the hatch distance decreases. Although this would result in a smoother surface, it could also potentially increase production time [12].

The same bonding relationship that was observed in Fig. 9 has been observed in the cross-sectional analysis of the double layers (Fig. 10). The layers produced at the 80 µm hatch distance had a greater track to track bonding as compared to the cross-sections of the layers produced at greater hatch distances. Defects such as intra-layer porosity and delamination of the layers were not observed in this analysis.

The homogeneity of the produced layers before and after the rescanning strategy is shown in Fig. 11. It was expected that it would be difficult to obtain a good material homogeneity due to the elemental nature of the powder blend employed in this study. However, the homogeneity of the material before the rescanning strategy was applied was quite fair, although areas that are rich in Al can be seen on the surface of the layer. This can be attributed to the low melting point and specific density of the elemental Al, in the melt pool, the molten Al tends to rise above the molten Ti and V hence there are areas that are rich in Al [29]. The distribution of the Ti and V in the bulk material was fair although there are areas that are rich in V. The rescanning strategy was able to redistribute the Al metal into the bulk of the alloy, therefore resulting in a homogenous alloy.
layers at 200 W; 0.6 m/s at a hatch distance of 80µm.

The Boeing Scholarship Programme (Project No: TBC-3-5-2) for supplying the Ti and MA powders.

Fig. 11. BSE images and Ti, Al and V K EDS maps of double layers at 200 W; 0.6 m/s at a hatch distance of 80µm.

IV. CONCLUSION

The results obtained from this study confirmed that non-porous and homogenous multiple layers can be produced by laser power and scanning speed combinations of 200 W; 0.6 m/s and 250 W; 0.6 m/s with a hatch distance of 80 µm using a rescanning strategy. Ideally, the rescanning strategy would be recommended for application after the production of each layer to ensure the production of homogeneous and defect free parts, however, this would have a significant impact on the time and cost of production. The deposition of a new layer on top of the previous layer will be effective in re-melting some of the satellite particles formed at the surface of the layers. For this reason, rescanning can be applied to the final outer layer only for surface quality enhancement.

Pending further confirmation from the actual production of 3D parts, the authors have obtained sufficient confidence from the obtained results that in-situ alloying of blended elemental powders could potentially be used to manufacture 3D Ti6Al4V parts through the DMLS process.

ACKNOWLEDGMENTS

The authors would like to acknowledge and express gratitude to the following entities: The Boeing Scholarship Programme (Project No: TBC-3-5-2) for supplying the Ti and MA powders.

The University of Stellenbosch (Mechanical and Mechatronic Engineering) for blending and characterising the powder used in this experiment.

REFERENCES


Examining Various Mixing Techniques and their Effect on the Uniform Dispersion of Carbon Nanotubes in a Ti6Al4V (ELI) Matrix

Mpho Mashabela
Department of Mechanical and Mechatronics Engineering
Central University of Technology
Bloemfontein, South Africa.
mhosiek0@gmail.com

Maina Maringa
Department of Mechanical and Mechatronics Engineering Central University of Technology
Bloemfontein, South Africa.
mmaringa@cut.ac.za

Thywill. C. Dzogbewu
Department of Mechanical and Mechatronics Engineering Central University of Technology
Bloemfontein, South Africa
tdzogbewu@cut.ac.za

Abstract—Carbon nanotubes offer the possibility to improve the mechanical properties of Ti6Al4V(ELI) alloy. Their low density, high strength, and high Young’s modulus make them a preferred choice for reinforcement. However, their small size and tendency to agglomerate pose a challenge to achieving homogeneous dispersion in a matrix. Three different techniques were investigated experimentally in the present study to examine the effect mixing processes have on achieving a homogenous mixture between carbon nanotubes and Ti6Al4V(ELI) and were seen to have different outcomes. Keywords—Carbon Nanotubes, Ti6Al4V (ELI), uniform dispersion, mixing techniques.

1. INTRODUCTION
Carbon nanotubes (CNTs) have drawn interest from scientists, physicists, material scientists, chemists, and electronic engineers due to their exceptional structural, mechanical, optical, and chemical properties. These unique properties originate from the parent material known as graphene. Carbon nanotubes are made from rolled up graphene sheets with a one dimensional structure made of nano scale diameters which significantly strengthens matrix materials when added to them as a reinforcement material [1,2]. Their use as reinforcement material has increased over the last ten years especially with metal matrices. However, carbon nanotubes exhibit poor dispersion and homogeneity within matrix materials. Moreover, their tendency to agglomerate may lead to a deterioration of their unique reinforcement properties [2].

To successfully incorporate carbon nanotubes within a matrix it is desired to de-agglomerate the particles, by balancing the attractive forces between nanoparticles. Strong van der waals forces exist between the carbon nanotubes which keeps them bundled up together thus posing a challenge when it comes to achieving uniform dispersion and homogeneity. De-agglomeration of the particles can be achieved by using electrostatic stabilization also known as mechanical or physical stabilisation, or chemical stabilisation [1]. Electrostatic stabilization utilises ultrasonication which is a process that applies sonic waves to the reinforcement to de-agglomerate and break apart the bundles. In this process, ultrasound waves are applied to a specimen with frequencies in the non-audible range above 20 Hz, and as the frequency increases so does the strength of agitation increase. During ultrasonication, an electric charge is placed on the surface of the particle the purpose been to achieve kinetic stability. This process is carried out in a liquid medium hence the particles would have to be suspended within a liquid, which requires the use of a process control agent [3].

Steric stabilisation is a chemical methodology that incorporates a surfactant (a surface active agent used to reduce surface tension) or polymer onto the nano particles. These larger molecules are adsorbed on the surfaces of nanoparticles and act to prevent agglomeration of nanoparticles. Increasing the concentration of the adsorbed molecules increases osmotic repulsive forces between the nano particles affected, which then decreases their agglomeration. The presence of the large concentrations of such polymers on the surfaces of particles keeps them out of the range of strong van der waals forces. This can be explained by the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory which considers the total potential energy of a colloidal system comprised of the attractive van der waals forces and the repulsive force formed at the surfaces. According to the DLVO theory the colloidal system is stable when the repulsive forces overcome the attractive forces. In this case the polymer is used to increase the repulsive forces to try and achieve stabilisation [4]. Steric stabilisation is dependant on the concentration and solubility of the polymer, and prevailing temperature [5]. Due to the short-range (above 3 nm for a higher concentration solution according DLVO theory and down to 5 nm) as shown in Figure 1. interaction of the process is not dependant on the size particles [6,4].
The use of steric stabilisation and electrostatic stabilisation facilitates the attainment of uniform dispersion of nano particles within a matrix. The strong van der waals forces between particles will always pose a challenge when working with nano particles. To achieve uniform dispersion of nano particles within a matrix various methods of blending and dispersion are available which include colloidal mixing, magnetic stirring, molecular-level mixing, nanoscale dispersion processing, particle composite system mixing, friction stir processing, layer stacking, ball milling, and roller mixing. Of the aforementioned processes, the most commonly used methods include molecular-level mixing, ball milling, and colloidal mixing [7].

A process control agent is utilised in all these commonly used processes for mixing. In the case of ball milling, ethanol is used to prevent cold welding of the matrix and to prevent agglomeration of powder particles during ball milling. In molecular-level mixing the CNTs are first treated in an acid then dispersed in a solvent using ultrasonic agitation. Colloidal mixing makes use of dimethylformamide or ethylene glycol to achieve a stable dispersion of CNTs [3].

A number of distinguished works are available on high energy and low energy ball milling to mix CNTs and metal matrices. However, little literature exists for the remaining processes, which is the focus of the present study to determine a mixing process that is effective in achieving a homogenous mixture of CNTs and Ti6Al4V (ELI) matrix. In this study, molecular-level mixing, colloidal mixing, and magnetic stirring are examined to decide on whether these methods of mixing can be effective in successfully incorporating CNTs in a Ti6Al4V (ELI) matrix.

I. COMMON METHODS OF MIXING

Common methods of mixing which include ball milling, molecular-level mixing, and colloidal mixing have been adopted by different authors. Jinzhi Lao [8] found that high energy ball milling produced better uniform dispersion of CNTs compared to low energy ball milling, and where a polyester binder-assisted (PBA) technique (where the mixture was melt blended in a Haake twin-screw mixer) was used. In the case where high energy ball milling was used to mix the aluminium powders and CNT’s, CNTs embedded themselves within the aluminium matrix and agglomeration was observed to reduce significantly. However, some parts did not show a uniform dispersion of CNTs due to factors such as gravity-separation because of the difference in densities of the two materials. Light CNTs were observed to settle on the upper parts of the metal powder (due to their low density compared to Al powders) and the large metal powder particles were thought to inhibit the CNTs from successfully dispersing within the aluminium matrix. In this work, the author assumes that smaller metal powders could aid in the uniform dispersion of CNTs.

Low energy ball milling is a simple approach that does not require a lot of time and is cost efficient. Using this method a moderate dispersion of CNTs particles was observed within the aluminium matrix in the works of Jinzhi Lao [8], but was considered inadequate. Compared to high energy ball milling
Mechanical Mixing

In the present work, experimentation was done using spherical gas atomized Ti6Al4V (ELI) powder and aligned multi walled carbon nanotubes with a purity > 96%, outside diameter of 8-18 nm and surface area of 30-300 m²/g. The CNTs were mixed into the Ti6Al4V matrix at a weight fraction of 8% as preliminary work to guide later mixtures of other volume fractions including of CNTs of 3%, 15%, 20%, 25%, and 30%. Magnetic stirring was used without a separation process agent. Then, magnetic stirring was used followed by the addition of ethanol (process agent) into the mixture, and then an ultrasonic bath from a SCIENTECH model 704 was employed to agitate the particles for 10 min, and at a frequency of 35 Hz. The mixture was then oven-dried at 50°C for 20 min to evaporate the ethanol, leaving behind the powder mixture. Finally, acetone (an organic solvent) was added to the mixture to act as a medium into which the carbon nanotubes can be dispersed, which was then stirred magnetically and thereafter oven-dried at 70°C for 15 min.

The mixed samples were analysed using the ZEISS Merlin FE scanning electron microscope (SEM), with nano - scale image and micro – and cryo – EDS analytical capabilities. Its voltage can be varied from 20 kV to 30 kV, beam currents from 7 pA to 40 nA and is able to achieve resolutions of up to 0.6 nanometers at 30 kV and 1.6 nanometers at 1 kV. The stubs for SEM were prepared by cleaning them in a sonic bath and cleaning their surfaces with isopropanol. Carbon paper was placed on the stubs and thereafter, while holding the end of the stub, were inserted into the powder sample and then placed in a clean container. The powder samples were not sieved prior to being inspected with SEM.

A. Ethanol

The carbon nanotubes used in this work were supplied by Sabinano Tubes™. The CNTs were synthesised by Sabinano Tubes™ through a catalytic chemical vapour deposition process, and then purified through an acid treatment, chemical process. Dispersion of carbon nanotubes was carried out in 10 ml of ethanol in a plastic container. A weight fraction of 8% of carbon nanotubes was used. Initially it was proposed to use volume fractions of mixtures. However, this was not achievable due to lack of facilities to measure the flowability of carbon nanotubes at the laboratory, to obtain the apparent density of the material which is different from the given bulk density. This would significantly affect the results initially desired because there is a non-linear relationship between mass and volume of the material due to the packing factor of particles [14]. The air gaps between particles contribute to the volume but not the mass of the container. As such the mass percent of carbon nanotubes would be significantly different from the volume percent. Sonication of the mixture was then carried out for 10 min at a frequency of 35 Hz (the maximum frequency possible with this sonic bath) in an ultrasonic bath from a SCIENTECH model 704 employed to agitate the particles. The mixture was removed from the ultrasonic bath and 9.92 g of Ti6Al4V powder added into the slurry mixture, which was further oven-dried. 50°C for 20 min in order to ensure all the ethanol was evaporated from the powder. Lastly the dried mixture was stirred magnetically for 5 min.

B. Acetone

The carbon nanotubes used in this work were dispersed in acetone to help de-agglomerate and break down the nano tube bundles. A weight fraction of 8% of CNTs was dispersed in 10 ml of acetone in a plastic container. This slurry mixture was then put in a SCIENTECH model 704 ultrasonic bath and sonication carried out for 10 min at a frequency of 35 Hz. After sonication, 9.92 g of Ti6Al4V (ELI) powders was added to this slurry mixture. The mixture was then oven-dried at 70°C for 15 min in order to evaporate the acetone completely. Thereafter, magnetic stirring was carried out for 10 min.

C. Mechanical Mixing

The carbon nanotubes were weighed and placed into a plastic container which was initially filled with argon gas to make it
The Ti6Al4V (ELI) powders were added into the plastic container containing CNTs. This mixture was then blended mechanically using a spatula to mix the powders by stirring it manually for an hour.

III. RESULTS AND DISCUSSION

A. Samples of mixed powders

Images of a powder sample of ethanol mixing of CNTs and Ti6Al4V (ELI) at various stages in the process are provided in Figure 2(a, b and c). Figure 2(a) shows the mixture slurry of CNTs and Ti6Al4V at the initial stage of mixing where ethanol and CNTs/Ti6Al4V mixture is a wet mixture. It was observed in this stage that CNTs attached themselves to the inside of the mixing container. Even after oven-drying in the second stage following the wet mixture as shown in Figure 2(b), some CNTs were still visible on the inside of the mixing container. This is a concern in the health and safety aspect of handling carbon nanotubes as it provides an indication to take extra safety measures such as discarding of the used containers after use, and to thoroughly clean the inner surfaces of mixing containers and any equipment used. It also raises concerns about loss of material and demands efforts to minimise it. In the slurry mixture the CNTs are clearly visible in Figure 2(a) in the form of the black powder. However, after some evaporation of ethanol more of the Ti6Al4V (ELI) matrix becomes visible as shown in Figure 2(b). The image shown in Figure 2(b) illustrates the mixture of the two materials in lumps as the ethanol had not completely evaporated. Once the ethanol was completely evaporated, it is evident in Figure 2(c) that the CNTs were not sufficiently dispersed in the Ti6Al4V matrix and a homogenous mixture is not visible. Gravity separation of the two powders is also visible as was reported by Jin Lao [8] due to the difference in densities of the two powders.

B. Scanning electron microscopy images of the two powders mixed mechanically

Figures 3, 4, and 5 show micrographs of powders that were mixed mechanically in the present work. The figures show that despite mixing the powders mechanically for an hour, the powders did not mix effectively. This is thought to be a result of the strong van der waals forces between the carbon nanotubes which would not allow them to disperse within the Ti6Al4V matrix (spherical particles in the figures). Figure 3 shows a presence of CNTs within the Ti6Al4V (ELI) matrix though not in all parts of the matrix. There are visible clusters of carbon nanotubes within the Ti6Al4V (ELI) matrix and no attachment of CNTs onto the Ti6Al4V (ELI) particles is evident. However, entanglement of carbon tubes was not visible at either one of these two magnifications and it was not possible from the micrographs to determine whether the tubes were separated or remained entangled after mechanical mixing. It is evident therefore, that this mixing technique was not successful in achieving de-agglomeration of the CNTs and in delivering a homogenous dispersion of CNTs in the Ti6Al4V matrix.

At a magnification of x 200, the micrograph shown in Figure 4 depicts large clusters of CNTs which did not disperse but are bundled together.

At a magnification x250, the micrograph shown in Figure 5 shows agglomerated CNTs within the Ti6Al4V (ELI) matrix. No attachment of CNTs onto the Ti6Al4V (ELI) particles is visible. The micrograph also shows some irregularly shaped Ti6Al4 (ELI) particles.
C. Scanning electron microscopy images of the two powders mixed in ethanol

Figures 6, 7, and 8 provide micrographs of the mixed powders where ethanol was used as a process control agent.

The CNTs were dispersed in ethanol to help separate the nanotubes to aid with their attachment onto Ti6Al4V (ELI) particles. The slurry mixture went through sonication to agitate the particles, as was the case in the work by Tao Peng [12]. The micrographs show the presence of agglomerated carbon nanotubes within the Ti6Al4V (ELI) matrix and implies that the process was not effective in breaking down the CNTs bundles as was expected. This is likely to have occurred be due to the short duration of sonication that was applied. Tao Peng [12] reported a sonication time of 4 h, whilst the present experiments only applied a time limit of 10 min due to a limitation of the low maximum frequency of 35 Hz for the sonification equipment used here and the time available to carry out sonification. Evidently, sonication time and frequency both play a significant role in dispersion given the existence of agglomerates seen here. Tao Peng [12] used a sonic bath at a frequency of 42000 Hz. Attempting to achieve the same degree of dispersion obtained in this work with the low frequency of the equipment available in the present work would have meant running the sonic bath for days, which was not considered time efficient.

Figure 6 shows a mixed sample of the two powders where the CNTs were first dispersed in ethanol. Several clusters of CNTs of various sizes are visible in this figure. Some CNTs are clustered CNTs are larger relative to others

Smaller CNTs clusters in the sample

Clustered CNTs are large relative to other clusters

Smaller CNTs in sample

Irregular shaped Ti6Al4V (ELI) particle

Fig.8: SEM micrograph of CNTs/Ti6Al4V (ELI) powder where the CNTs were dispersed in ethanol and then exposed to ultrasonic vibration (x500)

Figure 7 shows a micrograph at x200 magnification which shows that although large CNTs were observed in Fig.6 there appears also relatively smaller agglomerates which are not as large as seen in Figure 6. There is also a single Ti6Al4V (ELI) particle that has an attached CNT. As was observed in Figure 5 irregular shaped Ti6Al4V (ELI) particles were also observed in this sample.

Figure 8 at x500, gives a clear view of agglomerated CNTs that occurred in clusters even after efforts to disperse the CNTs in ethanol.
D. Scanning electron microscopy images of the two powders mixed in acetone

Figures 9, 10, and 11, shows micrographs of the powder mixture where acetone was used as a process agent. The CNTs were dispersed in acetone and sonication carried out for 10 min. Figures 9 and 10 show smaller bundles of CNTs attached onto spherical particles of Ti6Al4V (ELI). However, this is not on a larger scale and is only visible in a few places and will only have a small effect on the Ti6Al4V (ELI) matrix. Figure 11 shows small, agglomerated carbon nanotubes and when this is compared to Figures 6 and 7 where ethanol was used as a process agent, although ethanol provides a better dispersion of CNTs it comes with the disadvantage of increased agglomeration of CNTs.

Figure 9 shows CNTs attached onto Ti6Al4V (ELI) particles. An elongated CNT is also evident between some particles of Ti6Al4V (ELI).

Fig.9: SEM micrograph of CNTs/Ti6Al4V (ELI) powder where CNTs were dispersed in acetone and then exposed to ultrasonic vibrations (x424)

Fig.10: SEM micrograph of CNTs/Ti6Al4V (ELI) powder where CNTs were dispersed with acetone and then exposed to ultrasonic vibrations (x450)

Smaller CNT clusters compared to the case of dispersion with ethanol

Smaller CNT agglomerates compared to the case of dispersion with acetone

Fig.11: SEM micrograph of CNTs/Ti6Al4V (ELI) powder where CNTs were dispersed in acetone and then exposed to ultrasonic vibrations (x450)

This implies the need for a more rigorous process such as ball milling to break down these forces. However, as reported by Jinzhi Lao [8] and Al-Aqeili [13] ball milling leads to flake like appearance of the matrix powders as opposed to their original spherical structure, at longer milling times and high speeds.

The samples that had the biggest CNT agglomerates were seen in the mechanically mixed powder, followed by powder mixtures where CNTs were dispersed with ethanol, and lastly with acetone. This shows that acetone was more effective in breaking down the agglomerates than ethanol and certainly much more than mechanical mixing. The effect of sonification frequency and time on the degree of agglomeration of CNTs, is the subject of further experimentation.
The powder samples for the mechanically mixed, dispersion in ethanol, and dispersion in acetone all had Ti6Al4V (ELI) satellites present. There was also irregularly shaped Ti6Al4V (ELI) particles amongst the satellites present. There was also irregularly shaped Ti6Al4V in ethanol, and dispersion in acetone all had Ti6Al4V (ELI) mixing used were not the cause for the different morphologies the right milling time and speeds to achieve a homogenous mixture without compromising the structure of the matrix particles. Such future work should also look into using a polyester binder-assisted method where a polyester is used to coat the matrix powder particles to reduce their surface tension thus making it easy for CNTs to attach themselves onto the Ti6Al4V powder particles. In the studies carried out by Tao peng where a turbula mixer was used, a uniform dispersion of CNTs was achieved without altering the shape of the aluminium matrix powder particles. It is therefore of interest for future experiments to consider using a turbular mixer for achieving dispersion of CNTs.

ACKNOWLEDGMENT

The department of industrial Engineering at Stellenbosch University and Stellenbosch Technology Central Laboratory for Advanced Manufacturing and their staff are appreciated.

REFERENCES


Comparative Analysis of the High Velocity Impact Behaviour of Wrought Ti6Al4V and Stress Relieved DMLS Ti6Al4V (ELI)

Teboho Moleko
Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Built Environment and Information Technology, Central University of Technology Free State, Bloemfontein, South Africa
moleko_t@yahoo.com

Maina Maringa
Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Built Environment and Information Technology, Central University of Technology Free State, Bloemfontein, South Africa
mmaringa@cut.ac.za

Willie du Preez
Centre for Rapid Prototyping and Manufacturing, Faculty of Engineering, Built Environment and Information Technology, Central University of Technology Free State, Bloemfontein, South Africa
wdupreez@cut.ac.za

Abstract—The comparison presented here is based on the minimum thickness required to prevent through penetration, and further, fractography of the fracture surfaces and microstructural changes around and radially away from the penetration hole. The high velocity ballistic impact tests conducted on both types of Ti6Al4V alloys revealed a minimum thickness to prevent through penetration that was between 14 mm and 18 mm. Fractographic analysis revealed both alloys exhibited brittle behavior and ductile behavior at the entry point and exit point of the penetration holes, respectively. Microstructural analysis further revealed changes that are consistent with the effects of high temperature.

Keywords—Direct metal laser sintering, Adiabatic shear band, Fractographic Analysis, Failure mode, Microstructural analysis

I. INTRODUCTION

In previous work, testing was conducted on wrought Ti6Al4V as an alternative to aluminium alloy AA 5083 and Rolled Homogeneous Armour (RHA) steel for high velocity impact applications [1]. In this paper, a comparative analysis is conducted on the results obtained from this testing and further unpublished work done on as-built and stress relieved Direct Metal Laser Sintering (DMLS) Ti6Al4V (ELI).

In high velocity ballistic impact applications, one of the criteria used to rate the performance of a metal is its resistance to penetration [1][2]. The resistance to penetration is normally quantified through an optimum thickness to prevent through penetration of a projectile [1][2].

Additively manufactured Ti6Al4V (ELI) with its higher value of hardness (326 BHN) compared to the wrought alloy (300 BHN) is expected to perform better by providing more effective blunting of projectiles and hence achieving better resistance to penetration [3][4]. Furthermore, its higher value of yield strength (1089 MPa) compared to that of wrought Ti6Al4V (948 MPa) implies a higher capacity to absorb energy during elastic deformation and therefore a higher capacity to stop the penetration of projectiles [4][5].

The transient high strain rates prevalent during high velocity impact are known to lead to adiabatic temperature rises of target materials [6]. Therefore, it is important to understand whether the temperature rise during impact is significant enough to bring about microstructural changes of the target material [6]. Depending on the temperatures attained during high velocity impact of Ti6Al4V, the hexagonal close packed α phase of the alloy existing at room temperature can undergo an α to β transformation [7][8].

As the temperature of the Ti6Al4V alloy increases, the percentage of α grains in the microstructure of the two phase region decreases [7][9]. Ti6Al4V can exist in four different microstructural morphologies at room temperature as a function of the heat treatment [7][9]. The four microstructural morphologies are acicular martensitic α, fully lamellar, equiaxed, and duplex or bimodal [7][9][10]. Figure 1 shows these Ti6Al4V microstructures (a) martensitic α, (b) equiaxed microstructure, (c) bimodal microstructure, (d) lamellar microstructure.

The martensitic α microstructure is distinguishable by the randomly oriented fine needle-shaped morphology [9]. The fully lamellar microstructure compared to the equiaxed microstructure is distinguishable by a greater α/β surface area and more orientated colonies of alternate α and β grains that form the lamellae. Equiaxed microstructure has a structure composed of equiaxed α grains (lighter shade) and grain boundaries of β grains (darker shade) [7][9][10]. Moreover, the bimodal microstructure consists of alpha primary (αp) grains and colonies of α laths that are separated by ribs of β grains in the form of lamellae [9].

Figure 1: Ti6Al4V microstructures (a) martensitic α microstructure, (b) bimodal microstructure, (c) equiaxed microstructure and (d) lamellar microstructure.

Funded by: South African Department of Science and Innovation through the CSIR for the Collaborative Program in Additive Manufacturing, Contract No.: CSIR-NLC-CPAM-18-MOA-CUT-01
The projectile holes in targets impacted by high velocity projectiles display features of fracture, that speak of the type of deformation prevalent at particular points in them [9][10]. Determination of the mode of failure, ductile or brittle fracture, from the features of the surfaces of projectile holes, is important for gaining insight into the behaviour of target materials under high velocity impact [9][10]. Adiabatic shear bands are common in cases of high strain rate and are likely to occur in cases of ballistic impact failure, due to the prevailing high strain rates and the consequent thermosoftening [11].

In the case of through penetration of a target, the projectile leaves a hole with a fractured surface [11]. It is important in this case to determine whether the fracture formed is ductile, brittle or a combination of the two, to get insight into the behaviour of the target material [11]. Ductile fracture is characterized by extensive plastic deformation [12][13][14]. The term ductile rupture refers to the failure and complete separation of highly ductile materials. When this type of failure occurs, the material pulls apart forming dimples, micro-cavities and voids before failure, instead of failure through cracking [11][13].

On the other hand, brittle fracture is characterized by little or no plastic deformation prior to failure, which is denoted by formation of cracks and cleavage marks as surface features on the fracture surface [13][14]. Figure 2 shows a scanning electron microscope (SEM) micrograph exhibiting dimple and cleavage rupture mechanisms in a fracture zone.

Adiabatic shear bands (ASBs) are also common in cases of high strain rate and are likely to occur in cases of ballistic impact failure [15][16]. Figure 3 shows an optical micrograph of an adiabatic shear band in a bimodal microstructure of Ti6Al4V [15].

II. METHODOLOGY

In previous papers, as-built and stress relieved DMLS Ti6Al4V (ELI) and also wrought Ti6Al4V plates of dimensions 100 mm by 100 mm and thicknesses varying from 6 mm to 18 mm, were tested against 7.62 x 39 mm armour piercing incendiary (API) bullets travelling at an average velocity of 700 m/s [1]. Upon conducting the ballistic impact tests, the plates were sectioned and fractography of the fracture surfaces was conducted using a JEOL JSM-6610 scanning electron microscope.

Additionally, microstructural analysis was conducted on the sections using a ZEISS Axioscope.5 Pol optical microscope. Optical micrographs were taken near the edge of the projectile hole and at distances of 2 mm, 4 mm and 6 mm from there moving radially outwards, in order to investigate the change in microstructure with distance away from the penetration hole during impact. This paper compares the data obtained from the testing of both alloys.

III. RESULTS AND DISCUSSIONS

A. High Velocity Ballistic Impact Testing

In the velocity range of about 700 m/s the minimum thickness to prevent through penetration of the as-built and stress relieved DMLS Ti6Al4V (ELI) and also wrought Ti6Al4V was established to be between 14 mm and 18 mm. The as-built and stress relieved DMLS Ti6Al4V (ELI), was expected to perform better than the wrought Ti6Al4V due to its higher strength and hardness. To the contrary, the higher strength and hardness of the alloy coupled with the high velocity impact may have led to significantly reduced plastic deformation compared to that prevailing under normal strain rates, which is lower than that of the wrought Ti6Al4V. Furthermore, in the as-built and stress relieved condition DMLS Ti6Al4V has poor ductility and hence low toughness.

As plastic deformation absorbs much more energy than elastic deformation, this reduction of plastic deformation may partly explain this negation of the advantages expected from the higher strength and hardness of the as-built DMLS Ti6Al4V (ELI). This is despite the known increase of yield stress due to high strain rates.

B. Fractographic Analysis

For both the alloys, all the micrographs at the entry points of the penetration holes through all the plate thicknesses exhibited a predominance of cracks and ridges, which denotes brittle fracture. Furthermore, from the same micrographs, it was observed that the identified cracks were inclined to the
horizontal direction (direction of penetration of the projectile). This inclination was in a direction perpendicular to that of the induced tensile waves that propagate circumferentially away from the projectile hole. This is consistent with shear failure of materials along the directions of maximum shear stress.

In this section the SEM secondary electron image (SEI) micrographs presented are representative of the phenomena observed on both alloys. Figure 4(a) is a SEM SEI micrograph of the surface at the entry point of the penetration hole through a 10 mm thick plate. The arrow in the figure indicates the direction of penetration (DOP). Figure 4(b) is a higher magnification micrograph at the entry point through the same plate.

For both alloys, at the middle points of the penetration holes for all the plate thicknesses, the fracture surfaces lacked clearly defined fracture features. It was not possible in such cases to determine the prevailing mode of failure of the material.

Figure 5(a) is a SEM SEI micrograph of the surface at the middle point of the penetration hole through a 10 mm thick plate. Figure 5(b) is a higher magnification micrograph at the middle point of the projectile hole through the same plate.

At the middle points, the fracture surfaces showed grooves, which were attributed to smearing resulting from the friction effect of the projectiles as they penetrated the various plates. The grooves were inclined at an angle relative to the direction of penetration, which is likely to be a result of the rotational motion of the projectiles as they went through the respective plates.

At the exit points of the penetration holes through all the plate thicknesses for both alloys, the predominant surface features were dimples. The predominance of dimples at the exit points of the penetration holes confirms ductile fracture. Furthermore, at the exit points of the penetration holes, the tensile shock waves, reflected from the exit free edges of the plates, led to failure in planes that were orthogonal to the direction of penetration of the projectile ahead of the projectile, which then opened up with through penetration of the projectile leading to the formation of petals.

Figure 6(a) is a micrograph of the surface at the exit point of the penetration hole through a 10 mm thick plate. Figure 6(b) is a higher magnification micrograph at the exit point of the projectile hole through the same plate.

The dimples at the exit points were caused by the coalescence of microvoids, as a result of tensile failure due to the reflected tensile stress wave and shear failure due to the effect of the penetrating projectile. The existence of ductile failure at the exit point implies a lower rate of strain than what existed at the entry point, which then allowed the material to deform as it would normally under lower strain rates.

C. Microstructural Analysis

In this section the micrographs presented are from 10 mm thick plates, and are representative of the phenomena observed in all the plate thicknesses for each alloy.

Microstructural analysis of both alloys for all the plate thicknesses revealed formation of ASBs near the edges of the projectile holes. Evidence of this can be seen in Figure 7(b) and Figure 8(b).

Figure 7(a), (c) and (d) are wrought Ti6Al4V optical micrographs of areas at and near the edge of the projectile hole for the randomly selected plate of 10 mm thickness. Figure 7(b) is a scanning electron microscope (SEM) micrograph showing ASBs near the edge of the projectile hole. It should be noted that the area investigated is labelled (A) on the schematic above these micrographs. The micrographs (b), (c) and (d) are higher magnification micrographs of micrograph (a).
Figure 7: (a) Wrought Ti6Al4V optical micrograph, (c) and (d) are higher magnification optical micrographs; (b) higher magnification SEM SEI micrograph of the indicated area on an ASB, all near the edge of the projectile hole through a 10 mm thick plate.

Figure 8(a) is an as-built and stress relieved DMLS Ti6Al4V (ELI) optical micrograph, (b) and (c) are higher magnification optical micrographs, all near the edge of the projectile hole through a plate of 10 mm thickness. It should be noted that the area investigated is labelled (A) on the schematic above these micrographs. The micrographs (b) and (c) are higher magnification micrographs of (a).

Further microstructural analysis of the wrought Ti6Al4V plates, revealed a gradually decreasing refinement of grains and measured average values of the thickness of $\alpha$-laths, radially away from the edge of the projectile holes, as is detailed in Table 1 and the ensuing discussion.

**Table 1: Thickness of $\alpha$-laths at different distances from the edge of the projectile holes**

<table>
<thead>
<tr>
<th>Distance from the edge of the projectile holes</th>
<th>Average thickness of the $\alpha$-laths ($\mu$m)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>near the edge</td>
<td>7.76 - 8.61</td>
<td>0.17 - 0.59</td>
</tr>
<tr>
<td>2 mm</td>
<td>14.96 - 15.68</td>
<td>0.50 - 0.94</td>
</tr>
<tr>
<td>4 mm</td>
<td>18.76 - 19.20</td>
<td>0.31 - 0.79</td>
</tr>
<tr>
<td>6 mm</td>
<td>20.81 - 22.51</td>
<td>0.66 - 1.69</td>
</tr>
<tr>
<td>25 mm</td>
<td>2.17 - 2.33</td>
<td>0.15 - 0.30</td>
</tr>
<tr>
<td>40 mm</td>
<td>2.19 - 2.29</td>
<td>0.10 - 0.34</td>
</tr>
</tbody>
</table>

Table 1, shows that at distances of 25 – 40 mm from the edge of the projectile holes, the average thickness of the $\alpha$-laths fell within the range 2.17 $\mu$m – 2.33 $\mu$m. At distances between 25 mm and 6 mm there was an increase in the average thickness of the $\alpha$-laths from a range which fell within 2.17 $\mu$m – 2.33 $\mu$m to 20.81 $\mu$m - 22.51 $\mu$m, respectively. It is also clear from Table 1 that from distances 6 mm to near the edge of the projectile holes, there was a refinement of the $\alpha$-laths leading to the average thickness of the $\alpha$-laths which fell within the range 7.76 $\mu$m - 8.61 $\mu$m, at the latter.

Figure 9(a) and (b) are optical micrographs, with (b) at a higher magnification, both of the initial microstructure of wrought Ti6Al4V from a 10 mm thick plate. The micrographs were all taken at a distance 40 mm from the edge of the projectile hole.

Figure 9: (a) Optical micrograph and (b) higher magnification optical micrograph, both of the initial microstructure of wrought Ti6Al4V from a 10 mm thick plate.

At 40 mm from the edge of the projectile holes, the wrought Ti6Al4V showed a lamellar microstructure, with incidences of globulisation, which was an indication of the initial microstructure of the alloy.

Further microstructural analysis of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates, revealed that moving radially outwards there was a variation in the $\alpha$ phase and $\beta$ phase fractions, with a decrease in the $\beta$ phase fraction, radially away from the edge of the projectile holes.

Figure 10(a) and (b) are optical micrographs, with (b) at higher magnification, showing the initial microstructure of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates used here. The micrographs were all taken at a distance 40 mm from the edge of the projectile hole.

Figure 10: (a) Optical micrograph and (b) higher magnification optical micrograph, showing the initial microstructure of wrought Ti6Al4V from a 10 mm thick plate.
At 40 mm from the edge of the projectile holes, the alloy showed a basket-weave microstructure within elongated prior $\beta$ columnar grains, which was an indication of the initial microstructure of the alloy.

For both Ti6Al4H alloys, the micrographs presented here reveal a change in the microstructure due to high velocity impact. Evidence of this for the wrought Ti6Al4V can be seen in the lamellar microstructure, with incidences of globulisation in Figure 9(b), that changed to a fine lamellar microstructure in Figure 7(c), near the edge of the projectile holes. The size of $\alpha$-laths in the impacted plates was also seen to increase continuously from the edge of the projectile hole through distances of 2, 4 and 6 mm radially away from here.

For the as-built and stress relieved DMLS Ti6Al4V (ELI), evidence of the effect of ballistic impact is seen in the variation of the $\alpha$ phase and $\beta$ phase fractions between the initial microstructure and the microstructure near the edge of the projectile holes. Figure 8(b) and Figure 10(b) show a decrease in the $\beta$ phase fraction (lighter shade), with distance radially away from the edge of the projectile hole.

For both Ti6Al4H alloys, the changes in microstructure at areas close to the projectile holes imply an increase of temperature above the $\beta$-transus temperature of 980°C during impact. In the case of the wrought Ti6Al4V, the refinement of the microstructure at these areas can be attributed to rapid cooling of the alloy, to an ambient temperature of 25°C, during ballistic impact testing, which is higher than the annealing cooling rate of the wrought Ti6Al4V.

In the case of the as-built and stress relieved DMLS Ti6Al4V (ELI), the increase in the $\beta$ phase fraction at these areas can be attributed to the fact that during the DMLS process, the alloy is cooled within an environment of argon gas, while during the ballistic testing it experienced cooling in the open air at an ambient temperature of 25°C. The significant factor in the two cases is different starting temperatures of 3000 K and above 1000 K for the DMLS process and ballistic testing, respectively. The cooling rate in the DMLS process is very rapid and varies between $10^5$-$10^6$ K/s and is higher than the air cooling prevailing in case of ballistic impact.

IV. CONCLUSIONS

In the velocity range of about 700 m/s the minimum thickness to prevent through penetration of both alloys during testing was established to lie between 14 mm and 18 mm. This is higher than that of RHA of 11.43 mm and less than that of AA 5083 of 19.8 mm.

Fractographic analysis of both alloys revealed that, although Ti6Al4V is usually classified as a ductile metal under normal loading conditions, when exposed to high velocity impact, the alloy exhibits both a brittle and ductile behaviour as is evident in Figure 4(b) and Figure 6(b), respectively.

During high velocity ballistic impact, the high strain rate imposed on the plates led to the generation of high temperatures in both alloys that brought about microstructural changes within a limited area radially outwards from the projectile holes. For the wrought Ti6Al4V, this is clear from the gradually decreasing refinement of grains and measured average values of the widths of $\alpha$-laths, radially away from the edge of the projectile holes. Furthermore, for the as-built and stress relieved DMLS Ti6Al4V (ELI), this is clear from the decrease in the $\beta$ phase fraction radially away from the edge of the projectile holes.

For both alloys, the high strain rate and attendant high rise in temperature arising from high velocity impact was enough to cause the formation of ASBs, whose incidence reduced with distance away from the edge of the projectile holes.

ACKNOWLEDGMENT

The Centre for Rapid Prototyping and Manufacturing (CRPM), of the Central University of Technology, Free State is gratefully acknowledged for preparing the DMLS specimens.

REFERENCES


Additive Manufacturing
Material Development
Characterization of Polypropylene Powder Produced by Precipitation for Powder Bed Fusion Additive Manufacturing

Joseph Nsengimana
Department of Mechanical & Mechatronics Engineering
Central University of Technology, Free State
Bloemfontein, South Africa
jnsengimana@cut.ac.za

Jacabus G van der Walt
Department of Mechanical & Mechatronics Engineering
Central University of Technology, Free State
Bloemfontein, South Africa
jgvdwalt@cut.ac.za

Deon J de Beer
Centre for Rapid Prototyping and Manufacturing
Central University of Technology, Free State
Bloemfontein, South Africa
ddebeer@cut.ac.za

Ernst HG Langner
Department of Chemistry
University of the Free State
Bloemfontein, South Africa
LangneEH@ufs.ac.za

Abstract—Powder bed fusion additive manufacturing is a technology that uses a laser to selectively melt powder to manufacture fully dense parts for medical and many engineering applications. The limited selection of polymeric materials to produce powder suitable for laser sintering (LS) remains a challenge to overcome. Polypropylene is a polymeric material with potential to increase the selection of polymers for the LS process. Precipitating a mixture of HNR100 and HTV145 polypropylene grades from SASOL in xylene with talc added, a powder with particle size suitable for LS was obtained.

Keywords—polypropylene, powder, laser sintering, characterization

I. INTRODUCTION

Goodridge et al. [1] reported that although laser sintering (LS) can process a wide range of materials, 95% of LS production processes of prototypes and functional parts that are based on polymers, involves only nylon polyamides PA11 or PA12. Polypropylene (PP) presents properties favourable for LS and can be used to increase the selection of polymers for the process. Cryogenic grinding is one of the techniques through which polymeric granules can be converted into powder particles of average size ranging from 50 to 125 µm which is suitable for LS. The pellets are cooled down to a temperature lower than the glass transition temperature and fed into a counter-rotating pinned disc mill that uses an impact crusher principle to reduce the size of the pellets. Wet grinding in a solvent media such as ethanol, n-hexane, butanol, n-octane or a water solution of mannitol can be used to reduce the size of the particles [2, 3]. It is however challenging, time consuming and costly to grind the polymeric pellets into a powder of particle size below 100 µm. This particle size range can only be achieved through a series of multiple grinding stages that can lead to discoloration which is evidence of degradation of the polymer. The produced powder is sieved, screened down and air classified to a desired particle diameter. A significant amount of wastage may result from non-fractionated material to a desired shape and particle size, thus reducing the productivity of the powder production process [4, 5]. The predominance of particles with irregular shapes containing fibrous, fibrous fragmented, fibrous agglomerates and lamellae morphologies is the main drawback of particles obtained through comminution grinding. Processing such particles through LS results in poor flowability of the powder [4, 6].

Spray-drying, fluidization in a downer reactor, immiscible blends and Liquid-Liquid Phase Separation (LLPS) are other techniques that can be used to reduce PP pellets to particles of smaller sizes. LLPS is a physico-chemical technique whereby a polymer in the form of granules or pellets is heated in a solvent such as xylene while continuously stirring until complete dissolution is obtained [7]. Under quiescent conditions, the cooling and precipitation of such a solution results in the formation of spherical particles that can be used as a polymeric powder for the LS process. This study aimed to characterize powder obtained through precipitation of polypropylene pellets from SASOL to determine its suitability for powder bed fusion additive manufacturing.

II. METHODOLOGY AND EXPERIMENTAL SETUP

A. Dissolving and precipitation of PP granules

Spherical granules of two isotactic homopolymer polypropylene grades, namely HNR100 and HTV145 were supplied by SASOL Limited, South Africa. Under a nominal load of 2.16 kg and test temperature of 230°C, the Melt Flow Rates (MFR) of HNR100 and HTV145 were determined to be 12 and 50 g/10 min, respectively [8]. A mixture of 400 g composed of HNR100 (70 wt%) and HTV145 (20 wt%) pellets, together with talc (10 wt%) was prepared. This specific ratio of HNR100 to HTV145 was determined through experimentation. HNR100 precipitated in xylene produces large particles of 100 – 200 µm while HTV145 produces small particles of 10 – 30 µm. Mixing the two grades of PP pellets in the mentioned ratio before precipitation produces particles with the size ranging from 20 to 90 µm suitable for LS. Little
information is available on the proprietary properties of the specific grades of SASOL polymers used except for that they are isotactic homopolymers. The two grades of PP pellets are largely used in the injection moulding industry and available at low cost (R35/kg). The 10% talc that was added to the batch is to reduce the high crystallinity of PP which can cause parts to warp during LS. The 400 g batch was introduced into 5.5 litres of xylene contained in a double walled stainless-steel pot. The wall of the outer pot was insulated to retain heat generated in the solution by a Snappy Chef model SM-CO2D induction stove (Fig 1). Stirring of the mixture was performed through a rotating blade rigidly connected to the chuck of a RYOBI, model PD-650 electrical drill. The mixture was heated from room temperature to a temperature of 130°C at an average heating rate of 15°C/10 min while continuously stirring until the PP was completely dissolved into the xylene.

Once complete dissolving was achieved, the stirring and heating were stopped, and the solution left to cool down to room temperature at an average cooling rate of 3°C/10 min. This allowed for the precipitation of the dissolved PP mixture through the nucleation and growth of PP crystals for the formation of spherical microscopic particles in the form of a gel. The heating and cooling rates were monitored using an 8-channel Pico® Technology TC-08 data logger through four thermocouples that were installed in the double walled pot.

**B. Drying and grinding of the PP powder**

Most of the xylene was removed from the obtained precipitated PP gel using a modified TRE SPADE sausage filler machine. The gel was introduced into the machine’s stainless-steel barrel and compressed by hand cranking a rack and pinion mechanism that was connected to a piston. This action forced the xylene through a filter at the bottom of the barrel from where it flowed through a flexible pipe to a container for re-use (Fig. 2).
Fig. 2: Removing xylene from PP gel in order to produce powder

The obtained cake still contained about 10% of xylene and needed to be dried. It was spread on the stainless-steel base of the flow cabinet shown in Fig. 1 & 2 and the xylene allowed to evaporate through air passing through the cabinet. The particles were largely agglomerated in the cake and needed to be separated to improve flowability of the powder. The powder was therefore introduced into a Fritsch Analysette 3 sieve shaker with stone tumbling media. This proved to be a slow means of breaking up the agglomerated particles but was sufficient for the amount of powder required for the research. The ground powder was next sieved to 90 µm which is a suitable size for processing through LS. Since the powder will be processed in a Sintratec S1 laser sintering machine with a low power diode laser in the next phase of the research, it needed to be coloured dark grey. One gram of carbon black was therefore added to every 400 g batch of the dry powder to enhance the laser absorption and also to improve the flowability of the powder.

III. CHARACTERIZATION OF THE PP POWDER FOR LASER SINTERING

Characterization of the PP powder for laser sintering was performed through Differential Scanning Calorimetry (DSC), Thermogravimetric (TGA) and Scanning Electron Microscopy (SEM) analyses.

A. Differential Scanning Calorimetry analysis

Differential Scanning Calorimetry (DSC) is a thermal analysis method which measures the difference between the rate of the heat flow into a specimen and a reference specimen as a function of temperature and/or time. The main stages in the LS process involve heating of the powder from ambient temperature to just below the melting temperature to allow sintering and then cooling back down to room temperature for consolidation of the part. The thermal behaviour of the powder can be predicted through DSC analysis to determine the window of sinterability of polymeric powders for the LS processes.

The window of sinterability also commonly known as processing window is defined as the difference between the onset melting (T_m-onset) and the initial onset crystallization (T_c-onset) temperatures [9]. In LS of semi-crystalline polymers, for a full coalescence of polymer particles in the top powder layer as well as its adhesion with previous sintered layers, crystallization temperature should be inhibited during processing as long as possible at least for several sintered layers. In other words, the processing temperature must be controlled within the processing window. If the bed sintering temperature is too low or close to peak crystallization temperature, curling due to premature crystallization is induced. This results in accumulation of stresses in the parts, leading to their distortion after releasing from the surrounding powder bed. On the other hand, a high bed processing temperature too close to peak melting temperature will lead to powder caking which results in a loss of exact definition of part features as the powder particles located in the direct neighbourhood of the laser, stick on the molten surfaces and prevent the desired resolution of the part topography [10, 11].

A standard heating and cooling rate of 10°C/min or 10°K/min under nitrogen atmosphere according to DIN EN ISO 11357 [4, 12] can be used to generate DSC curves in order to determine the window of sinterability for the LS process. A sample of 5 mg from the new PP/talc/carbon black batch was subjected to DSC analysis using a Mettler Toledo DSC 822e at the University of the Free State. The sample was subjected to three cycles of heating and cooling at a rate of 10°C/min under a nitrogen atmosphere (Fig. 3).
Each cycle consisted of heating the sample from 25 to 190°C, followed by cooling from 190 to 25°C. The melting and crystallization behaviour during the first cycle is used to determine the degree of crystallinity and the sintering parameters of the powder. After the first cooling, the powder sample is transformed into a bulk solid, with the talc and carbon black components now dispersed in the polymer matrix. To investigate the thermal behaviour of the solid bulk material, the second and third cycles were run. The dispersion of the talc and carbon black in the polymer matrix was the cause of the earlier onset of melting observed during the second and third heating cycles, as well as the lowering of the degree of crystallinity (Table 1).

**Discussion on the results of the Differential Scanning Calorimetry analysis.**

The degree of crystallinity of semicrystalline polymers varies from 10 to 80% [13] and it ranges from 40 to 70% for isotactic PP [14]. Under moderate conditions, the spherulites obtained while solidifying iPP in quiescent conditions at a moderate cooling rate are roughly made up of 50% α phase crystals and 50% of amorphous phase. If the cooling rate is low enough, the resulting spherulites are richer in α phase at about 60% while the amorphous content of spherulite will be lowered down to be around 40% [15]. The first cycle of conducted DSC analysis is representative of the SL process as the sintering of the powder must take place between the crystallization and melting temperatures. After the completion of the fabrication of the part, the cake powder is cooled down to room temperature and can be reused for another new sintering process. The obtained window of sinterability of 28.26°C i.e. allowing sintering within a range from 128.40 to 156.66°C (Table 1) is greater and comparable to a window of sinterability of 25.8°C obtained by Fang, Wang and Xu [16]. The obtained degree of crystallinity of 39.12% indicates that the filling with talc and coating with carbon black contributed to decreasing the degree of crystallinity, thus affecting positively on the level of shrinkage and warpage during the cooling stage leading to consolidation of the laser sintered parts.

**B. Thermogravimetric analysis**

To investigate the mass loss of the PP composite as a function of heating temperature, a Thermogravimetric Analysis (TGA) was conducted using a Mettler Toledo TGA/SDTA 851e at the University of the Free State. A mass of 6.03 mg was subject to continuous heating up to 600°C with a constant heating rate of 10°C/min under a nitrogen atmosphere, as shown in Fig. 4. The thermal behaviour of the PP composite through the TGA analyses is summarized in Table 1.

**Discussion on the results of the Thermogravimetric analysis**

Fig. 4 shows that the degradation of the PP sample starts at 385°C and terminates at 495°C, implying a degradation range of 110°C where 88% of the polymer degrades...
The powder contains 10% of tale and a negligible mass of carbon black, an amount of 12% that is not degraded represents the tale and the carbon black for which the applied temperatures were not sufficient to cause degradation. The degradation at much higher temperatures ranging from 385 to 494°C confirms that, the relatively lower temperatures of the LS process should not lead to the degradation of the newly produced PP composite powder.

Table 1: Summary of thermal behaviour of the PP composite

<table>
<thead>
<tr>
<th></th>
<th>First cycle</th>
<th>Second cycle</th>
<th>Third cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melting properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting melting temperature (T_ms), °C</td>
<td>144.71</td>
<td>134.44</td>
<td>130.51</td>
</tr>
<tr>
<td>Final melting temperature (T_mf), °C</td>
<td>173.74</td>
<td>171.77</td>
<td>168.65</td>
</tr>
<tr>
<td>Peak melting temperature (T_mp), °C</td>
<td>166.86</td>
<td>161.74</td>
<td>158.65</td>
</tr>
<tr>
<td>Onset melting temperature (T_m-onset), °C</td>
<td>156.66</td>
<td>140.14</td>
<td>131.30</td>
</tr>
<tr>
<td>End-set melting temperature, (T_m-endset), °C</td>
<td>170.94</td>
<td>166.90</td>
<td>165.66</td>
</tr>
<tr>
<td>Heat of melting (J/g)</td>
<td>80.97</td>
<td>76.34</td>
<td>72.91</td>
</tr>
<tr>
<td>Degree of crystallinity (%)</td>
<td>39.12</td>
<td>36.9</td>
<td>35.22</td>
</tr>
<tr>
<td><strong>Crystallization properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting crystallization temperature (T_cs), °C</td>
<td>132.03</td>
<td>131.67</td>
<td>132.03</td>
</tr>
<tr>
<td>Onset crystallization temperature, (T_c-onset), °C</td>
<td>128.40</td>
<td>127.00</td>
<td>126.49</td>
</tr>
<tr>
<td>End-set crystallization temperature, (T_c-endset), °C</td>
<td>117.23</td>
<td>115.50</td>
<td>113.45</td>
</tr>
<tr>
<td>Peak crystallization temperature (T_cp), °C</td>
<td>123.21</td>
<td>122.38</td>
<td>121.14</td>
</tr>
<tr>
<td>Final crystallization temperature (T_cf), °C</td>
<td>106.24</td>
<td>101.44</td>
<td>97.09</td>
</tr>
<tr>
<td>Heat of crystallization (J/g)</td>
<td>76.79</td>
<td>75.04</td>
<td>66.43</td>
</tr>
<tr>
<td>Supercooling temperature, T_m-onset, °C</td>
<td>41.71</td>
<td>40.1</td>
<td>36.62</td>
</tr>
<tr>
<td>Range of LS processing temperatures [T_c-onset, T_c-onset] and, °C</td>
<td>From 128.40 to 156.66</td>
<td>From 127.00 to 140.14</td>
<td>From 126.49 to 131.30</td>
</tr>
<tr>
<td>Sinterability window, T_m-onset - T_c-onset, °C</td>
<td>28.26</td>
<td>13.14</td>
<td>4.81</td>
</tr>
<tr>
<td><strong>Degradation properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range of degradation temperature</td>
<td>385 to 494</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass loss (%)</td>
<td>88</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4: TGA analysis of the PP composite
C. Scanning Electron Microscope analysis

Ideal powder for the LS process should have particles of high sphericity to facilitate the flow of the powder during the recoating process, and to reduce the surface area to volume ratio which improve the packing efficiency. Poor flowability and low bulk density leads to inhomogeneous deposition of the powder during the recoating stage, thus resulting in parts with high level of porosity, poor surface finish, poor dimensional inaccuracy and reduced mechanical properties. Spherical, potato and irregular shapes are three main morphologies of powder particles that have been identified by Schmid et al. [17]. An investigation of the size and morphology of the particles of the composite PP powder as described in this research was carried out at the Department of Geology at the University of the Free State. Samples of the powder were scanned on a JEOL JSM 6610 SEM at an accelerating voltage of 20 kV. The particle sizes and morphology of the new produced powder were compared to that of a commercial PP powder, CP75 from Diamond Plastics GmbH. For enhancement of electrical conductivity, polymeric samples are usually coated with gold or carbon in a vacuum environment before SEM analysis. A sputter coater turbo evaporator, model Quorum Q150TE was used to deposit a carbon film on the surfaces of both polymeric powder samples and fixed on inserts which were fitted into the SEM. Fig. 5 shows a comparison between the morphologies of the commercial powder PP CP75 (Fig. 5a, c, e, g) versus the morphologies of the newly produced PP powder (Fig. 5b, d, f, h) at different magnifications.
Fig. 5: Comparison of morphologies for particles of a commercial PP CP75 and new produced powder.

**Discussion on the results of the Scanning Electron Microscope analysis**

The particles of PP CP75 are characterized by generally irregular and potato shapes while the particles of the new produced powder are mostly spherical in shapes. The PP CP75 powder furthermore has a significant number of very small, dispersed fractioned particles or attached to relatively bigger particles while the new powder particles are separate or
attached to particles having almost equal diameters. The attached small particles on the surfaces of big particles of PP CP 75 powder will result in a rough surface topography contrary to the particles with smooth surfaces for the new powder. The diameter sizes of particles with nearly spherical shapes, dimensions of agglomerates, and the overall dimensions of particles with potato or irregular shapes were evaluated as shown in Fig. 6.

A chemical analysis performed using the SEM, confirmed the presence of talc particles in the powder (Fig. 7). This is evident through the presence of silicon dioxide (SiO₂) and magnesium oxide (MgO) which make up the main components of talc.
Table 2 summarizes the chemical composition of the talc at different locations of the powder.

<table>
<thead>
<tr>
<th>POINTS</th>
<th>Chemical composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
</tr>
<tr>
<td>1</td>
<td>83.01</td>
</tr>
<tr>
<td>2</td>
<td>69.52</td>
</tr>
<tr>
<td>3</td>
<td>69.22</td>
</tr>
<tr>
<td>4</td>
<td>85.67</td>
</tr>
</tbody>
</table>

The talc remains suspended within the dissolved polypropylene in xylene and upon drying and grinding of the mixture, the talc particles are intermixed with the PP particles.

IV. CONCLUSION

The increase in the number of polymeric materials suitable for powder bed fusion additive manufacturing provides many engineering applications in the medical, automobile and aerospace industries. Polypropylene is a semi crystalline polymeric material with more than 20 varieties of grades that can be combined to obtain a composite polymer with improved properties to produce a powder for the LS process. This study demonstrated that the mixture of two PP grades, HNR100 and HTV145 dissolved and precipitated in xylene can produce a gel composed of spherical particles. A SEM analysis showed that drying of the gel followed by grinding resulted in smooth spherical particles with average diameter of 37.4 µm. This should ensure good flowability of the powder and a high bulk density. Talc added to the PP before precipitation was found to be well dispersed in the powder and a high bulk density. Talc added to the PP before precipitation was found to be well dispersed in the powder after drying. A DSC analysis showed that the newly produced powder has a wide window of sinterability of 28°C and a degree of crystallinity of 39%. This should make it well suited for processing through LS with low shrinkage and/or warpage of produced parts. A TGA analysis indicated that the newly produced powder degrades at relatively high temperature ranging from 385 to 494°C. With the building chamber temperature maintained at 120°C and the powder bed heated to 140°C during the LS process, the temperature that the PP powder is exposed to is far from the degradation point of the polymer as indicated by the TGA results. This indicates the potential for recycling of the used powder for a next LS build without significant negative effects on mechanical properties, roughness and dimensional accuracy of the produced parts. Future work will elaborate the characterization of the newly produced powder focusing on particle size distribution (PSD), flowability and mechanical properties of subsequent laser sintered parts.

ACKNOWLEDGMENT

The financial support from the South African Research Chairs Initiative of the Department of Science and Technology and National Research Foundation of South Africa (Grant № 97994) and the Collaborative Program in Additive Manufacturing (Contract № CSIR-NLC-CPAM-15-MOA-CUT-01) is gratefully acknowledged. Thanks also to the University of the Free State and Central University of Technology, Free State collaborative programme for funding support. Profound gratitude to the Department of Geology, University of Free State, for their assistance with SEM results as well as the Department of Chemistry, University of Free State, for DSC and TGA results.

REFERENCES


Parameters Affecting the Mixing of Powders and the Results of Mixing SiC and Ti6Al4V(ELI) Powders

Masenate Thamae  
Department of Mechanical and Mechatronics Engineering,  
Central University of Technology, Free State, Bloemfontein, South Africa.  
Masenate.a.thamae@gmail.com

Maina Maringa  
Department of Mechanical and Mechatronics Engineering,  
Central University of Technology, Free State, Bloemfontein, South Africa.  
mmaringa@cut.ac.za

Willie du Preez  
Department of Mechanical and Mechatronics Engineering,  
Central University of Technology, Free State, Bloemfontein, South Africa.  
dwpreez@cut.ac.za

Abstract - Segregation and agglomeration are major problems in the mixing of powder intended for use in additive manufacturing and the prevention and limitation of these phenomena are very important in powder-mixing. The particle size distribution of the constituents used in a powder mixture is one of the key factors that determine the homogeneity of the mixture, though differences in particle density and shape are also known to cause segregation in mixtures. This paper specifically addresses the mixing of SiC/Ti6Al4V(ELI) powders for additive manufacturing and the results of powders obtained after SEM. The parameters affecting the quality of mixture that are considered in this paper include powder homogeneity and heterogeneity, size distribution, particle shape, and methods of mixing.

Keywords - powder mixing, segregation, agglomeration, sampling,

I. INTRODUCTION

Powder mixing is an important process in blending of components as it combines different powders into single products that must meet specifications and standards based on the homogeneity of mixes [1]. Powder mixing is widely used in areas such as pharmaceuticals, powder metallurgy, as well as processing of food and cement. Additive Manufacturing (AM) is a technique which uses 3D model data to build parts in a process of layer-by-layer building and fusion of layers until a complete component is produced. Additively manufactured parts are affected by powder segregation and agglomeration during production. Powder segregation is defined as the separation of portions of particles caused by differences in the physical properties of particles such as size, shape and density [4,2]. Agglomeration is defined as the sticking of individual particles to one another because of forces between them [2]. The study of Markuss et.al [13] showed that the sphericity of the particles is favourable for good flow behaviour in the Laser Powder Bed Fusion (LPBF) processes for layer deposition. Leitz et.al [14] further proved that the LPBF processes are highly sensitive to the powder particle arrangement in the powder layer. The authors further noted that variations or imperfections in the powder layer influence the width of the molten track during sintering.

Direct metal laser sintering requires metallic powders with good sphericity, low oxygen content and fine particle size [13]. The powder properties such as morphology, surface texture, impurity content can have a direct effect on the manufacturing process and final properties of 3D build parts. Benson et al. [13] indicated that the major powder parameters that should be taken into consideration when characterising a metallic powder for AM are particle shape, and chemical composition.

This paper addresses the mechanisms of mixing powders and the methods used for mixing SiC/Ti6Al4V powders. The individual and mixed powders are analysed with the Scanning Electron Microscope (SEM) to check for aggregation, homogeneity, and morphology of the mixed powder. The results of batch automated mixing of silicon carbide (SiC) and Ti6Al4V(ELI) at different volume fractions of SiC particles are presented and discussed based on (SEM) of the mixed powders. The SEM images of the individual powders are also presented and discussed.

II. SEGREGATION AND AGGLOMERATION.

The most important mechanisms of segregation are percolation, trajectory and segregation due to vibration. Percolation segregation occurs whenever a mixture of particles of different sizes is disturbed in such a way that rearrangement of particles occurs. During disturbance of particles, gaps open between the larger particles and the smaller particles travel down through these gaps and settle at the lower levels [5]. When a mixture of particles of different sizes is vibrated, the smaller or finer particles settle below the larger ones. Trajectory segregation occurs during the transfer and pouring out of powder where the larger and heavier particles fall further away from the material’s origin than the finer and lighter particles [3]. This is because the inertia of particles depends on their size and density, and therefore, given the same exit/injection velocity the larger and heavier particles will travel further [7]. The shape of particles of constituent powders is less important than the difference in particle size distribution, assuming all other parameters affecting mixing remain constant. A greater variety of sizes will cause greater density. Particles with rough surfaces have less surfaces available for friction, though this is subject to the level of surface roughness and shape, and hence will flow more easily [7].

In addition, at the correct ratio, powders of different sizes are better able to fill the spaces in between particles. Therefore, powders with different particle size distributions may become more compact on vibration. Sheno et al. [2] observed that light particles are mainly collected on the top and outer regions, while heavy particles are collected in the inner and bottom regions of a mixer. Agglomeration occurs through the effect of strong interparticle forces when particles come in close contact and stick together, thus forming lumps that create inhomogeneity in mixtures [5]. Another aspect that causes agglomeration is the moisture content of powder; higher moisture content increases friction and may result in larger particle agglomerates and lowers the flowability of powder.

Funded by: South African Department of Science and Innovation through the Collaborative Program in Additive Manufacturing (Contract No.: CSIR-NLC-CPAM-18-MOA-CUT-01)
III  Mechanisms and Methods of Mixing SiC and Ti6Al4V Powders

Mixing of powders refers to the setting in motion of different particles inside a mixer. The external supply of energy needed is either provided by the motion of a vessel, a blade passing into the particles, gravity, or a combination of some of these methods [8]. The mixing of powder proceeds by the three main processes of convective, diffusive and shear mixing. Convective mixing means the collective transfer of groups of particles from one location to another within a mixture caused by the motion of a rotating blade [17]. This convective mixing is usually carried out in large scale mixing such as in continuous methods of mixing. In diffusive mixing, the individual particles of powder move randomly, typically rolling down when their container is rotated. Here, there is no forced pattern caused by the agitators in the mixer, but rather the particles move individually, when the motor is switched on, causing the vessel to rotate [17]. Shear mixing of powder is defined by the exchange of momentum of particles with different velocities between two clumps of particles of powder. In this mechanism, a shearing surface appears and leads to the reorganization of particles. The inter-particle forces are broken between the two groups of particles thus causing the dislocation of particles which are then reorganized by both convection and diffusion mixing mechanisms. Shear mixing applies in both batch mixing and continuous mixing methods [16].

There are two broad categories of methods of mixing powder, continuous and batch mixing. Continuous methods involve the mixing of different powders at a constant mass flow rate, where the powder is fed continuously into a mixer with an equal amount of powder being continuously discharged on the other side of the mixer as the mixing continues [10]. The other method is known as batch mixing, which is the preferable method used in this study to mix SiC-Ti6Al4V powders [6]. In batch mixing, the constituent powders are loaded into a mixer, mixed until the powder is homogenous then discharged as a single batch. The loading, mixing and discharge processes are done consecutively, one after another. The diffusive mechanism is the main mixing mechanism prevalent in the batch method, as it encourages the individual movement of particles within the vessel and does not require impellers to move the particles.

IV. SAMPLING OF POWDER MIXTURE

The effectiveness of a mixing process is determined through analysis of a sample of the mixed powder. Therefore, the application of an internationally accepted sampling procedure, such as ASTM B215-10 [14] is essential to ensure a reliable assessment. Several samples are taken from a bulk powder at random and the variation of their composition is determined. The sample size and number of samples are important in sampling of powder and the size of samples is determined by the packages or bags in which a mixture is contained. If the sampling is done for powder being transferred from discharge to a package bag or container, samples should be taken when the container is ¼, ½, and ¾ filled [14]. The more homogeneous the mixture, the lower the expected variance. There are several common methods of analysing mixtures that are used, including the cone and quartering, sampling using a spatula, as well as the Keystone sampler method.

V. MATERIALS AND METHODS

A. Weighting and Sieving of Powder Mixture

The Ti6Al4V(ELI) powder was sieved before use to remove any agglomerates or other large particles to ensure even consistency of the metal powder. The Ti6Al4V (ELI) powder was sieved using an 80 μm sieve, while the SiC powder was sieved by the supplier. Six sealed containers of SiC and Ti6Al4V(ELI) powders with varying vol% (5% to 30 vol%) of SiC powder were prepared for mixing. The sealed containers had diameter 42 mm and length of 140 mm. Each of the containers weighed a mass of 16.3 g empty. Figure 1 shows an image of the plastic containers used to collect the powders. The powder in each container was quarter full.

![Fig.1. An Image of plastic containers used for collecting powder](image)

The mass of the containers (m_c) was first measured, and respective powder poured into the containers whose total mass (m_T) was then measured. The mass of each container was then subtracted from the total mass to obtain the mass of powder (m_p) in it in accordance with Equation 1:

\[ m_T - m_c = m_p \]  

(1)

B. Mixing of SiC and Ti6Al4V Powders

The rotary multiple tube batch mixer shown in Figure 2 was used to mix SiC/Ti6Al4V powders in the present work and is an example of a batch mixer. The mixer had five tubes that can hold powders. The powders were mixed for thirty minutes.

![Fig.2: An image of a rotary multiple tube batch mixer](image)

C. Sampling of SiC/Ti6Al4V Powder Mixture

The effectiveness of a mixing process is determined through analysis of a sample of the mixed powder. The SiC/Ti6Al4V powder mixture was sampled using a spatula. Six different portions of powder mixture were taken from each container of powder mixture with different SiC volume fractions using a spatula. Micrographs of the samples were then examined on SEM.

D. Morphology of SiC and Ti6Al4V Powder

The morphology of mixed and individual types of powders was determined using a JSM-6610 Scanning Electron Microscope
The 22nd Annual International RAPDASA Conference
Digital Manufacturing: Industrialising Africa

The Ti6Al4V(ELI), SiC and mixed powders, with different volume fractions for the latter, were sampled using a spatula and then mounted on a double-sided carbon tape which was attached to the platform of the SEM. The shape, size and surface topography of individual powders, as well as mixed powders, were then studied.

E. Elemental Composition of Ti6Al4V (ELI) Powder

The chemical composition of the Ti6Al4V (ELI) powder was determined using inductively coupled plasma-optical emission spectroscopy (ICP-OES). This is a technique which uses a plasma as the excitation source to determine how much trace elements are in a sample [12]. The source of energy is heat from an argon plasma that operates at high temperatures approximated in the range 6000-10 000 K, because it is sufficient for breaking down the sample into atoms and provide energy for ionisation and excitation [12]. The powder sample was dissolved in an acid solution and fed into a plasma that was set to high temperature conditions. The intensity of the emission lines of the different metal elements was measured in the plasma and produced qualitative elemental data.

VI. RESULTS AND DISCUSSION

A. Mass of Powder in each Container

The results of weighing the two types of powder are summarized in Table 1, which details the masses of the mixed powder in each container.

<table>
<thead>
<tr>
<th>Percentage of SiC powder</th>
<th>Type of Powder</th>
<th>Mass of powder (g)</th>
<th>Total mass of powder per container (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>SiC</td>
<td>5.5</td>
<td>158.3</td>
</tr>
<tr>
<td></td>
<td>Ti6Al4V</td>
<td>152.8</td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>SiC</td>
<td>11.1</td>
<td>155.9</td>
</tr>
<tr>
<td></td>
<td>Ti6Al4V</td>
<td>144.8</td>
<td></td>
</tr>
<tr>
<td>15%</td>
<td>SiC</td>
<td>16.6</td>
<td>153.3</td>
</tr>
<tr>
<td></td>
<td>Ti6Al4V</td>
<td>136.7</td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>SiC</td>
<td>22.2</td>
<td>150.9</td>
</tr>
<tr>
<td></td>
<td>Ti6Al4V</td>
<td>128.7</td>
<td></td>
</tr>
<tr>
<td>25%</td>
<td>SiC</td>
<td>27.7</td>
<td>148.4</td>
</tr>
<tr>
<td></td>
<td>Ti6Al4V</td>
<td>120.7</td>
<td></td>
</tr>
<tr>
<td>30%</td>
<td>SiC</td>
<td>33.2</td>
<td>145.8</td>
</tr>
<tr>
<td></td>
<td>Ti6Al4V</td>
<td>112.6</td>
<td></td>
</tr>
</tbody>
</table>

B. Morphology and Surface Features of mixed Powders

Secondary electron (SE) SEM images of the mixed powders are shown in Figures 3 and 4. The overall shape of Ti6Al4V(ELI) particles was spherical with most particles smaller than 50 μm in the SE micrographs as is evident in Figures 3(a) and (b). The SiC particles are angular, prismatic as is evident in Figures 3 (c), (d) and (f), and were typically smaller than the Ti6Al4V powder particles. For 5% - 10% volume fractions of SiC, the SiC particles were dispersed randomly amongst the Ti6Al4V(ELI) particles, without clustering or agglomeration. Clustering or agglomeration of particles was seen to occur at a volume fraction of 15% SiC and higher. The agglomeration of powder at high SiC volume fractions is expected to cause formation of irregularities during deposition of powder layers, which according to the findings of Liets et.al [14] influences the width of the molten track during sintering. Reduced segregation was observed after mixing of the powders in the rotary multiple tube batch mixer as compared to the original hand mixed samples. Satellites and small particles of SiC on the surfaces of larger Ti6Al4V(ELI) particles were observed to increase with the addition of SiC particles.
Fig. 3. SEM SE micrographs of SiC/Ti6Al4V (ELI) mixtures at different SiC volume fractions, at magnifications of ×300 (images in the left column) and ×500 (images in the right column), (a) and (b) 5% SiC vol. fraction, (c) and (d) 10% SiC vol. fraction, (e) and (f) 15% vol. fraction.
Fig. 4. SEM SE micrographs of SiC/Ti6Al4V (ELI) mixtures at different SiC volume fractions, at magnifications of ×300 (images in the left column) and ×500 (images in the right column), (a) and (b), 20% vol. fraction, (c) and (d) 25% vol. fraction, and (e) and (f) 30% vol. fraction.
C. Elemental Composition of Ti6Al4V (ELI) Powder

The chemical composition of SiC powder from the supplier measured by X-Ray diffraction is presented in Table 2.

**TABLE 2: THE CHEMICAL COMPOSITION TRACE ELEMENTS IN OF SiC POWDER AS DETERMINED BY THE SUPPLIER.**

<table>
<thead>
<tr>
<th>Elements</th>
<th>Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Ca</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Ti</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Fe</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Y</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

Table 2 shows that the supplied SiC powder had very small trace elements, the rest of the percentage being SiC powder. The results of chemical composition of Ti6Al4V (ELI) powder obtained at NECSA by ICP-OES are shown in Table 3.

**TABLE 3: THE CHEMICAL COMPOSITION OF Ti6Al4V (ELI) POWDER**

<table>
<thead>
<tr>
<th>Element</th>
<th>Results</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>89.7</td>
<td>ICP-OES-FULL-GEN</td>
</tr>
<tr>
<td>Al</td>
<td>6.35</td>
<td>ICP-OES-FULL-GEN</td>
</tr>
<tr>
<td>V</td>
<td>3.73</td>
<td>ICP-OES-FULL-GEN</td>
</tr>
<tr>
<td>Fe</td>
<td>0.17</td>
<td>ICP-OES-FULL-GEN</td>
</tr>
</tbody>
</table>

Table 3 shows that almost 90% of the alloy is titanium powder that is alloyed with small amounts of Aluminium (6%) and vanadium (4%), with some small trace elements of iron.

**CONCLUSION**

The following conclusions are drawn from the foregoing material:

- The homogenous mixtures with low segregation that were obtained at the low volume fractions of SiC (5% -15% vol) are expected to lead to the production of good quality build parts, and thus places an upper limit to the volume of SiC that can be recommended using the present method of mixing.

- The SEM micrographs of the mixed powders showed a distinct difference in the sizes and shapes of the two types of powders, with the Ti6Al4V (ELI) powders being spherical and larger, while the SiC powders were prismatic, irregular in shape and smaller. This from the review is good as it enhances mixing and increase density of the mixture.

**REFERENCES**


Laser Metal Deposition of TiB₂/TiC/Ti6Al4V Composites

Nomahlubi Thunyiswa
Department of Physics
University of Pretoria
Pretoria, South Africa
u16401477@tuks.co.za

Paul Lekoadi
National Laser Center
Manufacturing Cluster
Council for Scientific and Industrial Research
Pretoria, South Africa
PLekoadi@csir.co.za

Chris Theron
Department of Physics
University of Pretoria
Pretoria, South Africa
chris.theron@up.ac.za

Bathusile Masina
National Laser Center
Manufacturing Cluster
Council for Scientific and Industrial Research
Pretoria, South Africa
BMasina@csir.co.za

Abstract—Ti6Al4V alloy is used in aerospace, marine and automotive industries due to its excellent properties such as superior strength, high stiffness, and exceptional corrosion resistance. However, its application is limited due to poor high-temperature mechanical properties, while titanium matrix composites offer good high-temperature mechanical properties. In this study, TiB₂ and TiC reinforcements were added in Ti6Al4V ELI bulk matrix to produce titanium matrix composites, TiBw/TiCp/Ti6Al4V ELI. The effect of laser reinforcement material on the microstructure and hardness properties of the TiB₂/TiC/Ti6Al4V ELI composites were investigated.

Keywords—Ti6Al4V ELI, titanium matrix composites, reinforcement, microstructure

I. INTRODUCTION

Titanium (Ti) alloys, specifically Ti6Al4V, has become a material of choice in aerospace, marine and automotive industries due to its excellent properties such as superior strength, high stiffness and exceptional corrosion resistance, and biocompatibility [1]–[3]. Despite of its high demand, manufacturing of Ti6Al4V products is constantly challenging due to its poor thermal conductivity, the tendency to strain hardening and chemical reactivity to oxygen [1]. To overcome these shortcomings, titanium matrix composites (TMCs) have been developed by adding reinforcements such as TiC, TiB₂, B₄C, TiN, WC, and SiC using various manufacturing techniques [3]–[7]. One of the disadvantages of building TMCs through conventional manufacturing is that machining composites with complex configurations become more difficult due to hard and brittle reinforcements [8]. Compared to conventional manufacturing methods, with additive manufacturing (AM) it is possible to the build near-net-shaped components with great design flexibility using metals and their composites in a layer-by-layer form [4]. Moreover, in situ fabrication is the most favoured among many manufacturing methods available for Ti matrix composites, due to the low cost and possibility of producing large composites and good interfacial bonding between reinforcement and matrix material [9]. Among the reinforcements, TiC and TiB are reported as two best reinforcements due to their high modulus, remarkable thermodynamic stability, and excellent bonding interface with Ti matrix [3], [7], [10]. Both TiB and TiC reinforcements display great compatibility with the Ti matrix due to their comparable densities and coefficients of thermal expansion (CTE) [10]. TiB whisker is a preferred reinforcement since it has high modulus, excellent chemical resistance and tensile strength along with CTE to those of Ti matrix [8]. On the other hand, TiC can generate dislocations and prevent crack initiation due to the comparatively big difference of CTEs between Ti6Al4V and TiC, which can improve the strength of TMCs. TiC is also considered due to its excellent physio-chemical stability at elevated temperatures [11]. Furthermore, adding (TiB + TiC) can also improve the oxidation and abrasion resistances of Ti-6Al-4V matrix [3]. Wei et al reported an improved wear resistance that was accomplished by (TiB + TiC) reinforcement [11]. This study aims to investigate the effects on the microstructure of Ti6Al4V ELI when simultaneously added with TiC and TiB₂ reinforcement powders. An in-situ laser metal deposition method was used to fabricate single-track TiB/TiC/Ti6Al4V matrix composites using fixed powder feeding rate of Ti6Al4V ELI powder while varying the powder feeding rate of both TiB₂ and TiC powders. The microstructure properties of TiB/TiC/Ti6Al4V ELI matrix composites with different powder feeding rate were investigated.

II. MATERIALS AND METHODS

The matrix material used in this study was Ti6Al4V ELI (extra low interstitial) with nearly spherical shape and size distribution of 40-100 μm supplied by TLS-Technik, whereas
The reinforcement materials were irregular shaped TiB₂ and TiC powders with size distribution of 40-100 μm supplied by SABINANO are presented in Fig. 1. The substrate used in this study was Ti6Al4V base plate, which was sand blasted prior to the laser metal deposition process.

Fig. 1: SEM images of the morphology of (a) matrix powder, Ti6Al4V ELI (b) reinforcement powder, TiB₂ and (c) reinforcement powder, TiC.

The details of the experimental setup that was used in this study can be found in [12]. The experiment was carried out using a 1073 nm Ytterbium IPG Fiber laser attached to the cladding head together with a three-way nozzle and then integrated to a KUKA robot-arm for easy movement. Two GTV powder feeder systems fitted with three hoppers were used to deliver the three powders (Ti6Al4V ELI, TiB₂ and TiC) into the three-way nozzle and into the melt pool via the argon carrier gas set to 1.5 l/min. The argon gas was also used as a shielding gas and was set to an optimized value of 15 l/min to prevent oxidation of the produced samples. The laser power, scanning speed and laser beam diameter were kept at 1500 W, 0.5 m/min and 2 mm, respectively. Therefore, the energy density computed using equation (1) was the same for all samples and equal to 89.9 J/mm². The powder feeding rate of Ti6Al4V ELI was set to 2.5 rpm while the reinforcements powder feeding rate was varied from 0.3 to 0.5 rpm. During the metal deposition process, three single-track line samples were produced using 89.9 J/mm² while varying the reinforcements powder feeding rate.

\[ E = \frac{P}{v \cdot d}, \quad (1) \]

where \( E \) (J/s) is the surface energy density, \( v \) (mm/s) is the scanning speed and \( d \) (mm) is the beam diameter of 2 mm.

Table 1 presents the process parameters and powder feeding rates used in the experiment. Metallographic samples were prepared using standard mechanical polishing methods and the polished samples were chemically etched for 10-15 s in a Kroll reagent (10 ml HF: 45 ml HNO₃: 45 ml H₂O). Optical microscope (OM) and a scanning electron microscope (SEM) were used to characterize the microstructure of the TMCs. Lastly, the hardness of the TMCs samples were measured using the Zwick/Roell Indentec Vickers’ hardness tester. During indentation, a 300-gf load with a dwelling time of 10 seconds was used. The results were given by an average of three patterns of 20 indentations for sample S1 because it had a bigger clad. While three patterns of 13 indentations for samples S2 to S4 were measured since these samples were smaller.

### Table 1: Laser metal deposition processing parameters that were used to fabricate the single-track line samples.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Laser Power (W)</th>
<th>Scanning Speed (m/min)</th>
<th>Beam Diameter (mm)</th>
<th>Energy Density (J/mm²)</th>
<th>Powder Feeding Rate (rpm)</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>1500</td>
<td>0.5</td>
<td>2</td>
<td>89.9</td>
<td>7.5</td>
<td>Ti6Al4V ELI</td>
</tr>
<tr>
<td>S2</td>
<td>1500</td>
<td>0.5</td>
<td>2</td>
<td>89.9</td>
<td>2.5</td>
<td>TiB₂ and TiC</td>
</tr>
<tr>
<td>S3</td>
<td>1500</td>
<td>0.5</td>
<td>2</td>
<td>89.9</td>
<td>2.5</td>
<td>0.3</td>
</tr>
<tr>
<td>S4</td>
<td>1500</td>
<td>0.5</td>
<td>2</td>
<td>89.9</td>
<td>2.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### III. RESULTS AND DISCUSSION

#### 4. Microstructure evaluation

Fig. 2 presents the optical micrograph showing a cross-section of the single-track line sample produced using only the Ti6Al4V ELI powder which was set to 7.5 rpm.

As presented in Error! Reference source not found., the microstructure of Ti6Al4V ELI sample appeared to be an acicular αʹ martensitic microstructure, which is corresponding with literature [1], [13], [14]. This was concurred by the SEM result as presented in Error! Reference source not found.. This is due to the rapid cooling during the LMD process. The OM micrograph also presents big voids as well as homogenously distributed micro particles all over the structure. However, the acicular αʹ martensite microstructure seems to be overlaid by microporosity as shown in Fig. 2(b); which were not observed on the OM micrograph. Most often, defects such as microporosity are observed on the AM samples. Possibly, the porosity might be due the entrapment of gas in the molten Ti6Al4V ELI alloy. The larger voids may be the result of digressing from melting conditions due to insufficient laser power.

Fig. 3 to Fig. 5 presents the optical micrographs showing a cross section of the single-track lines produced using 2.5 rpm Ti6Al4V ELI powder together with both 0.3–0.5 rpm TiB₂ and TiC reinforcements, respectively.
The microstructures observed appeared to be dendrites across all three samples. The microstructure has slightly different sections; the top section has fine dendritic grains. Whereas the middle and bottom sections are coarser. The middle section is a mixture of dendrites and equiaxial microstructure with an array of equiaxed grains dominating. And the bottom section is composed of columnar dendritic microstructure. One possible reason for the formation of different grains in the same microstructure has to do with the thermal gradients during the LMD process. The top fine-grained section may have cooled faster than the coarser middle and bottom sections of the samples. Another observation in these microstructures are the dark irregular shaped unmelted particles spread across all three sections. Some of these unmelted particles are held within defects. The unmelted particles may be due to insufficient energy density; the powder feeding rate increase while power remained unchanged which resulted to the powders not fully melted. Both laser power and powder feeding rate are amongst the most critical parameters affecting the resulting microstructure [15].

The reinforcements powders, TiB₂ and TiC, are difficult to melt, while titanium alloy can melt through heat transfer [16]. TiB₂ (3253 °C) and TiC (3067 °C) have high melting points that are far higher than that of Ti (1670 °C) [16], [17]. The interface of all three samples seems to have pores. White round structures which vary in size distributed all over the top section of the microstructure of the three samples. According to the author’s knowledge, these round structures have not been reported in literature therefore are novel. At present, the reason for the formation of this novel structure is still unclear and remain under investigation.

Fig. 3 presents the microstructure of 0.3 rpm (TiB₂/TiC)/Ti₆Al₄V ELI single-track line matrix composite. In this sample, equiaxial grains formed a thin array in between the top and bottom regions of the microstructure due to the difference in the temperature gradients and cooling rates during the LMD process.

Fig. 4 presents the microstructure of 0.4 rpm (TiB₂/TiC)/Ti₆Al₄V ELI single-track line matrix composite. In this sample, the equiaxial grains have slightly increased, which makes the array thicker than the one observed in Fig. 3. As mentioned above, the formation of this kind of microstructure has to do with cooling rate distribution throughout the sample. Another observation is the increase in the size and quantity of unmelted particles, with more of these particles sitting at the top section. This is due to an increase in the volume percentage of the reinforcements while energy density remained unchanged. The shape of these unmelted particles has transformed; some are still irregular, and others have become elliptic. Porosity observed has also increased because there was more powder needed to be melted while the laser power remained unchanged. These defects were more on the bottom section, some extended across the substrate.

Fig. 5 presents the microstructure of 0.5 rpm (TiB₂/TiC)/Ti₆Al₄V ELI single-track line matrix composite. As the powder feeding rate increased, the array of equiaxed grains became thicker, and the array of columnar dendrites became thinner, implying that the columnar grains at the bottom section had transformed to equiaxed grains. According to literature, powder deposition rate tends to promote the transformation of columnar grains to equiaxed by providing heterogeneous nucleation on partially melted powder particles [18]. As compared to the TMCs discussed above,
the unmelted particles have increased in the bottom section and are much bigger in size. The most compelling explanation is that the dissipation of cooling rates in the bottom was much slower. During directional solidification of the melt pool, the substrate serves as the heat sink [19]. An extreme increase on microporosity and large pores is also observed. In this case porosity is widespread across the bottom section.

Fig. 6 highlights the defects and unmelted particles discussed above.

Sample S2 had a clad of 961.28 μm radius and a heat-affected zone (HAZ) of 824.28 μm; unmelted particles range between 15 and 57 μm in length, and the diameter of the white round structures is between 37-62.10 μm. The radius of the clad for Sample S3 was 985.88 μm with HAZ of 853.76 μm. The unmelted particles are between 21 and 205.50 μm, and the measured diameter of white round structures was between 24 and 65 μm. Lastly, Sample S4 had a clad of 984.32 μm radius and 834.56 μm HAZ. In this sample, the length of unmelted particles was between 19 and 174 μm. The diameter of the white round structures was between 34 and 73 μm. The measurements indicate that the size of unmelted particles increased as the powder feeding rate increased. Contrary, the size of white round structures in all samples was comparable. Also, as observed in the size of each of the three samples, the quantity was approximately equal. The size of pores as well as their quantity increased with (TiB2/TiC) powder feeding rate. These pores dominated the bottom of the microstructure and at the interface.

The microstructure observed across all the TMCs has different regions of fine and coarse dendrites microstructure. With columnar and equiaxed grains present in the coarser regions and dendrites in the finer regions. Overall, the microstructures were mainly composed of dendrites. The thermomechanical processes during the LMD had a significant influence on the resulting microstructure of the TMCs; as a result, the observed unmelted particles, and defects such as porosity highlighted the critical role played by energy density during the melting and solidification stages.

The samples were also characterized using SEM. The resulting microstructures are exhibited in Fig. 7 to Fig. 9, respectively. A mixture of grains was observed across all the TMCs, such as irregular, columnar, and cellular grains. The matrix was identified to be the Ti6Al4V ELI. The grains at the top and center of the microstructure were found to be similar. Hence, Fig. 7 and Fig. 8 show the center and bottom, while Error! Reference source not found. shows the top and bottom. The reinforcements (TiB2/TiC) precipitated on the grain boundaries as shown in Fig. 7 to Fig. 9. The white particles were identified as TiC and the dark rod were TiB whisker. A similar structure was reported by Wei et al., claiming that the boundaries were TiC and TiB reinforcements selectively distributed over the Ti6Al4V powder [11], [14], [20]. According to the report, TiC particles separate the nearby Ti6Al4V alloy matrix by assembling with each other and act as the “grain boundaries”. Similar observations were reported for the needle-shaped TiB whiskers [20]. There is evidence on the microstructure that adding reinforcement hinders the growth of the α’ acicular martensite structure. Since Fig. 7 to Fig. 9 are showing the reduced acicular α’ martensite structure. This transformation of the Ti6Al4V ELI microstructure upon adding TiB2 and TiC reinforcements is comparable to the one found in literature [20]. In particular, what seems like microporosity and large voids were observed (Fig. 7 and Fig. 8), as well as unmelted particles (Error! Reference source not found.). Furthermore, in Fig. 7 and Fig. 8 the white particles in the boundaries were quite solid and irregular. As can be seen from Fig. 9, the white particles seem to be dissolving, especially in the top section where the grains were much finer.

Fig. 7: SEM micrographs of the single-track line produced using 0.3 rpm (TiB2/TiC)/(Ti6Al4V ELI).
B. Evaluation of hardness

Hardness was measured for each sample of Ti6Al4V ELI matrix and (TiB2/TiC)/(Ti6Al4V ELI) composites with a load of 300 gf for 10 s, 100 μm spacing between the corresponding indentations. Three hardness patterns were measured for each sample and average hardness was calculated. The samples were indented from the top of the clad through the clad up until the substrate. The average hardness profile results are shown in Fig. 10 and Fig. 11, respectively. Fig. 10 presents the hardness profile for the Ti6Al4V ELI matrix. The clad had a hardness average value of 354 ± 6 HV0.3. This value is corresponding to values found reported in literature [21]–[23]. The highest values of hardness on the substrate were measured at the heat affected zone (HAZ) and the average value is 367 ± 7 HV0.3. Fig. 11 presents the average hardness profile of TMCs at different feeding rates. There was an increase in hardness of the TMCs with the gradual increase of powder feeding rate of the reinforcements is observed. The highest hardness average value was, 428 ± 24 HV0.3, obtained for the clad produced using 0.5 rpm (TiC/TiB2)/Ti6Al4V ELI. According to Wang et al, a gradual increase of TiC powder feeding rate intensely improves the hardness of Ti6Al4V [24]. As well as the presence of high modulus TiB whiskers, enhance the hardness [8]. Mahamood et al. reported an increase in microhardness for laser power between 0.8 and 2.0 kW for a Ti6Al4V/TiC composite [19]. This laser power range includes the laser power employed in this work which was 1.5 kW. The high hardness measured at 700 μm depth show measurements taken on the unmelted particles. Therefore, the reinforcements increased the hardness of the TMCs.

IV. CONCLUSION

In summary, TiB2/TiC/Ti6Al4V ELI composites with reinforcements of different volume fractions were successfully built by LMD process across the same process parameters. Optical and Scanning electron micrographs of the cross-sections of Ti6Al4V ELI sample and TiB/TiC/Ti6Al4V ELI samples were observed and grain morphology and size were discussed. The resulting Ti6Al4V ELI microstructure is a martensite with microporosity homogeneously spread across the structure. The observed microstructure on the TMCs is composed of fine grain dendrites at the top and coarse grain columnar and equiaxial in the middle and bottom sections. Addition of reinforcements require high energy density; this was evident by the significant number of defects observed in the microstructure which include unmelted particles, microporosity and large voids. These results substantiated that laser power and powder feeding rate contribute significantly to the microstructure. The emerged novel white round structure is still investigated. The hardness profile results of Ti6Al4V ELI matrix are comparable with the results reported in literature. As expected, an increase in the powder feeding rate of the reinforcements increased the hardness of the TMCs.

V. ACKNOWLEDGMENTS

The authors would like to acknowledge the Council for Scientific and Industrial Research for supporting this research and making their resources available to us.

REFERENCES


Additive Manufacturing
Process Development
A Risk Based Classification Method for Powder Bed Defects

Francois Du Rand
Department of Electrical Engineering
Vaal University of Technology
Vanderbijlpark, South Africa
francoisdu@vut.ac.za

Malan van Tonder
Technology Transfer and Innovation
Vaal University of Technology
Sebokeng, South Africa
malanvt@vut.ac.za

Andre van der Merwe
Department of Industrial Engineering
Stellenbosch University
Stellenbosch, South Africa
andrevdm@sun.ac.za

Abstract—The detection and classification of surface defects that occur during powder bed additive manufacturing processes, is currently receiving of attention from various researchers. Most research studies focus on the detection and classification of defects to make the technology more reliable. However, it is very important to determine the risks that these defects pose to the outcome of the build and final part. This study aims to develop a risk-based defect classification method. The results will be used to develop a defect decision matrix that could be used to determine the appropriate course of action during a build for the different types of defects.

Keywords—risk, risk assessment, binder jetting, laser sintering

I. INTRODUCTION

With the steady adoption of AM technologies in industry, part of the drive to make AM technologies more stable, repeatable, certifiable and increase industry adoption has given rise to new quality control methods. An area of research that has grown steadily has been the detection and classification of powder bed surface defects that occur during the printing process [1],[2]. Most of these studies focused on the detection of defects [1],[2], with some studies looking to classify defects according to type using machine learning algorithms [3]. Since few AM machines make use of closed loop feedback systems yet, repairing defects during the build process is very difficult and requires an operator to physically monitor the build process. In order to autonomously monitor the build, the detection and classification of defects must be performed automatically without any user intervention. To develop a closed loop feedback system, it is necessary to first determine what risk the defect poses to the build and the part. Once the defect risk can be determined, risk mitigation methods can be implemented to limit or eliminate these defects.

II. BACKGROUND

Since this study will be focusing on the defects that occur on powder bed-based AM technologies, the basic components found in most, if not all powder bed-based AM technologies are illustrated in Figure 1. The main difference between the different technologies are the powder fusion methods (a) which usually takes the form of a laser/electron beam or a binder spraying head. The rest of the components are the same, only the construction differs as different manufacturers have different machine designs.

The additive manufacturing process starts with the build platform (f) being raised to the top of the build chamber. Next, the powder feeding platform (c) is raised slightly, and the recoater (b) scrapes powder from the powder feed platform (c) to create a new layer on the build platform (f). Once the powder has been spread on the build platform, the powder fusion source (a) fuses the powder in the shape of the part geometry (d) that ultimately becomes the part being manufactured. When the powder has been fused, the recoater once again scrapes a new layer of powder over the build platform to create the next layer. This process is repeated for each layer of the part until the entire part has been fabricated. The surrounding unfused powder (e) remains in place to support the manufactured part until the build process is completed. For this study, defects will be considered that occur during the re-coating process as well as some of the defects that may occur during the powder fusion process.

As discussed in the introduction, an important aspect that should be considered for the development of a closed loop feedback system, is to determine the effect a given defect could have on the outcome of a build and its individual parts. However, before the effects of the different defects can be quantified, it is necessary to compile a type of defect library that contains all the types of defects that has been encountered using powder bed-based technologies. A list of defects has been identified, through literature, and is summarised in Table 1. The possible causes for the defects as well as the effect it has on the final part or build is also listed.
III. METHODOLOGY

For this next section, the methodology that will be followed to assess the risks that each defect poses to the outcome of a build will be discussed. Each defect must be analysed individually as each defect has its own risks. In order to ensure that the risk assessment results are accurate and verifiable, it is necessary to use a standardised risk assessment method. According to literature there are several risk assessment methods that can be used, namely: Checklist, What-if analysis, hazard and operability study (HAZOP), failure mode and effect analysis (FMEA) and lastly fault tree analysis (FTA) [8].

Although the purpose of this study is not the selection of a risk assessment method, it is necessary to do a brief review of the listed risk assessment methods. The first method that will be discussed is the checklist. In this method a checklist of known hazards or threats to a process/product/environment is used to identify any possible issues in the product or process being analysed. This accuracy of this method is largely dependent on the experience and capability of the user as well as the completeness and quality of the checklist [8]. The second method called the What-if analysis method is a type of risk assessment method that is used ask questions about the product or process in question to determine what could possibly go wrong as well as what effect these issues could have on the outcome. For this method experts from the field are required that have experience in all the possible problems that may occur. The third method that will be discussed is the HAZOP method. This method is mostly used to identify hazards that may pose a risk to people, property, or the environment. The process being analysed is broken down into steps, and all the possible variations in the process is considered to see what may go wrong. Due to the way the process is meticulously broken down, it has become a very popular risk assessment method in the chemical industry [9].

The fourth method that will be looked at is the FMEA. This method was developed in the 1940s by the U.S. Military to identify possible failures in a design, manufacturing or assembly process [10]. A FMEA is used to identify possible problems in the process called failure mode, identify the effect it may have on the outcome of the process, recommend possible corrective actions that can be taken to mitigate or eliminate the failure mode. The last method that will be discussed is the FTA. FTA is a risk assessment that is used to determine what combinations of errors can cause specific problems.
problems to occur. This method is a graphical deductive method that starts with a specific problem and works through the problem from the top down. In comparison to FMEA, FTA is easier to perform as it focuses on all the reasons why a specific problem occurs, whereas a FMEA focuses on all the problems regardless of the severity level [11].

Since this study is mostly about looking at the causes of a defect and the effect it would have on the parts being manufactured as well as the overall outcome of the build, it was decided that the FMEA risk analysis method would be the best suited method to the study. This decision is also supported by another AM related study conducted by Martínez-Marquez et al. on the effect that different types of manufacturing defects could have on additively manufactured patient-specific implants [12]. In this study a FMEA was used to great effect to draw up a risk matrix for the different defects that has been encountered during the manufacturing lifecycle. From this risk matrix it was possible to calculate a risk priority number that was used to arrange the defects according to the priority in which they must be addressed when they occur.

A. FMEA Process

In order to conduct a FMEA, there are a number of steps that must be followed to ensure that the end result is valid and can be used to mitigate the risks each defect poses to an acceptable level. The diagram in Figure 2 demonstrates the steps that must be followed to conduct a FMEA in line with the AS9100 standards for aviation [13].

The first step in a FMEA is to select the process that must be analysed. It is important to describe the product or process in detail to avoid any misunderstandings. In this study the process being analysed will be the powder bed-based AM process. It must be noted that the study is not limited to a specific technology within this category but will be looking at all the technologies contained in the category as a whole.

Because the objective of a FMEA is to determine what factors causes problems in the process and what effect these factors have on the process, it is important to consult with a variety of industry and academic experts in the field. These experts need to range from researchers in academic settings such as universities and research institutes, to engineers designing parts for AM technologies and operators of the machines so as to tap on as wide range of knowledge as possible. This because literature on its own is not always sufficient, and actual hands-on industry experience can become invaluable when conducting risk assessments. For the purposes of this study, it will be important to have these experts do the different ratings as outlined in the FMEA process to ensure that reliable data is collected based on actual industry experience.

The next step is to identify all the different failure modes that may occur in the process being analysed. Each of the defects that have been identified in the previous section is considered a failure mode as each defect has the potential to affect the build process and the final part quality.

Once all the failure modes have been identified, it is important to identify all the effects that each defect may have on the final part, as well as the overall outcome of the build. This is done to ensure that the impact each defect has on the build has properly been assessed.

Once the impact for each failure mode has been established, each of the failure modes must be assigned severity rating according to how significant an impact the failure mode would have on the part or build. It is important to have this severity rating performed by the experts to ensure that reliable data is collected. These severity ratings are usually ranked on a scale of 1 to 10, where 1 is insignificant and 10 is catastrophic.

The next step is to determine the root cause of the different failure modes. This can be done by using analysis tools as well as draw on the knowledge and experience from the industry and academic experts. There are several methods outline in literature that can be used to do a root cause analysis.

When the root causes of the failure modes have been determined, it is necessary to assign an occurrence rating to each cause of the failure modes. The occurrence ratings are usually ranked on a scale of 1 to 10, where 1 would be rare and 10 would be inevitable.

For each identified cause it is also necessary to identify all the process controls that are normally used to prevent these failure modes from impacting the customers. For each control method identified, it is also necessary to assign a detection rating to each control. This rating is used to identify how well the control will be able to detect the failure mode when it occurs. The detection ratings are also ranked on a scale of 1 to 10, where 1 would be that the failure mode will be detected by the control with absolute certainty, and 10 would be where the control measure would most likely not detect the failure mode when it occurs. Once all the different ratings have been given, a risk priority number (RPN) can then be calculated. This value is then used rank the different failure modes on a priority scale. This risk priority number is calculated using the product of the severity rating, occurrence rating and the detectability rating (S x O x D).

The RPN value can now be used to make decisions on how the defect should be addressed. This RPN value can play a very critical role in developing a closed loop feedback system as it can be used to determine the appropriate corrective action to take, and to make decisions on the fly as to whether the defect should be immediately addressed, left as it is or stop the build prematurely to prevent further loss of raw materials.

IV. FMEA QUESTIONNAIRE

In order for the industry experts to be able to assist with the FMEA for the different types of that has been encountered with powder bed-based AM technologies, it is necessary to consult with industry experts to gain valuable insights that
cannot be otherwise obtained by literature alone. However, due to the COVID-19 situation at the time of writing, having large gatherings of people is discouraged. Thus, alternative options were considered such as remote meetings and digital data collection methods. Since most of the industry experts are working at companies, it was decided that using digital data collection methods such as a questionnaire would be better suited as the experts can fill these in on their own time. Using digital data collection methods also makes the aggregation of the data easier and eliminates the need to have meetings recorded and transcribed for accuracy and traceability. Thus, a questionnaire will be created that would be completed by the experts.

The questionnaire will be created following FMEA process discussed in section 3.1. All the failure modes relevant to this study has been highlighted in Table 1. The first portion of the questionnaire will be focusing on the description of the failure mode. A description for each failure mode is created by describing what the defect looks like as well as a brief description of how the failure mode formed. Alongside this description, an image of each failure mode will also be included in the questionnaire to ensure that the reviewing experts gets a clear idea of what the failure mode represents. It is important that the description create an image in the mind that resembles closely what the actual failure mode looks like. The next portion of the questionnaire will be focusing on the effect that the defect may have on a build. A list of effects that the defect may have on a build is drawn up from literature, but the experts will also have an opportunity at this point to add additional effects to the list that may not have been covered in literature. Once the effect of the defect has been determined, it is now necessary to do the root cause analysis of what may have caused the defect. As with the effect analysis, the possible causes that may cause the failure mode to occur are firstly compiled from literature. Then the reviewing experts will also be given an opportunity to highlight any additional root causes that may have been missed by the literature review.

For the identified root causes, it is important to identify controls that can be used to detect the various failure modes if and when they occur. For this study the controls of choice is computer vision as the proposed monitoring system is based on using imaging systems to monitor the powder bed surface for defects that may occur. At this point in the study corrective measures can also be considered part of the control measures. An opportunity will also be granted to the experts to give their advice on how these failure modes can be mitigated or repaired during the build process. Although it is a bit out of sequence as listed in the FMEA process, the rating of the severity of the failure modes, the rating of the occurrence of the failure modes and the detection rating of the control measures are done together. This makes the rating process easier as reviewing experts already have all the information required for each failure mode, and can thus provide a more accurate rating for the different failure modes. An example of what the questionnaire would look like for a specific failure mode (defect) is illustrated in Figure 3.

![Figure 3 Questionnaire Template](image)

For each of the identified failure mode the same type of questionnaire will be used for evaluation to ensure that consistent data is collected for each defect. Once the questionnaires have been reviewed and filled in by the collaborating experts, the information from these questionnaires can be compiled together. Using this data metrics such as the RPN can be calculated to determine the priority for each defect, as well as the criticality [10]. These numbers can then be used to rank the defects in the order in which they should be addressed. Furthermore, from this data conclusions can hopefully also be drawn about what the possible corrective actions can be to repair these defects or avoid their occurrence all together.

V. FUTURE WORK

For future work, a group of collaborating experts will be recruited for the study to conduct the FMEA with. As discussed previously these experts must be recruited from a wide variety of knowledge bases ranging from academic experts down to machine operators to ensure a wide variety of expertise. These experts will also be split up into 2 separate groups to try and reduce the bias as well as provide feedback on if there might be something missing from the initial FMEA questionnaire.

VI. CONCLUSION

For the development of an additive manufacturing monitoring system, it is necessary to determine the risk that each defect may have on the outcome of the build process. In order to do this, it is necessary to conduct a thorough risk assessment to gauge the impact of these risks. Based upon information gathered in literature about standard risk assessment methods, a Failure Mode and Effect Analysis was selected as the best suited risk assessment method for the AM process. This decision was also supported by a previous study on AM in literature. Based on the steps of the FMEA process, a questionnaire was developed that could be used by collaborating experts to review the different defects encountered in the powder bed type AM process. The data
collected using these questionnaires can then be used to calculate metrics that can ultimately be used to rank these defects in the order in which they should be addressed, as well as provide some solutions that can be used to repair the defects or avoid the defects altogether. This information can now be used to develop a decision matrix for a closed loop feedback system that can autonomously make decisions about defects that occur during the build process without external operator intervention.

REFERENCES

Abstract—Several IN718 clads were produced with a laser cladding technique that used 1073 nm, high power continuous wave (CW), IPG Ytterbium fibre laser while varying laser power and scanning speed. The quality of IN718 clad was determined in terms of dilution, aspect ratio and defects. Optical microscope analyses found a finer and coarse dendritic with inter-dendritic Laves phase microstructure from the middle to the top of the quality IN718 clad. Columnar dendritic microstructure with inter-dendritic Laves phase was found as segregates and concentrated at the edges and interface of the quality IN718 clad. SEM-EDS analyses concluded that the overall quality IN718 clad microstructure was achieved with ≤12.14 wt.% Nb in the formed Laves phase particles. For structural engineering ≤20wt.% Nb, in the Laves-phase particles is required otherwise crack nucleation in the columnar phase occurs thereby compromising the overall built structure.

Keywords—Laser Cladding, Inconel (IN718), Laves-phase particles, Niobium (Nb)

I. INTRODUCTION

Inconel 718 (IN718), also known as niobium (Nb) bearing nickel-based super-alloys [1], is widely used in aeronautics and energy industries because of its excellent mechanical properties and thermal corrosion resistance up to 650 °C [2]. Nb is a significant element in the IN718 super-alloy as it forms these phases; γ(Ni3Nb), γ( Ti(Nb)C and Laves phase particles (Ni, Fe, Cr)2(Nb, Mo and Ti) [3-4]. The main problem with the as-produced IN718 component, by laser material processing techniques such as laser cladding and laser welding, is the formation of Nb-rich Laves phase particles in the γ-matrix [5-6]. The formed Nb-rich Laves phase particles are as a result of the segregation of Nb element and the non-equilibrium phase transformation. It is proven that the presence of Nb-rich Laves phase particles in the IN718 component reduces its performance in ductility, ultimate tensile strength, fatigue life and fracture toughness [7-8]. Furthermore, columnar dendrite structure with the inter-dendritic Laves phase particles in the IN718 part results in the initiation of hot micro-crack nucleation [3].

It is well known that to improve the IN718 performance, Nb segregation, which results in the formation of the Laves phase particles should be inhibited. Several studies [4-6, 9] show that heat treatment is an effective post-processing method necessary to controlling the formation of Laves phase particles in the IN718 part. Heat treatment causes recrystalization, grain growth in the heat-affected zone (HAZ) and distortion of the processed IN718 parts [9]. These are some of the reasons that a search for other methods that can be used in the control of Nb-rich Laves phase particles in IN718 alloy during processing is continuing. It has been demonstrated by several studies that the cooling rates of IN718 alloy influences the segregation of Nb [10-12] and therefore the formation of the Laves phase particles. Solidification conditions can be altered by varying the process parameters such as laser power, laser scanning speed and laser beam diameter during laser cladding. The laser cladding process was used in this study to produce IN718 clads.

The laser cladding technique is one of the laser material processing technologies that is used in the repair and manufacture of near net shape blades and turbine structures due to freedom of processing [13]. This technique makes use of a high-power laser beam to melt the powder material into a layer/coating which is called a clad layer on base material/substrate preferably with low dilution. This technique offers a profound metallurgical bonding between the clad layer and the base material. One can produce a good quality clad by optimizing the laser cladding process parameters. Fig. 1 presents the geometrical quantities of the

Fundied by the Council for Scientific and Industrial Research – National Laser Centre, Thematic Research Funds: Project number LMTRAMC.
clad such as clad height, clad width, clad area, and dilution area. A good quality clad is defined by dilution and aspect ratio [14, 15]. The dilution and aspect ratio were determined by using the following equation (1) and equation (2), respectively.

\[
\text{Dilution} = \frac{DA}{(DA + CA)} \times 100\% (1)
\]

Where \( D_A \) is the clad area and \( C_A \) is the clad area.

\[
\text{Aspect ratio} = \frac{C_w}{C_H} \quad (2)
\]

where \( C_w \) is the width and \( C_H \) height of the clad, respectively.

The clad dilution measures the amount of the substrate and the clad material that has been mixed during the laser cladding process. Minimum dilution is required to have a good metallurgical bonding and also to prevent the degradation of the coating properties. Good metallurgical bonding is expected when a clad is produced with a dilution of about 3 to 5% [14]. Aspect ratio relates to the possibility of the development of porosity and crack(s) in overlapping or multiple tracks. Aspect ratio ranging from 3 to 5 [15] is essential to avoid porosity and cracks on overlapping or multiple tracks clad.

In this work, several laser cladded IN718 samples were produced using various process parameters. This was done to determine optimised laser cladding process parameters that would produce quality IN718 clads. IN718 clads characteristics: microstructure, chemical composition and hardness will be presented and discussed.

II. MATERIALS AND METHODOLOGY

A. Materials

Commercial IN718 powder with a particle size distribution of 45 to 90 µm, which was supplied by Weartech (Pty) Ltd, was used in this study as a processing material. Fig. 2 shows the morphology of the powder. The powder particles are spherical as indicated in Fig. 2. The composition of the processed IN718 powder was 54.17 Ni, 19.76 Cr, 19.00 Fe, 4.44 Nb, 3.09 Mo, 1.05 Ti, 12.57 Al and 0.70 Si in wt.%. Mild steel plates with dimensions of 45 mm x 90 mm x 10 mm were used as the base material/substrate because it was readily available. Furthermore, the interest of this study was the quality of the IN718 clad and its composition. The mild steel composition was 0.20 C, 0.14 Cr, 0.0023 V, 0.35 Si, 1.1 Mn and Fe is the balance in wt.%.

Fig. 2. Morphology of the IN718 alloy powder as supplied.

B. Methodology

A schematic diagram of the laser cladding system that was used in this study is shown in Fig. 3 [16]. A Precitec cladding head together with the laser fibre cable were attached to the Kuka robot arm for easy movement. A 3000 W Ytterbium IPG fiber laser was used in the set-up as presented in Fig. 2. During processing, a laser beam diameter of 0.4 cm, power feeding rate of 2 rpm, carrier gas of 2 l/min, shielding gas of 12 l/min and scanning speed of 0.8 cm/s were used to produce single track-layers of IN718 alloy on the mild steel plate while varying the laser power from 1000 to 2000 W. Furthermore, similar experiments were carried out using the same process parameters while fixing the laser power at 1000 W and varying the scanning speed from 0.8 to 2.5 cm/s. Argon gas was used as both the shielding and carrier gas. Laser energy density was calculated using equation (3),

\[
\text{LED} = \frac{P}{Dv} \quad (3)
\]

where LED is a laser energy density (J/cm²), \( P \) is a laser power (w), \( D \) is a laser diameter (cm) and \( v \) is a scanning speed (cm²/s). Table 1 shows the laser cladding process parameters that was used to produce the IN718 clads.

Fig. 3. Schematic diagram of the laser cladding experimental setup that was used in this study.
TABLE 1. LASER CLADDING PROCESSING PARAMETERS THAT WERE USED TO PRODUCE THE IN718 CLADS

<table>
<thead>
<tr>
<th>Samples</th>
<th>Power (W)</th>
<th>Scanning speed (cm/s)</th>
<th>Energy density (J/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 3(a)</td>
<td>1000</td>
<td>0.8</td>
<td>3000</td>
</tr>
<tr>
<td>Fig. 3(b)</td>
<td>1500</td>
<td>0.8</td>
<td>4518</td>
</tr>
<tr>
<td>Fig. 3(c)</td>
<td>2000</td>
<td>0.8</td>
<td>6024</td>
</tr>
<tr>
<td>Fig. 4(a)</td>
<td>1000</td>
<td>0.8</td>
<td>3000</td>
</tr>
<tr>
<td>Fig. 4(b)</td>
<td>1000</td>
<td>1.7</td>
<td>1500</td>
</tr>
<tr>
<td>Fig. 4(c)</td>
<td>1000</td>
<td>2.5</td>
<td>1000</td>
</tr>
</tbody>
</table>

Metallographic samples of the IN718 clads were prepared using standard mechanical polishing methods. The polished samples were chemically etched with Kalling’s No 2. An optical microscope and Joel JSM-6010PLUS/LAM scanning electron microscopy (SEM) were used to study the microstructure and characteristics of the IN718 clads. Moreover, the SEM with energy dispersive X-ray analysis (EDS) was used to study the chemical composition of the microstructure of the IN718 clads. Zwick/Roell Indentec Vickers’ hardness tester was used to measure the microhardness of the IN718 clads. During indentation, a load of 500 gf with a dwelling time of 10 seconds was used. This load was applied because it was found to be the best load since IN718 clad doesn’t deform when indenting.

III. RESULTS AND DISCUSSION

A. Analysis of the clads

Fig. 4 presents cross-sections of the single track IN718 clads that were produced when laser power was varied from 1000 to 2000 W while the scanning speed was fixed at 0.8 cm/s. The corresponding calculated laser energy density of these process parameters were 3000 J/cm², 4518 J/cm² and 6024 J/cm² as shown in Table 1. Fig. 5 presents a cross-section of the single track of IN718 clads that were obtained by fixing laser power output at 1000 W while varying scanning speed from 0.8 to 2.5 cm/s. The corresponding calculated laser energy density of these process parameters were 3000 J/cm², 1500 J/cm² and 1000 J/cm² as shown in Table 1. Figs. 4 and 5 indicate the characteristics of the clad which are clad area, clad height, clad width, cladding depth/bonding zone and heat-affected zone (HAZ). The bonding zone for the IN718 clads that were produced by varying the scanning speed was found to be very small as indicated in Fig. 5. Table 2 shows the characteristics of the IN718 clads.

TABLE II. GEOMETRICAL QUANTITIES OF TRACKS

<table>
<thead>
<tr>
<th>Track</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
<th>Aspect ratio (w/h)</th>
<th>Dilution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 3(a)</td>
<td>2.5</td>
<td>0.8</td>
<td>3.2</td>
<td>4</td>
</tr>
<tr>
<td>Fig. 3(b)</td>
<td>3.0</td>
<td>0.6</td>
<td>4.8</td>
<td>53</td>
</tr>
<tr>
<td>Fig. 3(c)</td>
<td>3.5</td>
<td>0.6</td>
<td>6.3</td>
<td>63</td>
</tr>
</tbody>
</table>
Fig. 4 and Table 2 show that as the laser power/energy density output increased, the clad depth and width increased while the clad height decreased. Fig. 5 and Table 2 depict that as the scanning speed increased which correspond to the decrease of the laser energy density, the height of the clad decreased. Meanwhile, the clad width decreased and reach constantly as the scanning speed increased (as the laser energy density decreased). The dilution and aspect ratio of all the produced IN718 clads were determined using well-known equations [17, 18] as shown in Table 2. Table 2 shows an increase in aspect ratio and dilution of the IN718 clads as the laser power/energy density increased. Meanwhile, there was no clear trend on the aspect ratio and dilution when the scanning speed increased or laser energy density decreased as depicted in Table 2. According to the determined dilution and aspect ratio, Figs. 4(a)/5(a) clad is a good quality clad since it has 4% dilution and a 3.2 aspect ratio as indicated in Table 2 [14, 15]. These results correspond very well with the clad cross-section since it shows a good metallic bonding as presented in Figs. 4(a)/5(a). Moreover, few micro-particles and micro-pores were observed as shown in Figs. 4(a)/5(a).

B. Microstructure analysis of the clads

Fig. 6 presents optical microscopy images of the good quality IN718 clad produced using 3000 J/cm² energy density. The good quality IN718 clad microstructure consisted of columnar, equiaxial grains and dendrite as shown in Fig. 6. Similar microstructures were observed as well on the other IN718 clads that were produced using the other laser energy density which are not shown in this paper. It is well known that the growth direction of the dendritic microstructures tends to be perpendicular to the solidification interface. Columnar dendritic microstructures were mostly observed at the interface and edges of the quality IN718 clad where gradient temperature is the highest as shown in Fig. 6. This is understandable since it is known that the columnar dendritic microstructure grows where gradient temperature is the highest and at the interface [10]. Finer and coarse dendritic microstructures were observed inside the equiaxial grain from the middle to the top of the quality IN718 clad as depicted in Fig. 6. The finer dendritic microstructure seems beneficial to the quality of IN718 laser clads because most often the hot micro-crack nucleation does not initiate through them. It is believed that finer dendritic is due to the fast solidification which is a result of the high cooling rates of the process [19]. This corresponds very well with the microstructure of the good quality IN718 clad that was observed at the middle to top part, where fast solidification occurs at the toe of the clad than in the middle of the clad. Fewer micro-porosity were found on the produced quality IN718 clad as indicated in Fig. 5.

| Fig. 4(a) | 2.5 | 0.8 | 3.2 | 4 |
| Fig. 4(b) | 1.5 | 0.5 | 3.1 | 2 |
| Fig. 4(c) | 1.5 | 0.3 | 5.7 | 7 |
greyish/whitish particles that are irregular and globular in shape and have Nb/Mo-rich precipitates along the interdendritic boundaries. A similar microstructure was observed to all other IN718 clads as presented in Figs. 10 to 13, respectively. These precipitates are well-known as the Laves phase particles which were segregated during rapid solidification of the laser cladding process as confirmed by EDS-SEM analysis in Tables 3 to 7. As observed in all the Figs, the whitish/greyish segregation particles are rich in Nb, Mo and a trace amount of Ti as shown in Tables 3 to 7. These results are consistent with those that are reported in the literature [21-22]. The whitish/greyish particles in the interdendritic region measured the highest concentration amount of 12.41 Nb, 4.29 Mo and 1.27 Ti elements in wt.% for the top centre dendritic microstructure of the good quality IN718 clad as presented in Fig. 9 and Table 3. The Nb concentration that is reported in this study is lower in comparison to Nb of the IN718 laser clad or weld which is reported in the open literature [1, 3-4]. The concentration amount of Nb, Mo and Ti are \( \leq 6.00 \% \) in the \( \gamma \)-matrix for all the microstructures as reported in Tables 3 to 5. The compositional elements of the \( \gamma \)-matrix area are rich in Fe, Ni and Cr as presented in Tables 3 to 5. These results show that the majority of the precipitated particles are lying in the inter-dendritic boundaries of the microstructure.

![Fig. 9. SEM micrograph of the quality IN718 clad produced using energy density of 3000 J/cm\(^2\) indicating the top centre, middle centre and bottom centre of the clad.](image)

![Fig. 10 SEM micrograph of the IN718 clad produced using energy density of 1500 J/cm\(^2\) indicating the top centre, middle centre and bottom centre of the clad.](image)

**TABLE III. CHEMICAL COMPOSITION (wt.%) OF THE QUALITY IN718 CLAD PRODUCED USING ENERGY DENSITY OF 3000 J/cm\(^2\) SHOWING TOP CENTRE, MIDDLE CENTRE AND BOTTOM OF THE CLAD**

<table>
<thead>
<tr>
<th>Element</th>
<th>Top-White Particles</th>
<th>Top-( \gamma )-Matrix</th>
<th>Middle-White Particles</th>
<th>Middle-( \gamma )-Matrix</th>
<th>Bottom-White Particles</th>
<th>Bottom-( \gamma )-Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>-</td>
<td>0.67</td>
<td>0.74</td>
<td>0.67</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>8.92</td>
<td>10.02</td>
<td>-</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>-</td>
<td>0.80</td>
<td>-</td>
<td>0.51</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>1.27</td>
<td>0.77</td>
<td>1.04</td>
<td>0.72</td>
<td>1.26</td>
<td>0.96</td>
</tr>
<tr>
<td>Cr</td>
<td>15.27</td>
<td>18.76</td>
<td>18.19</td>
<td>18.87</td>
<td>13.69</td>
<td>14.61</td>
</tr>
<tr>
<td>Fe</td>
<td>15.01</td>
<td>20.53</td>
<td>19.61</td>
<td>20.81</td>
<td>34.25</td>
<td>40.47</td>
</tr>
<tr>
<td>Ni</td>
<td>44.08</td>
<td>50.31</td>
<td>54.37</td>
<td>54.16</td>
<td>42.76</td>
<td>42.22</td>
</tr>
<tr>
<td>Nb</td>
<td>12.14</td>
<td>5.04</td>
<td>2.58</td>
<td>7.31</td>
<td>4.38</td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>4.29</td>
<td>2.47</td>
<td>2.51</td>
<td>1.98</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>4.66</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Hg</td>
<td>-</td>
<td>8.99</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE IV. CHEMICAL COMPOSITION (wt.%) OF THE QUALITY IN718 CLAD PRODUCED USING ENERGY DENSITY OF 1500 J/cm\(^2\) SHOWING TOP CENTRE, MIDDLE CENTRE AND BOTTOM OF THE CLAD**

<table>
<thead>
<tr>
<th>Element</th>
<th>Top-White Particles</th>
<th>Top-( \gamma )-Matrix</th>
<th>Middle-White Particles</th>
<th>Middle-( \gamma )-Matrix</th>
<th>Bottom-White Particles</th>
<th>Bottom-( \gamma )-Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>0.90</td>
<td>1.37</td>
<td>1.17</td>
<td>0.85</td>
<td>0.97</td>
<td>0.83</td>
</tr>
<tr>
<td>Cr</td>
<td>20.64</td>
<td>22.22</td>
<td>18.77</td>
<td>20.54</td>
<td>16.56</td>
<td>15.78</td>
</tr>
<tr>
<td>Fe</td>
<td>21.96</td>
<td>21.24</td>
<td>19.98</td>
<td>22.53</td>
<td>32.77</td>
<td>39.27</td>
</tr>
<tr>
<td>Ni</td>
<td>56.18</td>
<td>53.78</td>
<td>52.34</td>
<td>56.51</td>
<td>45.54</td>
<td>43.21</td>
</tr>
<tr>
<td>Nb</td>
<td>3.38</td>
<td>5.08</td>
<td>8.01</td>
<td>-</td>
<td>5.54</td>
<td>5.11</td>
</tr>
<tr>
<td>Mo</td>
<td>-</td>
<td>-</td>
<td>3.78</td>
<td>-</td>
<td>2.81</td>
<td>1.92</td>
</tr>
</tbody>
</table>

**TABLE V. CHEMICAL COMPOSITION (wt.%) OF THE QUALITY IN718 CLAD PRODUCED USING ENERGY DENSITY OF 1000 J/cm\(^2\) SHOWING TOP CENTRE, MIDDLE CENTRE AND BOTTOM OF THE CLAD**

<table>
<thead>
<tr>
<th>Element</th>
<th>Top-White Particles</th>
<th>Top-( \gamma )-Matrix</th>
<th>Middle-White Particles</th>
<th>Middle-( \gamma )-Matrix</th>
<th>Bottom-White Particles</th>
<th>Bottom-( \gamma )-Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.88</td>
<td>-</td>
</tr>
<tr>
<td>Ti</td>
<td>1.06</td>
<td>0.90</td>
<td>1.35</td>
<td>0.64</td>
<td>1.23</td>
<td>0.69</td>
</tr>
<tr>
<td>Cr</td>
<td>19.84</td>
<td>20.41</td>
<td>17.63</td>
<td>19.74</td>
<td>15.88</td>
<td>18.39</td>
</tr>
<tr>
<td>Fe</td>
<td>22.63</td>
<td>23.05</td>
<td>21.27</td>
<td>26.05</td>
<td>28.87</td>
<td>31.55</td>
</tr>
<tr>
<td>Ni</td>
<td>53.73</td>
<td>55.17</td>
<td>49.52</td>
<td>53.70</td>
<td>44.52</td>
<td>49.84</td>
</tr>
<tr>
<td>Nb</td>
<td>5.49</td>
<td>3.69</td>
<td>9.58</td>
<td>-</td>
<td>8.38</td>
<td>-</td>
</tr>
<tr>
<td>Mo</td>
<td>-</td>
<td>-</td>
<td>3.93</td>
<td>-</td>
<td>3.39</td>
<td>-</td>
</tr>
</tbody>
</table>
C. Hardness Vickers measurements

Fig. 14 shows that the average hardness results of the IN718 clads as a function of laser energy density. The average hardness was 276.9 HV0.5, 273.7 HV0.5, 296.2 HV0.5, 210.2 HV0.5, and 192.7 HV0.5 for 1000 J/cm², 1500 J/cm², 3000 J/cm², 4518 J/cm² and 6024 J/cm², respectively. Fig. 13 indicates that the average hardness increased as the laser energy density decreased until reached its limit. This is understandable since the laser energy density input needs to be high enough to deposit material onto a substrate with a bonding that is metallurgically sound. Tuch et al. [20] state that the grain size is inversely proportional to the hardness of the metal. It is well known that the cooling rates play an important role in determining the grain size which is related to the hardness of the material [23]. Furthermore, the increase of the cooling rate during the solidification by using lower laser energy density input will lead to finer grains. Whereas, the lower cooling rate would be achieved by using high laser energy density input which produces coarse grains. Finer grains lead to high hardness compared to coarse grains. Lower average hardness for high energy density input was observed as shown in Fig. 14. This corresponds very well with the concept of grain size and hardness relationship since high energy density produced coarse grains thus lowering high hardness. A similar average hardness value was found for IN718 clads produced using energy density of 1000 J/cm² and 1500 J/cm² as depicted in Fig. 14. This is understandable since similar grains were observed on both clad, excluding un-melted particles and pores for IN718 clad produced using 1000 J/cm² as presented in Fig. 10 and Fig. 11, respectively. High average hardness was measured on the IN718 clad produced using 3000 J/cm² as presented in Fig. 14. This energy density was high enough to produce finer grains as presented in Fig. 9 and good quality IN718 clad according to the clad characteristics as shown in Table II.

**TABLE VI. CHEMICAL COMPOSITION (WT.%) OF THE QUALITY IN718 CLAD PRODUCED USING ENERGY DENSITY OF 4518 J/CM² SHOWING TOP CENTRE, MIDDLE CENTRE AND BOTTOM OF THE CLAD**

<table>
<thead>
<tr>
<th>Element</th>
<th>Top-White Particles</th>
<th>Top-γ-Matrix</th>
<th>Middle-White Particles</th>
<th>Middle-γ-Matrix</th>
<th>Bottom-White Particles</th>
<th>Bottom-γ-Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>2.62</td>
<td>-</td>
<td>3.19</td>
<td>-</td>
<td>2.78</td>
<td>-</td>
</tr>
<tr>
<td>Si</td>
<td>0.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.31</td>
<td>-</td>
</tr>
<tr>
<td>Al</td>
<td>0.77</td>
<td>0.66</td>
<td>0.72</td>
<td>0.66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>2.85</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td>0.48</td>
<td>0.26</td>
<td>0.54</td>
<td>-</td>
<td>0.46</td>
<td>0.29</td>
</tr>
<tr>
<td>Ca</td>
<td>0.40</td>
<td>-</td>
<td>0.31</td>
<td>-</td>
<td>0.31</td>
<td>-</td>
</tr>
<tr>
<td>Ti</td>
<td>1.13</td>
<td>-</td>
<td>1.25</td>
<td>-</td>
<td>1.07</td>
<td>0.61</td>
</tr>
<tr>
<td>Cr</td>
<td>9.96</td>
<td>11.46</td>
<td>10.18</td>
<td>11.93</td>
<td>9.29</td>
<td>10.79</td>
</tr>
<tr>
<td>Fe</td>
<td>42.54</td>
<td>54.69</td>
<td>40.33</td>
<td>53.13</td>
<td>46.87</td>
<td>58.30</td>
</tr>
<tr>
<td>Ni</td>
<td>32.91</td>
<td>33.55</td>
<td>34.20</td>
<td>34.81</td>
<td>30.50</td>
<td>30361</td>
</tr>
<tr>
<td>Nb</td>
<td>11.72</td>
<td>-</td>
<td>12.73</td>
<td>-</td>
<td>11.25</td>
<td>-</td>
</tr>
</tbody>
</table>

**TABLE VII. CHEMICAL COMPOSITION (WT.%) OF THE QUALITY IN718 CLAD PRODUCED USING ENERGY DENSITY OF 6024 J/CM² SHOWING TOP CENTRE, MIDDLE CENTRE AND BOTTOM OF THE CLAD**

<table>
<thead>
<tr>
<th>Element</th>
<th>Top-White Particles</th>
<th>Top-γ-Matrix</th>
<th>Middle-White Particles</th>
<th>Middle-γ-Matrix</th>
<th>Bottom-White Particles</th>
<th>Bottom-γ-Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>7.01</td>
<td>6.44</td>
<td>7.52</td>
<td>6.51</td>
<td>7.69</td>
<td>-</td>
</tr>
<tr>
<td>Si</td>
<td>0.35</td>
<td>-</td>
<td>0.35</td>
<td>-</td>
<td>0.37</td>
<td>-</td>
</tr>
</tbody>
</table>
D. Conclusion

A good quality IN718 clad that has acceptable dilution, aspect ratio, fewer micro-particles and without micro-cracks was successfully produced using 3000 J/cm² energy density output of 1073 nm, CW IPG fibre laser. The good quality IN718 clad has a finer and coarse dendritic microstructure from the middle to the top of the clad, and the interface columnar dendritic microstructure on the edges. The concentration of Nb in the finer/coarse dendritic microstructure was found to be ≤12.14 wt.% which is lower than the concentration of over 20 wt.% Nb that is reported in the literature for IN718 coatings that were produced with laser welding and cladding techniques [1]. The results that we report here show that a good quality IN718 clad can be produced with a laser technique. However, this will only be achieved if the process parameters that fall within high cooling and solidification rate are optimised to obtain a finer dendritic microstructure with discrete Laves phase particles. This will lead to a suppression of Nb and Mo segregation.

ACKNOWLEDGEMENT

The authors thank Mrs Razia Adam for her technical support.

REFERENCES

Additive Manufacturing Part Characterisation
Influence of Ti and Cu on the Corrosion Properties of Laser-Deposited High Entropy Alloys in NaOH Solution

Modupeola Dada
Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Staatsartillerie Rd, Pretoria West, Pretoria, South Africa dadadupeola@gmail.com

Patricia Popoola
Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Staatsartillerie Rd, Pretoria West, Pretoria, South Africa popoolaAPI@tut.ac.za

Sisa Pityana
National Laser Centre, Council for Scientific and Industrial Research, Meiring Naudé Road, Brummeria, Pretoria, South Africa Spityana@csir.co.za

Olufemi Aramide
Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Staatsartillerie Rd, Pretoria West, Pretoria, South Africa foaramide@tut.ac.za

Ntombi Mathe
National Laser Centre, Council for Scientific and Industrial Research, Meiring Naudé Road, Brummeria, Pretoria, South Africa NMathe@csir.co.za

Thembisile Dlamini
National Laser Centre, Council for Scientific and Industrial Research, Meiring Naudé Road, Brummeria, Pretoria, South Africa TDLamini2@csir.co.za

Abstract—In this study, AlCoCrFeNiCu (Cu-based) and AlCoCrFeNiTi (Ti-based) high entropy alloys were fabricated using laser additive manufacturing. The influence of the alloying elements and the laser processing parameters, the laser power and scanning speed on the corrosion behaviour of high entropy alloys for improved corrosion resistance were examined. The corrosion resistance in 1 mol/L sodium hydroxide solution was investigated using potentiodynamic polarization in experimental conditions at ambient temperature. Results indicate that the scan speed and laser power are two interactive factors that influence the corrosion rates, however, the laser power had more influence. Optimization occurred at 1400 W laser power and a scan speed of 10 mm/s. The Cu-based alloy with a corrosion rate of 0.00197 mm/yr was more resistant to corrosion than the Ti-based alloy with corrosion rates of 0.002635 mm/yr under optimum conditions.

Keywords—Corrosion rate, High Entropy Alloys, Laser Additive Manufacturing, Sodium Hydroxide, Response Surface Methodology

I. INTRODUCTION

High entropy alloys (HEAs) are a new class of alloy system that supersedes the traditional strategy of alloy development where one or two principal elements are selected with other minor elements for modification purposes. According to Yeh et al. [1], HEAs have five or more principal element with an atomic percentage ranging between 5 and 35. These amalgams in literature have been reported to show excellent mechanical and high-temperature properties attributed to their characteristic feature of forming solid solutions at elevated temperatures [2, 3]. This attribute makes HEAs suitable for several applications which require thermal stability and strength. Zhang et al. [4] reported that HEAs are promising materials for aerospace applications. Zhu et al. [5] stated that the AlCoCrFeNi high entropy alloy (HEA) is one of the most studied compositions, which acts as an excellent binder for Titanium carbide attributed to its high entropy mixing effect and physicomechanical properties [6]. This alloying system has a wide range of other properties with the inclusion of other alloying elements. Ma et al. [7] investigated the influence of adding niobium (Nb) to the HEA composition, and the authors mentioned the alloy’s microhardness and yield strength increased linearly with an increase in Nb content. Dong et al. [8] studied the influence of vanadium in the AlCoCrFeNi HEA composition; the authors recorded an increase in the plastic strain, microhardness and compressive strength of the alloy with an increase in the vanadium (V) content. Chen et al. [9] reported that the minor addition of zirconium (Zr) to the AlCoCrFeNi HEA composition significantly increased the mechanical properties of the alloy. Most reports in literature were on the influence of these elements on the mechanical property of AlCoCrFeNi HEA; however, the reports on the corrosion resistance of AlCoCrFeNiCu and AlCoCrFeNiTi HEAs fabricated by laser additive manufacturing in 1 mol/L NaOH solution are limited. To get the best results from the corrosion experiments of laser HEAs, there is a need to first optimize the process parameters. According to Nemati-Chari et al. [10], conventional optimization methods like Statistical Package for the Social Sciences SPSS, Statistica and Minitab; do not consider all parameters at the same time; only one parameter at a time is measured while others are kept constant thus, making the optimization process time consuming and expensive. Response surface methodology (RSM) is an alternative method of optimization which evaluates various laser processing parameters and their desired responses in several runs or experiments [11]. Vakili-Azghandi et al. [12] used RSM to develop regressive models to predict the corrosion behaviour of an alloy coating. Barcelos et al. [13] applied RSM in evaluating the elemental content and weight loss of Ni-Ti commercial orthodontic wires and stainless steel in an NaOH solution.
artificial saliva solution. Goh et al. [14] used RSM to optimize the operating conditions, which use an inhibitor in reducing copper corrosion. Rashid et al. [15] used RSM to optimize parameters for the corrosion rate of carbon steel in saline water. Saiedi et al. [16] and wiped clean with acetone to increase the laser absorption with silica grit using SBC 350 vertical sandblasting machine. Baseplates with dimension 50 x 50 x 5 mm were sandblasted of 45 to 106 µm mixed to form AlCoCrFeNiCu (Cu-based) and AlCoCrFeNiTi (Ti-based) HEAs were fabricated using laser additive manufacturing (LAM) and potentiodynamic polarization was used to analyze the corrosion responses of the alloys in 1 mol/L NaOH solution for aerospace applications. Optimization of the process parameters; the scan speed and laser power was achieved using RSM and the results were confirmed with experimental results.

II. EXPERIMENTAL PROCEDURE

A. Sample preparation

Baseplates with dimension 50 x 50 x 5 mm were sandblasted with silica grit using SBC 350 vertical sandblasting machine and wiped clean with acetone to increase the laser absorption and reduce laser reflection during deposition. Table I shows the chemical composition of the HEAs according to the supplier with Aluminum (Al), Cobalt (Co), Chromium (Cr), Iron (Fe), Nickel (Ni), Copper (Cu) and Titanium (Ti) and reduce laser reflection during deposition. Table I shows the chemical composition of the HEAs according to the supplier with Aluminum (Al), Cobalt (Co), Chromium (Cr), Iron (Fe), Nickel (Ni), Copper (Cu) and Titanium (Ti) powder having (99.9%) purity with an average particle size of 45 to 106 µm mixed to form AlCoCrFeNiCu (Cu-based) and AlCoCrFeNiTi (Ti-based) HEAs and supplied by F.J Brodmann & CO., L.L.C, USA. The as-received powders were used to fabricate HEA clads using a 3 kW Rofin Sinar dY044 continuous-wave laser-deposition system fitted with a KUKA robotic arm on an A301 steel baseplate preheated in an oven at 400 °C, thus, producing defect free clads. The as-built clads were cut into sections and the subsections were ground and polishing.

B. Microstructural analysis

The laser deposited samples were cut into sections using a Struers Discotom-2 (30800) cutting blade machine. The microstructural characterization of the sectioned HEAs samples was achieved using a X-ray diffractometer, Jeol-JSM-7600F Field Emission Scanning Electron Microscope fitted with an Energy Dispersive Spectroscrometer.

C. Potentiodynamic polarization analysis

Potentiodynamic polarization tests were executed in a three-electrode cell consisting of a saturated silver/silver chloride electrode (Ag/AgCl) (3 M KCl) as the reference electrode, the HEAs samples as the working electrode and a graphite rod counter electrode. The samples were cleaned to remove impurities in ethanol before they were immerged in 1 mol/L NaOH solution. An Autolab Potentiostat (PGSTAT302) was used in carrying out the electrochemical measurements with Nova 1.0 software. The corrosion parameters; corrosion density (Icorr), corrosion rate (Cr), corrosion potential (Ecorr) and polarization resistance (Rp) were calculated with a Tafel extrapolation technique with a potential range between -1.5 and 1.5 V, OCP for 3600 secs and a scan rate of 0.001 mV s⁻¹. The procedure was repeated twice per process parameter for accuracy.

D. Response surface methodology

After using the sets of experiments to retrieve the output response; the corrosion rate (Cr), a central composite design was used to optimize and examine the influence of the laser processing parameters such as the scan speed and the laser power on the corresponding output response with a second-order polynomial equation shown below.

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i A_i + \sum_{i=1}^{k} \beta_{ij} A_i A_j + \sum_{i=1}^{k} \beta_{ij} A_i A_j + \varepsilon \]  

Where \( Y \) is the response, \( A_i \) and \( B_{ij} \) are variables, \( k \) is the number of parameters, \( \varepsilon \) is the error, while \( \beta_0, \beta_i, \beta_{ij} \) and \( B_{ij} \) are interaction coefficients of the quadratic, second-order and linear terms. The data were fitted into the model and the model was validated and used to construct three-dimensional surface plots and contour plots to show the relationship between the dependent variables and the independent variables. Statistical analysis and numerical optimization were done using STAT-EASE Inc. Design-Expert Software 11, version 11.1.2.0. According to the central composite design (CCD), different runs were carried out and the average of the different runs is summarized in Table II.
III. RESULTS AND DISCUSSIONS

A. Surface Morphology

Fig. 1 (a) and (b) show the XRD patterns of the laser-deposited AlCoCrFeNiCu and AlCoCrFeNiTi HEAs, which reveals the alloys are composed of FCC and BCC phases. According to these observations influenced by the elemental and chemical compositions, the volume fraction of the BCC phase was more than the FCC phase which could be attributed to the laser-deposition process [17]. While Fig. 2 (a) and (b) shows the SEM micrograph and the five samples of the Cu-based HEA and the four samples of the Ti-based HEA each showed dendritic microstructures.

![XRD graph of laser deposited (a) Cu-based and (b) Ti-based HEA at 1600 W and 10mm/s](image)

![SEM micrograph of laser deposited microstructures (a) Cu-based and (b) Ti-based HEA at 1600 W and 10mm/s](image)

B. Potentiodynamic polarization analysis

Polarization in electrochemistry is the potential shift away from the open circuit potential of a corroding system [18]. The tests in this study started at the cathodic potential to the corrosion potential, investigating the corrosion characteristics of HEAs in sodium hydroxide solution. Fig. 2 and 3 show the potentiodynamic polarization curves for the laser-deposited Ti-based and Cu-based HEAs in 1 mol/L NaOH solution respectively. Table III shows the linear fit kinetic parameters extracted from the corrosion process. Electrochemistry principles state that an increased corrosion potential, with a reduced current density, gives better corrosion resistance [19]. Nonetheless, the higher the polarization resistance, the smaller the corrosion current density; and the better the corrosion resistance [20] therefore, in this study, it was observed for the Cu based HEA that as the corrosion current density reduces, the polarization resistance increased and as the corrosion current density increases, the corrosion potential decreases with an increase in laser power from 1200 W to 1600 W. Therefore, it can be deduced that the corrosion resistance increased with an increase in laser power. The lowest corrosion density and corrosion potential were recorded at the lowest scan speed; however, as the scan speed increases, the corrosion current density and potential increased with an inverse observed with the polarization resistance. A low scan speed reduces convection, which evens out the alloy’s microstructure and results in fine microstructure that increases the corrosion resistance [21]. Furthermore, the corrosion resistance of the alloys can also be attributed to corrosion-resistant elements Cr, Co and Ni, which enhances the formation of passive films in alloy composition resulting in the resistance of the alloys to corrosion. Nonetheless, judging from the corrosion rates, the corrosion resistance of the alloys for Cu-based HEA can be ranked as B > C > E > A > D. Compared with the Ti-based HEA in 1 mol/L NaOH solution, the Cu-based HEA had much lower corrosion rates under the same conditions of the laser power, therefore, it can be deduced that the Cu-based HEA has better corrosion resistance in 1 mol/L NaOH solutions than the Ti-based HEA. On the other hand, the Ti-based HEA showed better polarization resistance than the Cu-based HEA attributed to the compositional difference attributed to the Ti and Al content having a large atomic radius which results in lattice distortion that helps improve the polarization resistance [22]. Sample G of the Ti-based HEA showed the lowest corrosion rates and highest polarization resistance and judging from the results, the polarization resistance can be ranked as G > I > F > H.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rp (Ωcm²)</th>
<th>Ecorr (V)</th>
<th>Icorr (A/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-Based</td>
<td>A 0.00305</td>
<td>-0.5312</td>
<td>2.243E-05</td>
</tr>
<tr>
<td></td>
<td>B 0.00221</td>
<td>-0.6211</td>
<td>3.705E-05</td>
</tr>
<tr>
<td></td>
<td>C 0.00200</td>
<td>-0.7413</td>
<td>4.521E-05</td>
</tr>
<tr>
<td></td>
<td>D 0.00201</td>
<td>-0.9112</td>
<td>4.953E-05</td>
</tr>
<tr>
<td></td>
<td>E 0.00137</td>
<td>-0.9201</td>
<td>5.26E-05</td>
</tr>
</tbody>
</table>

| Ti-Based | F 0.00257 | -0.6192 | 0.0873 |
|          | G 0.00650 | -0.7004 | 0.00995 |
|          | H 0.00221 | -0.4121 | 0.0838 |
|          | I 0.00609 | -0.5144 | 0.00802 |

![Fig. 5 shows the surface morphology after corrosion experiments in a sodium hydroxide solution at room temperature. The surface appearance roughened losing its original smoothness with Sample A of the Cu-based HEA showing pitting at 1200 W signifying that the laser parameter played an important role as the sample suffered damage in NaOH solution at a low laser power. Qian et al. [23] reported that pitting corrosion which occurs at a low laser power may be due to microsegregation. According to Choudhuri et al. [24], micro segregation occurs when the HEA begins solidification with an FCC phase but due to alloying elements like Al, ends up as a BCC crystal structure during...](image)
solidification; this was also observed by Zollinger and Fleury [25].

![Fig.3. Tafel polarization graphs of Ti-based HEA in 1 mol/L NaOH solution at room temperature](image)

![Fig.4. Tafel polarization graphs of Cu-based HEA in 1 mol/L NaOH solution at room temperature](image)

![Fig.5. SEM graphs of the surface morphology after Corrosion measurements in 1 mol/L NaOH Solution (a) – (c) are Cu-based HEAs and (f) – (i) are Ti-based HEAs](image)

100 μm

**C. Statistical modelling**

In this study, two factors were used to optimize and evaluate the process parameters on the response such as the corrosion rate of laser-deposited HEAs in 1 mol/L NaOH solution. According to the literature, for the central composite design in the design expert software, three to five runs is recommended to achieve a stable variance of the predicted response [26]. The final data is summarized in Table II. The CCD data were analyzed using regression linear and quadratic models with the analysis of variance results listed below in Table IV.

**D. Corrosion rate**

The ANOVA analysis for the Cu-based and Ti-based HEA for the corrosion rate process variable is shown in Table IV. The model and the model terms are significant for the response. This is attributed to the lack-of-fit (p-values) which are less than 0.05, according to Khajeh et al. [27].

Equation 2 and 3 shows the actual factors which were used to make predictions about the output response corrosion rate for each factor.

Corrosion rate = +0.002312 + 1.24322E − 06 ∗ Laser Power − 0.000187 ∗ Scan Speed (2)

Corrosion rate = −0.005492 + 5.52500E − 06 ∗ Laser Power − 0.000016 ∗ Scan Speed (3)

**TABLE IV. REGRESSION ANALYSIS OF THE RESPONSE PARAMETER (CORROSION RATE) FOR THE CU-BASED AND TI-BASED HEA**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>d</th>
<th>Mean Square</th>
<th>F-value</th>
<th>p-value</th>
<th>Significant Or Not</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-based</td>
<td>Model</td>
<td>5.100E-07</td>
<td>2</td>
<td>2.550E-07</td>
<td>82.35</td>
<td>0.0120</td>
</tr>
<tr>
<td>A-Laser Power</td>
<td>2.280E-07</td>
<td>1</td>
<td>2.280E-07</td>
<td>73.62</td>
<td>0.0133</td>
<td>significant</td>
</tr>
<tr>
<td>B-Scan Speed</td>
<td>4.139E-07</td>
<td>1</td>
<td>4.139E-07</td>
<td>134.6</td>
<td>0.0074</td>
<td>significant</td>
</tr>
<tr>
<td>Residual</td>
<td>6.193E-09</td>
<td>2</td>
<td>3.097E-09</td>
<td>13.8</td>
<td>0.0489</td>
<td>significant</td>
</tr>
<tr>
<td>Total</td>
<td>5.162E-07</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Ti-based | Model | 1.225E-06 | 2 | 6.126E-07 | 2450 | 0.0045 | significant |
| A-Laser Power | 1.221E-06 | 1 | 1.221E-06 | 4884 | 0.0029 | significant |
| B-Scan Speed | 4.225E-09 | 1 | 4.225E-09 | 169.0 | 0.0489 | significant |
| Residual | 2.500E-11 | 1 | 2.500E-11 | | | |
| Total | 1.225E-06 | 3 | | | | |

**E. Effect of Process Variables on the Corrosion Rate**

The significant relationship between the predicted and the experimental values of the output response corrosion rate for the Cu-based and Ti-based is shown in HEAs Fig. 6 (a) and (b). It was observed in both plots that the points were lined diagonally and according to Yetilmeszsy et al. [28], this indicates that the model is a good fit since this proves that
there is less difference between the experimental and predicted values [29]. The three-dimensional surface plots for the Cu-based and Ti-based HEAs used to study the interactive and individual influence of the process variables; scan speed and laser power, respectively is shown in Fig. 7 (a) and (b). The lowest corrosion rate was at 1200 W with 0.0015 mm/yr for the Cu-based HEA while the Ti-based HEA had its lowest rate at 1400 W with 0.00205 mm/yr and it was observed that the rates increased with an increase in laser power to 0.00242 for the Cu-based HEA and 0.00322 for the Ti-based HEA both at 1600 W. The numerical optimization graph used to find the optimal conditions of each factors are presented in Fig. 8. The results show the optimal parameters for improved corrosion rates are at laser power 1400 W and scan speed of 10 mm/s to give a corrosion rate of 0.00197 mm/yr for the Cu-based HEA and 0.002635 mm/yr for the Ti-based HEA is shown in Fig 8.

![Fig. 6: Parity Plots showing the Predicted and Experimental values for (a) Cu-based HEA, and (b) Ti-based HEA](image)

![Fig. 7: Showing the Surface Plots for (a) Cu-based HEA, and (b) Ti-based HEA](image)

![Fig. 8: Numerical Optimization for (a) Cu-based HEA, and (b) Ti-based HEA](image)

**IV. CONCLUSION**

The influence of the process variables; laser power and scan speed on the output response; corrosion rate of laser-deposited high entropy alloys in 1 mol/L NaOH solution was investigated using response methodology. The corrosion mechanism of both alloys was also examined at room temperature using potentiodynamic polarization, and the main results obtained are listed below:

- Both alloys showed FCC and BCC solid solution phases with dendritic structures. The corrosion resistance increased with an increase in laser power and reduction in scan speed. The Cu-based HEA showed better corrosion resistance, while the Ti-based HEA showed better polarization resistance.
- The p-values were all lower than 0.0500 showing that all the statistical model terms were significant for the output response; corrosion rate for both alloys. The Cu-based HEA had a model lack of fit value of 82.35 showing that the f-value is significant and there is only a 1.20% chance that the value occurred due to noise. While the Ti-based HEA had a model f-value of 24505.00 which indicates that the value only had a 0.45% occurrence due to noise.
- The Predicted R² values for both alloys were in reasonable correlation with the Adjusted R² value, with the difference less than 0.2 each. The signal-to-noise ratios for both alloys were greater than 4, which is very desirable in navigating the design space.
- Optimization occurred at 1400 W laser power and a scan speed of 10 mm/s to give a corrosion rate of 0.00197 mm/yr for the Cu-based HEA and corrosion rate of 0.002635 mm/yr for the Ti-based HEA.

**REFERENCES**


[28] Yetilmezsoy, K., S. Demirel, and R.J. Vanderbei, Response surface modeling of Pb (II) removal from aqueous solution by
Fractography of Polypropylene Laser Sintered Tensile Test Specimens

Fredrick M. Mwania  
Department of Mechanical and Mechatronics Engineering,  
Central University of Technology,  
Bloemfontein, South Africa.  
fredmulinge@gmail.com

Maina Maringa  
Department of Mechanical and Mechatronics Engineering,  
Central University of Technology,  
Bloemfontein, South Africa.  
mmaringa@cut.ac.za

Jakobus. G. van der Walt  
Department of Mechanical and Mechatronics Engineering,  
Central University of Technology,  
Bloemfontein, South Africa.  
jgvdwalt@cut.ac.za

Abstract - The failure edges of polymer laser sintered tensile specimens of two grades of commercial polypropylene powder (Laser PP CP 60 and Laser PP CP 75) were investigated in this study. The tensile test specimens printed using Laser PP CP 60 exhibited ductile fracture with fracture surfaces that were more jagged and fibrous, whereas those printed with Laser PP CP 75 were more brittle. The tensile specimens printed with Laser PP CP 75 powder, exhibited an increase of the ultimate strength up to the second re-use cycle, after which, the magnitude of the ultimate strength started to decrease with powder re-use cycles. This phenomenon can be attributed to the breakage of glass filler material in the Laser PP CP 75 powder, which might have led to a reduction in packing density of the samples.

Keywords - failure surfaces, ductile and brittle fracture, ultimate strength, and powder re-use cycle

1. INTRODUCTION

Fractography is the study of fracture surfaces to determine the origin of cracks, direction of crack propagation, failure mechanisms, and material defects [1]. The deformation and fracture behaviour of polymers is complex and varies with the composition of material, microstructure, stress conditions (magnitude, time, and temperature), and geometry of the component. In this study, the failure edges of parts printed using two grades of semi-crystalline polymers of commercial polypropylene powder, Laser PP CP 60 and Laser PP CP 75 from Diamond Plastics GmbH, were investigated. Such materials consist of both amorphous and crystalline regions, as illustrated in Figure 1 [2].

![Semi-crystalline polymer showing highly ordered crystalline and amorphous regions](image)

The deformation of semi-crystalline polymers can be attributed to inter- and intra-lamellar shear of lamellae. Figure 2 shows the difference between intra-laminar and inter-laminar. Inter-laminar failure occurs along the layers (shown by blue lines), whereas intra-lamina failure happens within the layers [3].
At the yield point, two lamellar deformation mechanisms occur; fine chain slip in between the lamellae and coarse slip within lamellae (Figure 3a and 3b, respectively). The two deformation mechanisms result in fragmentation of the lamellae, which then transforms into a fibrillar phase, with appearance of voids in the amorphous layers [2].

Polyamide 12 (PA 12) is suitable for rapid prototyping and manufacturing purposes using polymer Laser Powder Bed Fusion (L-PBF) and was considered as the reference material in this study. However, the prices of feedstock materials are significantly high, necessitating introducing more polymers, such as polypropylene [4]. Considerable research has focused on assessing the processing parameters, as well as the mechanical properties of printed parts to determine the applicability of new polymers in L-PBF [5, 6, 7, 8]. However, limited research has focus on analysing the tensile fracture of printed parts [9]. In this regard, the present study investigated the failure edges of tensile test parts printed using two grades of commercial PP powder, Laser PP CP 60 and Laser PP CP 75, from Diamond Plastics GmbH. Preliminary research focused on analysing the type of fracture of the tensile parts printed using both Laser PP CP 60 and Laser PP CP 75. The mechanical properties of the Laser PP CP 60 and Laser PP CP 75 printed parts were also compared. Further research analysed the effects of powder aging on the mechanical properties of the printed components using Laser PP CP 75 material. The effects of ageing on the mechanical properties of the printed parts were explained using fractography of the failed test specimens.

2. LITERATURE REVIEW

Considerable research has focused on assessing the processing parameters, as well as the mechanical properties of printed parts to determine the applicability of new polymers in L-PBF [5, 6, 7, 8]. Different process parameters affect the density and mechanical characteristics of components developed using L-PBF. Some of these factors include energy density/laser power, scan spacing, laser beam speed, and part orientation [8]. Other aspects that influence mechanical properties of printed parts include the uniformity of feedstock, evolution of microstructure, refresh rate, layer thickness, and nature of the powder used (virgin or aged powder) [8]. Dizon et al. [8] stated that low energy density produces porous, weak, and anisotropic parts. Higher laser energy results in strong, solid, and isotropic components. In addition,
the authors stated that small defects in layers of printed parts affect the strength of the parts, and failure is most likely to occur at the weakest link, leading to a jagged fracture. Dizon et al. [8] also found that an increase in laser energy density raises molecular weight, which in turn increasing the percentage elongation at break for PA 12 material. The authors further observed that high laser energy density increases the degree of particle melt, thus leading to an increase of the ultimate tensile strength of polymeric materials [8]. There is limited research focusing on determining types of tensile fracture of laser-sintered polymers [9]. This paper attempts to address this shortcoming using fractography to determine the nature of tensile fracture of parts printed using Laser PP CP 60 and Laser PP CP 75. The latter material has glass filler particles, whereas the former one is a neat PP powder. The glass particles were added to improve flowability and spreading behaviour of the PP powder. Materials used in lasering sintering should possess suitable flowability to ensure homogeneity of layers, which promotes mechanical properties of the printed parts by reducing chances of formation of pores and voids [22].

Mechanical properties of materials are crucial because they determine their engineering applications. Polyamide 12 is commonly used in polymer L-PBF because of not only its good processability properties, but also its good mechanical characteristics, such as tensile strength, hardness, and abrasion resistance [9]. Table 1 shows the ultimate tensile strengths and Young’s moduli for different grades of neat PA 12 commercial powder. The mechanical properties of virgin Laser PP CP 60 and Laser PP CP 75 printed using the same processing parameters were compared in the present study.

### Table 1. Values of ultimate tensile strength for different grades of PA 12 commercial powder [10, 11, 12]

<table>
<thead>
<tr>
<th>Property</th>
<th>EOS PA 2200</th>
<th>Duraform PA</th>
<th>Duraform ProX PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (MPa)</td>
<td>2158</td>
<td>2171</td>
<td>1770</td>
</tr>
<tr>
<td>Ultimate tensile strength (MPa)</td>
<td>49</td>
<td>51.2</td>
<td>50</td>
</tr>
</tbody>
</table>

The impact of aging of powder on the mechanical properties of the printed parts has also attracted considerable attention from researchers, but the conclusions arising are inconsistent. Yao et al. [13] found that the tensile strength of parts produced using PA 12 increases and then decreases with the re-use cycles. Zarrighalim et al. [14] found no considerable change in tensile strength of PA 12 printed parts but increasing percentage of elongation at break with re-use cycles. Wudy et al. [15] found that aged PA 12 powder lowers the tensile strength of the printed components. Therefore, it is crucial to determine the mechanism of aging of polymers to definitively determine how powder re-use affects the mechanical properties of printed parts. The study aims to investigate the changes in mechanical properties of Laser PP CP 75 powder with reuse.

3. METHODOLOGY

In the first part of the analysis, samples were printed using Laser PP CP 60 material from Diamond Plastics GmbH. Five samples were printed here using different laser sintering (LS) processing parameters as summarized in Table 2. An EOSINT P 380 laser sintering AM machine was used for printing tensile test specimens for Laser PP CP 60 according to ASTM D638 Test Type 1 in the xy plane. The printed specimens were subjected to uniaxial tensile loading with a testing speed of 1.5 mm/min, as stipulated by ASTM D638 standard, on an MTS Criterion TM, Model 43 universal testing machine till fracture. Thereafter, the failure edges of the fractured specimens were examined using a JSM-6610LV Scanning Electron Microscope (SEM) from the Department of Geology, University of Free State, South Africa, with the accelerating voltage set at 30 kV. The samples were first coated with carbon to negate possible effects of supercharging, which affects the quality of the images obtained. Images were then obtained using the SEM software, from which the nature of failure edges was determined.

In the second part of the study, fracture samples of specimens printed using virgin and recycled Laser PP CP 75 were investigated using SEM. The samples were printed according to ISO 572-2 Test Type 2 in the xy plane. The parameters given by the manufacturer of the powder were utilized, except for the process and removal chamber temperatures, as illustrated in Table 3. Five cycles of printing and four cycles of re-use of the powder were performed. The printed parts were loaded on the same universal testing machine used in the first part of this work, at an elongation rate of 1 mm/min as stipulated in ISO 572-2 standard procedure. The same SEM used in the first part of this work was also employed to examine the fractured specimens here as well.
TABLE II. PROCESS PARAMETERS USED TO BUILD STANDARD TENSILE SPECIMENS USING LASER PP CP 60 POWDER (ASTM D 638)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Hatch distance (mm)</th>
<th>Scanning speed fill (mm/s)</th>
<th>Laser power fill (W)</th>
<th>Energy density (J/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.25</td>
<td>2000</td>
<td>23.3</td>
<td>0.0466</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>2500</td>
<td>25.5</td>
<td>0.0408</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>2500</td>
<td>30.2</td>
<td>0.0483</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>3500</td>
<td>31.5</td>
<td>0.0360</td>
</tr>
<tr>
<td>5</td>
<td>0.25</td>
<td>4500</td>
<td>34.7</td>
<td>0.0308</td>
</tr>
</tbody>
</table>

TABLE III. VALUES OF PROCESS PARAMETERS USED TO PRINT LASER PP CP 75 TENSILE TEST SPECIMENS (ISO 572-2 TEST TYPE 2)

<table>
<thead>
<tr>
<th>Temp. of the removal chamber (°C)</th>
<th>Temp. of the building bed (°C)</th>
<th>Layer thickness (mm)</th>
<th>Hatch distance (mm)</th>
<th>Scanning speed fill (mm/s)</th>
<th>Laser power fill (W)</th>
<th>Scanning speed contour/edges (mm/s)</th>
<th>Laser power contour/edges (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>128</td>
<td>0.15</td>
<td>0.25</td>
<td>4500</td>
<td>35.0</td>
<td>1500</td>
<td>20.0</td>
</tr>
</tbody>
</table>

I. RESULTS AND ANALYSIS

A. Analysing the Tensile Fracture surfaces of Parts Printed Using Laser PP CP 60 and Laser PP CP 75

Figures 4 – 8 show the SEM images of specimens 1–5 that were printed using Laser PP CP 60 material for different parameter

![SEM image of the virgin powder](image)

Fibrils overlapping lines of crack propagation

Crack propagation along the direction of stress

Fig.4. SEM image for Sample 1 (Laser PP CP 60)
Jagged, fibrous failure surface.

Un-fused polymeric powder particles

Fibrils

Fig. 5. SEM image for Sample 2 (Laser PP CP 60)

Fig. 6. SEM image for Sample 3 (Laser PP CP 60)
Jagged, fibrous failure surface.

Delamination along the direction of loading.

Unfused powder particles

Cracks

Fig. 7. SEM image for Sample 4 (Laser PP CP 60)

Jagged, fibrous failure surface

Completely delaminated layers

Delamination along the direction of loading.

Fig. 8. SEM image for Sample 5 (Laser PP CP 60)
Brittle fracture occurs on planes normal to the direction of maximum principle tensile stress, where the local stresses exceed the strength of the material. The morphology of fracture is subject to the conditions of stress (strain rate, temperature, and magnitude) and nature of the material [16]. The difference between ductile and brittle materials is determined based on the macroscopic appearance of the fracture surface. Ductile failure surfaces come with significant distortion, appear fibrous and are inclined to the direction of application of load, as they occur in the planes of maximum shear stress [17]. Brittle fractures in the other hand appear smooth and shiny [17]. The morphology of the fracture surfaces of Laser PP CP 60 polypropylene specimens tested here is jagged and fibrous as illustrated in Figures 4–8. This is consistent with the observations of Becker & Emeritus [16]. The authors also stated that acrylonitrile-butadiene-styrene (ABS), polyethylene (PE), polyamide (PA), polybutylene, polycarbonate (PC), polyethylene terephthalate (PET), high-impact polystyrene, and polyvinyl chloride (PVC), exhibit similar tensile, ductile morphology of failure surfaces [16]. Fibrous failure surfaces denote ductile mode of failure [21]. The failure fracture of Laser PP CP 75 specimens was less fibrous and less jagged, as illustrated in Figure 9. The lower ductility of Laser PP CP 75 specimens than that of Laser PP CP 60 specimens can be attributed to the presence of glass filler material in the former unlike the latter, which has none. DeArmitt & Hancock [23] states that fillers, such as glass, mica, and talc increase yield strength of PP homopolymer at the expense of ductility.

Molecular scale microscopic inhomogeneities (free volume) exist within macromolecular structures of polymers [16]. Application of stress strengthens polymer chains and redistributes the free volume, which results in formation of microvoids [16]. Microvoids in polymers continue to grow under load resulting into their agglomeration and interpenetration causing either stress whitening, stress crazing, stress cracking, or fracture depending on the nature of the polymer [16]. A craze is a region consisting of microvoids and fibrils [16]. Crazing is associated with the long-chain polymers [16]. The phenomenon is commonly linked with amorphous polymers, but is also observed in semi-crystalline polymers, such as polypropylene [16]. Stress whitening leads to the emergence of cloudy and foggy appearances in transparent or translucent polymers under stress [16]. Figures 4–8 show the presence and fibrils, elongated fibrillar features, as well as delamination for Laser PP CP 60. Delamination occurs when subsequent layers get improperly sintered to the previous one [18, 19]. Failure of LS polypropylene occurs through stress cracking, as confirmed by Salazar et. al [20], which is the case for the two types of polypropylene materials tested here.

The presence of fibrils in the specimens loaded till failure might be attributed to the fact that some regions were weaker than others. The interlayer boundaries are speculated to be weaker than the rest of the component. Therefore, more extensive crack propagation in these regions (interlayer boundaries), as is evident in Figures 4, 7 and 8. It can be concluded that LS printed polypropylene parts experience both intra-laminar and inter-laminar failure mode because fragmentation of the lamellae, resulting into a fibrous fracture with an appearance of voids in the amorphous layers. Besides, the phenomenon illustrates inhomogeneity of the printed parts, probably due to improper coalescence of the particles of power attributed to inadequate laser power energy, possibly due to the process parameters used. Furthomre, the cause of separation of the layers in Laser PP CP 60 is thought to have been due to the presence of voids resulting from poor sintering of adjacent layers. Besides, Debris was observed on the fracture surfaces of all the specimens printed using Laser PP CP 60. The presence of the debris might have been due to un-fused polymeric powder particles (such as the
ones shown in Figures 4 and 6). Unfused individual particles were observed in all other micrographs. This implies that the laser energy density used for printing Laser PP CP 60 specimens was not adequate and underscores the need to carry out further work optimization of process parameters [22]. Process optimization for Laser PP CP 60 was conducted in [27], where it was concluded that the material properties might have hindered determination of suitable parameters. Hence, improper coalescence of the particles of power, separation of the layers, and presence of debris might be due to the material properties and not because of the EOS P380 machine.

### B. Comparing the Mechanical Properties of Parts Printed Using Laser PP CP 75 and Laser PP CP 60 Materials

The mechanical properties of parts printed using Laser PP CP 75 and Laser PP CP 60 materials determined here differ, probably due to the filler material in Laser PP CP 75. The percentage difference of the mechanical properties between the two materials was calculated using Equation 1. Table 4 and Figure 10 summarize the differences in the mechanical properties of parts printed using virgin Laser PP CP 75 and Laser PP CP 60 materials, at the same processing parameters. Both materials have small values of ultimate tensile strengths (21.2 MPa for Laser PP CP 60 and 6.7 MPa for Laser PP CP 75), indicating that they are unsuitable for heavy engineering applications. The values are much lower than those for EOS PA 2200 and Duraform PA, 49 MPa and 50 MPa, respectively [10, 12]. The specimens built with Laser PP CP 75 powder have almost double the magnitude of Young’s modulus than the ones built with Laser PP CP 60 powder. Hence, Laser PP CP 75 is weaker, less ductile, and stiffer than Laser PP CP 60. This is probably due to the presence of glass filler material in the former.

\[
\text{% difference} = 100 \times \frac{|A-B|}{(A+B)/2} \quad \text{(Eqn.1)}
\]

where,

- A = properties for material A (Laser PP CP 75)
- B = properties for material B (Laser PP CP 60)

#### Table IV. Differences in the Mechanical Properties of Parts Printed Using Virgin Laser PP CP 75 and Laser PP CP 60 Materials at the Same Processing Parameters

<table>
<thead>
<tr>
<th>#</th>
<th>Powder batch</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Young’s modulus (MPa)</th>
<th>Percentage of elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laser PP CP 75 (virgin powder)</td>
<td>6.7</td>
<td>1141.3</td>
<td>61.9</td>
</tr>
<tr>
<td>2</td>
<td>Laser PP CP 60 (virgin powder)</td>
<td>21.2</td>
<td>668.4</td>
<td>507.4</td>
</tr>
<tr>
<td>3</td>
<td>Percentage difference</td>
<td>103.9%</td>
<td>52.3%</td>
<td>156.5%</td>
</tr>
</tbody>
</table>

![Fig. 10. Differences in the mechanical properties of parts printed using virgin Laser PP CP 75 and Laser PP CP 60 materials at the same processing parameters](image-url)
Figures 11 and 12 represent the load vs. primary extension curves for Laser PP CP 60 and Laser PP CP 75 materials, respectively. The yield points and peak load are visible for the two materials, as represented by points 1 and 2, respectively. The two materials have little deformation after peak load, illustrating a higher rate of fracture [25]. The extension between yield point and peak load for Laser PP CP 75 is shorter than Laser PP CP 60, which indicates that the latter is significantly more ductile than the former. It is also evident in Figure 11 that the specimens printed using Laser PP CP 60 exhibit a rapid drop in load after the yield point followed by a gradual increase until the point of fracture. This is typical behavior exhibited by steel which depicts an upper and lower yield stress followed by strain hardening up to the point of maximum stress [26]. However, it is noted that the parts built with Laser PP CP 75 appear to maintain a constant value of stress beyond the yield point up to the point of fracture. It is not clear about the slight difference in behavior, which forms the need for future work. It can be stated that Laser PP CP 75 has higher toughness than Laser PP CP 60 due to the much longer elongation to failure and higher load exhibited. It can be noted that the addition of glass filler material reduces the ductility of the material, and therefore, there is no possible benefits of any crack bridging that comes with the addition of glass beads.
C. The Effects of Aging of Powder on the Mechanical Properties of Components Printed Using Laser PP CP 75

The average values of tensile strength, Young’s modulus, and percentage elongation at break for samples tested after each re-use cycle are outlined in Table 5, and trends of these mechanical characteristics illustrated in Figures 13, 14, and 15.

<table>
<thead>
<tr>
<th>#</th>
<th>Powder batch</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Young’s modulus (MPa)</th>
<th>Percentage of elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Virgin powder (1st print cycle)</td>
<td>6.7</td>
<td>1141.3</td>
<td>61.9</td>
</tr>
<tr>
<td>2</td>
<td>Aged powder (1st re-use cycle)</td>
<td>7.1</td>
<td>929.6</td>
<td>55.6</td>
</tr>
<tr>
<td>3</td>
<td>Aged powder (2nd re-use cycle)</td>
<td>7.4</td>
<td>807.7</td>
<td>29.7</td>
</tr>
<tr>
<td>4</td>
<td>Aged powder (3rd re-use cycle)</td>
<td>6.7</td>
<td>934.5</td>
<td>45.4</td>
</tr>
<tr>
<td>5</td>
<td>Aged powder (4th re-use cycle)</td>
<td>6.6</td>
<td>1080.1</td>
<td>46.5</td>
</tr>
</tbody>
</table>

Fig. 13. Ultimate tensile strengths of parts printed using Laser PP CP 75

TABLE V. SUMMARY OF THE MECHANICAL PROPERTIES OF PARTS PRINTED USING AGED LASER PP CP 75 POWDER
The tensile strength of the printed parts is seen in Figure 13 to have increased from an initial value of 6.7 MPa to 7.4 MPa with the re-use of powder up to the 2\textsuperscript{nd} 100\% re-use cycle. The strength then decreased to 6.6 MPa in the 4\textsuperscript{th} 100\% re-use cycle. The Young’s modulus of the printed parts is seen in Figure 14 to have decreased from an initial value of 1141.3 MPa to 807.6 MPa after the 2\textsuperscript{nd} 100\% re-use cycle, and then increased to 1080.1 MPa in the 4\textsuperscript{th} 100\% re-use cycle. The percentage elongation of the printed parts is seen in Figure 15 to have decreased from an initial value of 61.9\% to 29.7\% after the 2\textsuperscript{nd} 100\% re-use cycle, and increased to 46.5\% in the 4\textsuperscript{th} 100\% re-use cycle.

The fracture surfaces of the aged specimens were investigated using a SEM with the results illustrated in Figures 16, 17, and 18.
Fig. 16. Fracture edge of a part printed using virgin Laser PP CP 75

Fig. 17. Fracture edge of a part printed using aged Laser PP CP 75 (2nd 100% re-use cycle)
The SEM images of the fractured edge of the parts printed using virgin Laser PP CP 75 show no glass fragmentations in Figure 16, but significant glass particles appear displaced from the matrix. Figure 17 shows a micrograph of a fractured part after the second re-use cycle. It can be seen in this figure that the more glass particles were embedded into the matrix, thus reducing the number of voids in the polymer, and probably increasing packing density of the printed parts compared to the component printed using virgin Laser PP CP 75 (Figure 16). This is likely to be the reason for the increase of ultimate strength from 6.7 MPa to 7.4 MPa between the initial print and 2nd 100% recycle. Figure 18 shows the fractured surface of a part printed after the fourth re-use cycle. The number of imprints in the matrix of sections initially occupied by glass beads appear more in the 4th re-use cycle due to the fragmentation of glass beads and may explain the reason for the observed drop of the ultimate strength down to 6.6 MPa, with increasing number of re-use cycles.

Yao et al. [13] conducted an experiment to determine mechanism of the impact of aging of PA 12 on the mechanical properties of printed parts. The authors state that during the L-PBF process, the polymeric material is exposed to high temperatures leading to polymerization and crosslinking resulting in larger molecules and complex chains. This gives rise to inter-molecular forces, which increase the tensile strength of the printed components. However, more pores are formed with increasing re-use cycles of the material, leading to decrement of density of the printed parts, which eventually lowers their tensile strength. Pores are found between layers because of stratified nature of builds along the building direction [13]. Cracks can therefore easily propagate parallel to the layers. In addition, many defects can be observed with increasing recycling times, such as surface inhomogeneity, pores, torn dimples, and un-molten powders, which become prominent with increasing re-use cycles [13]. Reduction in ultimate strength of parts printed using Laser PP CP 75 powder seem to decrease after the 2nd cycle which is thought to be due to fragmentation of the glass filler material. Yao et al. [13] also noted that the re-use of PA 12 powder leads to an increase of the viscosity of polymeric materials, which causes an increase in the distribution of pores due to reduced coalescence of particles. Some polymers are also decomposed by heat releasing gases resulting in development of voids [13]. Aged powders have higher melting points, which translates to more and more particles that are not fully melted under the same laser density, and therefore, the formation of pores [13].
4. CONCLUSION

Tensile fracture analysis of parts printed using virgin Laser PP CP 60 exhibited jagged and fibrillar failure features that were absent in Laser PP CP 75 specimens whose failure was more brittle. Laser PP CP 75 specimens were observed to have a higher value of Young’s modulus and a lower value of percentage elongation at break than Laser PP CP 60, which is proof that the latter material is more ductile. The ultimate strengths for the two materials were found to be relatively low, indicating that the materials are not suitable for heavy engineering applications.

From the second part of testing carried out here, it was concluded that the ultimate tensile strength of Laser PP CP 75 increases up to the second re-use cycle because glass particles embed into the matrix, and probably result in an increment of the packing density of the printed parts. However, the magnitude of the ultimate strength starts to decrease with re-use cycles beyond here, which can be attributed to fragmentation of the glass filler material during recycling of the powders probably leading to a reduction of packing density and possible development of pores.

5. RECOMMENDATIONS

The following recommendations were made from the two experiments:

1. Suitable laser energy density for Laser PP CP 60 should be determined by varying either laser speed or power to reduce the number of unfused particles observed sintering at the processing parameters used presently.

2. Suitable filler agents should be used to replace the glass beads used in Laser PP CP 75 as they appear to fragment with re-use cycles, and thus reduce the tensile strength of the printed parts.

3. Appropriate glass filler volume fraction can also be determined to ensure the attainment of a suitable strength of L-PBF polypropylene without compromising its stiffness and ductility.

ACKNOWLEDGMENT

The funding support of the South African Department of Science and Innovation through the Collaborative Program in Additive Manufacturing, Contract No.: CSIR-NLC-CPAM-18-MOA-CUT-01 is acknowledged. Thanks also to the Centre for Rapid Prototyping and Manufacturing (CRPM) for technical support. Profound gratitude to the Department of Geology, University of Free State, South Africa, for their assistance with SEM experiments.

REFERENCES


Residual Stress, Porosity and Surface Roughness for Laser Powder Bed Fusion Manufactured Ti6Al4V at High Laser Powers

Nkutwane Washington Makoena  
National Laser Centre  
Council for Scientific and Industrial Research  
Pretoria, South Africa  
nmakoena@csir.co.za

Ina Yadroitseva  
Department of Mechanical and Mechatronic Engineering  
Central University of Technology  
Bloemfontein, South Africa  
iyadroitseva@cut.ac.za

Igor Yadroitsev  
Department of Mechanical and Mechatronic Engineering  
Central University of Technology  
Bloemfontein, South Africa  
iyadroitsev@cut.ac.za

Anton du Plessis  
Department of Physics  
University of Stellenbosch  
Western Cape, South Africa  
anton2@sun.ac.za

Lerato Tshabalala  
National Laser Centre  
Council for Scientific and Industrial Research  
Pretoria, South Africa  
ltsbabalala1@csir.co.za

Sisa Pityana  
National Laser Centre  
Council for Scientific and Industrial Research  
Pretoria, South Africa  
spityana@csir.co.za

Abstract—The use of high-powered lasers presents a unique opportunity to improve the LPBF productivity since a larger beam spot size and higher scanning speeds can be utilized to increase the process build rate. In this study, a custom-built LPBF system equipped with a 5kW fiber laser was used to investigate residual stresses, porosity, and top surface roughness using x-ray diffraction and computed micro-topography techniques. It was shown that it is possible to produce samples with low residual porosity and top surface roughness using high laser powers and build rates, and the effect of scanning speed and hatch spacing on residual stress, porosity, and surface roughness is presented and discussed. The results of this study have revealed the potential benefits of using high powered laser to increase the build rate, thus improving the LPBF productivity.

Keywords—Laser Powder Bed Fusion, Residual stress, Porosity, High power Selective Laser Melting, Titanium alloys, Surface roughness

I. INTRODUCTION

Laser Powder Bed Fusion (LPBF) is an emerging technology with a potential for high design freedom. As such, this technology has attracted many industries such as aerospace and medical since complex geometries are especially required [1]. Indeed, the unprecedented design flexibility, reduced material waste, and improved lead-time are the main benefits of additive manufacturing technologies like LPBF over conventional manufacturing routes. Despite its numerous advantages, several factors still hinder the widespread adoption of this technology as the end manufacturing technique. Some of these are random porosity, poor surface finish, high residual stresses, anisotropy of mechanical properties, etc. Aerospace parts are regularly subjected to high mechanical and thermal loads during their service life, and accordingly, certified parts are required to have high density, surface integrity, strength, and fatigue resistance [2].

In LPBF, the most influential variables are the process parameters, which include, among others, laser power, scan speed, hatch spacing, layer thickness, etc. Cumulatively with powder material properties, scanning, and building strategies, process parameters will consequently define a microstructure and part properties. The main research thrust has been to identify and tune the effect of process parameters on the end part structure and resulting properties. The achievable density after processing is the first and perhaps the most important concern in LPBF, hence achieving nearly full dense parts has been a focus of many earlier investigations [2-8]. Similarly, the build-up of residual stresses and the obtainable surface quality of LPBF parts are amongst other major issues of the process and have been the subject of many studies [9-14].

In recent years, machine manufacturers and researchers are focusing on expanding the capabilities of their machines by increasing the build rates and build volumes. For example, some equipment manufacturers, such as SLM Solutions and Concept laser, are employing multiple lasers to scan the build area to increase the build rate (e.g. SLM 800 and X line 2000R). This principle is called “Parallelisation” and the number of laser sources used can increase the theoretical build rate linearly [15]. Another method is to use high-powered lasers with a beam focal spot that has a larger diameter to instantly melt a larger area of the powder thus reducing the time required to scan each layer [16-18]. Thus, the focus of this study is to investigate the influence of high-powered laser on residual stress, porosity, and surface roughness of LPBF manufactured Ti6Al4V. This work will be the first to investigate these three properties in Ti6Al4V alloy manufactured at high laser powers; and contribute to the body of knowledge especially regarding process development and upscaling, in pursuit of increasing the LPBF productivity. The properties investigated are important in LPBF since they directly influence the structural integrity and mechanical properties of the part being manufactured.

II. MATERIALS AND METHODS

Gas atomized Ti6Al4V powder characterized with smooth spherical morphology was used in this study. The powder was supplied by TLS-GmbH, and the 10th, 50th, and 90th
percentiles of the equivalent diameters were 24 µm, 41 µm, and 57 µm, respectively. Nine cuboid samples (12 mm x 12 mm) were manufactured using a custom-built LPBF system equipped with a 5kW IPG YLS 5000 Ytterbium fiber laser operating at 1076 nm wavelength. The samples were processed at different laser powers and build rates as shown in Table 1. At 2000W, the scan speed was kept fixed and only varied the hatch spacing to change the build rate, while at 750W and 650W, the build rate was changed by varying the scan speed. The beam spot size, scan speed, and hatch spacing are not disclosed as this is considered proprietary information linked to the Aeroswift, see Ref. [19].

Processing of the samples took place under Argon atmosphere, with the layer thickness kept constant at 50 µm. All the samples were manufactured directly onto the base plate without support structures. Samples were scanned by the laser beam using the parallel scanning strategy (back-and-forth) with the y-direction aligned to the track length, see Fig 1.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Parameters</th>
<th>Power (W)</th>
<th>Build rate (mm^3/s)</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>2000</td>
<td>18.0</td>
<td>Hatch spacing</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2000</td>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2000</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>750</td>
<td>6.8</td>
<td>Scan speed</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>750</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>750</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>600</td>
<td>5.4</td>
<td>Scan speed</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>600</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>600</td>
<td>3.6</td>
<td></td>
</tr>
</tbody>
</table>

Residual stress was characterized by the x-ray diffraction method before removing the samples from the baseplate. Lattice deformations of the Ti-α (213) were determined using CuKα (1.541838 Å) radiation source 25 kV, 4 mA (12 kV, 4 mA). The residual stresses were calculated considering plane stress conditions using X-ray elastic constants of $\frac{1}{2}S2=11.89\times10^{-6}$ MPa^{-1} and $S1=-2.83\times10^{-6}$ MPa^{-1}. This method is described in detail by [20]. Porosity and surface roughness were measured using x-ray tomography following methods described by [8, 21].

![Fig. 1. Images of the samples investigated.](image)

### III. RESULTS AND DISCUSSION

Residual stress during LPBF is mainly due to thermal stress, and therefore, the stress at one point is related to its corresponding thermal history, which is also affected by the processing parameters. Fig. 2 shows the stresses measured in the different directions (i.e. 0°, 45°, 90°) to the scanning direction and the principal stresses (S1& S2). The stresses on the top surface are tensile because the shrinkage of top layers is restricted by the underlying layers as described by the temperature gradient mechanism [22]. Normally, residual stress in the scan direction is known to be the largest because the tracks mainly shrink along with the scanning the direction, and this is in good agreement with our results shown in Figure 2a, where the maximum stress was measured along the scan direction (i.e. 90°).

The effect of hatch spacing on residual stress is revealed by samples 1-3, which were manufactured at 2000 W at a fixed scanning speed. It can be seen that decreasing the hatch spacing lead to a reduction in residual stress, and this is believed to be mainly driven by the increased re-scanning of the tracks and heat accumulation, which in turn lowers the thermal gradient and consequently reduce the residual stress. It was also shown in other studies that re-melting results in increasing the peak temperature in the melt-pool and larger re-melted melt-pool size, thus, a larger re-melted melt-pool results in a large volume of material to cool and reduces the cooling rate [11, 22, 23].

![Fig. 2. Normal stresses (a) and principal stresses (b) were measured at the top surface of samples.](image)

Considering samples processed at 750 W (i.e. 4-6) and 600 W (i.e. 7-9), the maximum residual stress can be seen to be decreasing slightly with decreasing scanning, except for the case of samples 4 and 7 which had somewhat lower residual stress than expected. In other work [24, 25], the maximum residual stress was seen to be increasing with decreasing scanning speed, and this was mainly because at higher scanning speeds the residual stress was relaxed by the formation of porosity [1]. This is probably the reason why samples 4 and 7 had lower residual stress, and this can also be seen in Fig. 3, where samples 4 and 7 had higher porosity compared to the other samples processed at the same laser power. Elsewhere [26-28], it was found that increasing the
cross-sectional area of the melt pool by decreasing scanning speed leads to a reduction in cooling rate, more uniform shrinkage of the metal in and around the melt pool, and thus lower residual stress; and this is consistent with our results. Fig. 4 shows porosity distribution in the samples.

Overall, residual stress is seen to be increasing with increasing the build rate as shown in Fig. 5, where outliers are shown with a red border line representing the samples that had a higher percentage porosity. This can be interpreted as the effect of scanning time. A higher build rate will reduce the time the laser spent scanning the layer and increase the thermal gradient, thus increasing the residual stress.

Fig. 4 shows porosity distribution in the samples.

Overall, residual stress is seen to be increasing with increasing the build rate as shown in Fig. 5, where outliers are shown with a red border line representing the samples that had a higher percentage porosity. This can be interpreted as the effect of scanning time. A higher build rate will reduce the time the laser spent scanning the layer and increase the thermal gradient, thus increasing the residual stress.

The arithmetic mean areal roughness (Sa) of the top surface is plotted in Fig. 5a along with a CT image of the top surface. It can be seen that the hatch spacing had a minimal effect, within the range applied, on the surface roughness of the samples processed at 2000 W (Fig. 5b).

In LPBF, the surface roughness is affected by wetting and the time of solidification of adjacent tracks, which in turn are strongly influenced by the amount of energy input [11, 28-32]. High energy input, obtained by either increasing the laser power or decreasing the scan speed or a combination of both, will melt the powder and form a large enough melt pool that would ensure melt flow and wetting of adjacent tracks. Moreover, a high energy input will produce a melt pool having a relatively long solidification time to wet a large surrounding area. Another factor affecting the surface roughness is the satellite powders sintering to the top surface, which is also a contributing factor to the roughness measurements. The surface topography of sample 5 and sample 7 was relatively uneven, and this is probably caused by a combination of the unstable melt pool and inhomogeneous layer deposition. Sample 7 has the highest porosity in the image near the top surface, and also the highest roughness at the top surface.

IV. CONCLUSION

The use of high-powered lasers equipped with a larger beam focal spot size is one of the promising methods for improving the LPBF productivity since larger volumes of metal powder can be melted in a shorter time. In this study, a customized laser system equipped with a 5 kW fiber laser was used to investigate the development of residual stress, porosity, and surface roughness on Ti6Al4V samples. These
are among the most important response variables in LPBF since they affect the structural integrity and performance of the part. A thorough investigation was carried out using XRD and micro-CT to quantify residual stress, porosity, and top surface roughness. A trend in decreasing residual stress with decreasing hatch spacing and scanning speed was observed, and this is mainly due to heat accumulation at smaller hatch spacing, and increased interaction time at lower scanning speeds. Both of these scenarios lead to a reduction in thermal gradients and consequently reduces the residual stress. It was also shown that it is possible to produce coupons with low residual porosity using high build rates, and this is positive for the improvement of LPBF productivity. The top surface roughness of the samples produced at a high build rate was also shown to be smoother compared to the other samples produced at lower build rates. However, the vertical surface was not characterized in this study and will be the focus of a future study. Nevertheless, this study is the first to reveal the potential benefits of using high powered laser to increase the build rate, while obtaining lower residual porosity, residual stress and top surface roughness, which is positive for upsizing of the LPBF process. This work will be of interest to machine manufacturers and researchers working towards the improvement of the LPBF productivity.

Acknowledgment

XRD measurements were done at the Department of Mechanical Engineering of Nelson Mandela University (RSA). Special thanks to Dr. Bernard Dreyer for carrying out the XRD measurements.

References


Investigation of Microstructure and Hardness Properties of in-situ TiB/Ti6Al4V ELI Composite Manufactured by Laser Metal Deposition

Paul Lekoadi
National Laser Centre
Manufacturing Cluster
Council for Scientific Industrial Research
Pretoria, South Africa
PLekoadi@csir.co.za

Monnamme Tlotleng
National Laser Centre
Manufacturing Cluster
Council for Scientific Industrial Research
Pretoria, South Africa
&
Department of Mechanical and Industrial Engineering technology
University of Johannesburg
Johannesburg, South Africa
Mtlotleng@csir.co.za & Daopase@gmail.com

Bathusile Masina
National Laser Centre
Manufacturing Cluster
Council for Scientific Industrial Research
Pretoria, South Africa
&
Department of Mechanical and Industrial Engineering technology
University of Johannesburg
Johannesburg, South Africa
BMasina@csir.co.za

Abstract—This study investigated the microstructural formation and hardness properties of TiB/Ti6Al4V ELI composites produced with in-situ laser metal deposition technique. The TiB/Ti6Al4V composite samples were produced with varying the volume flow rate of TiB2 in the range 1.0-2.0 rpm on a Ti6Al4V base plate pre-heated at 400°C. It was found that the in-situ reaction resulted in the formation of two types of whiskers, and size increase with increasing TiB2 volume. Furthermore, the hardness increased linearly from 570 ± 18 HV to 736 ± 30 HV with increasing TiB2 volume.

Keywords—Laser metal deposition, microstructure, hardness

I. INTRODUCTION

The manufacturing of titanium and its alloys with additive manufacturing (AM) technology has attracted a great deal of attention in various industries such as aerospace and automotive [1,2]. AM is a three-dimensional (3D) printing technology that enables the production of parts in a layer-by-layer way guided by computer aided design (CAD) models [3,4]. The advantage and uniqueness of AM lies in its ability to produce complex geometries that are impossible to manufacture with conventional manufacturing methods, which provide opportunities in terms of productivity and competitiveness. There are various types of AM techniques for the fabrication of metallic components and are classified according to: (a) powder deposition method, (b) laser-powder interaction, and (c) metallurgical consolidation mechanism [5]. Laser metal deposition (LMD) is a type of AM technique that uses a laser beam as an energy source to form a melt pool on the surface of a metallic substrate into which the metal powder is injected by a gas stream and melted [6]. A schematic diagram of LMD process is shown in Figure 1.

LMD process involve radiation of a pre-placed substrate by heat from laser, forming a melt pool which catches and melt powder supplied by powder feeder (Figure 1). As the deposition head moves along a CAD defined trajectory, a first layer is formed on the substrate and a new position is set for the next deposition. Serving as a new substrate, the previously deposited layer is partially melted with the formation of new layer as depicted in Figure 1. The process is repeated layer-by-layer until a component is complete [7]. The advantages offered by LMD over other AM techniques include the ability to repair damaged parts, cladding of functional layers, lower heat input and smaller heat affected zone [8,9]. Moreover, LMD offers the advantage of processing various and multiple metallic materials such as steel, titanium and its alloys, nickel based super alloys and others [10,11].

Ti6Al4V is one of the most LMD processed titanium alloy due to its attractive features which include good strength-to-weight ratio, high corrosion resistance and biocompatibility [9,12]. In recent years, an extensive effort has been made to strengthen the mechanical properties of Ti6Al4V such as high temperature strength, ductility and corrosion resistance by alloying with various ceramic materials such as TiC, TiB, TiB2, SiC, WC and others to form titanium matrix composites (TMCs), with the aim of obtaining properties beyond those of LMD Ti6Al4V [13-16]. In-situ synthesized TMCs reinforced with these ceramics are considered as one of the promising
candidate materials in the aerospace, automotive, biomedical, electronic, and military industries [7,17,18]. Their success is attributed to their high specific strength, specific stiffness, low density, excellent wear resistance, outstanding chemical inertness, and high temperature performance [1,19,20]. Amongst these ceramics, TiB2 is considered one of most promising and effective due to its good chemical affinity with titanium and outstanding thermal stability [19,21]. Moreover, the similarity in density (4.5 g/cm³ and 4.52 g/cm³ for Ti and TiB, respectively) and thermal coefficient of expansion of TiB2 (8.00) and Ti (8.41) enhances the good bonding during LMD process [22].

There are several studies that were conducted on AM of TMCs in literature; Zhou et al. [22] reported on the microstructure and mechanical performance of in-situ synthesized TiC/Ti6Al4V composite that was manufactured using selective laser melting (SLM) technique. In their study, Ti6Al4V powder was initially pre-mixed with carbon nanotube (CNT) powder using electro-static self-assembly system before they were processed. The Ti6Al4V powder was used as the matrix, while the CNT volume varied in a range between 1.5 wt.% and 3 wt.% and TiB2 (8.41) was used as a reinforcing material. Specimens of dimension 4 x 4 x 1 mm³ were manufactured on a Ti substrate using a laser power of 20.6 W, scanning speed 10 mm/s, layer thickness 25 µm and hatch distance 100 µm. It was reported that in-situ reaction between Ti and C (Ti+ C→ TiC) promoted the formation of TiC whiskers with two kinds of morphologies. The morphologies of the TiC whiskers observed on the microstructure of the TiC/Ti6Al4V composite were identified as spherically shaped with diameter ~1-3 µm and needle-like shaped with TiB particles size in the range ~1-3 µm. Moreover, it was reported that the formed TiC whiskers underwent grain growth and coarsening with increasing in CNT volume.

In a different but related study, Verma et al. [23] reported the microstructure, wear performance and hardness of TiB/Ti6Al4V composite manufactured with SLM. Similarly, their study pre-mixed Ti6Al4V powder with boron (B) powder using planetary ball milling machine for a period of 2 hrs. The volume of the B powder was varied between 0.1-1.5 wt.%. Cylindrically shaped samples with dimension 10 x 10 x 50 mm³ were printed on a Ti6Al4V base plate using process parameters, laser power 400 W, scanning speed 7 m/s and beam diameter 100 µm. Their results showed the formation of TiB whiskers as a result of in-situ reaction between Ti and B (Ti+B→TiB). It was also reported that the effect of B addition was localised up to 0.2 wt.%, with the microstructure showing a mixture of martensitic α’ and normal α phases. Addition of B content in the range 0.5-1.5 wt.% completely refined the microstructure into equiaxed α-Ti. Moreover, the size and distribution of the TiB particles were reported to increase with increasing B volume. The hardness was reported to linearly increase with increasing B content from 370 HV to 480 HV, which also resulted in a significant improvement in wear resistance. Cai et al. [14] investigated microstructural evolution and tribological behaviour of in-situ synthesized TiB/Ti6Al4V prepared with SLM, using Ti6Al4V and TiB2 as their starting material powders. In their case, the volume of TiB2 was varied between 1.3-3 wt.%. Laser power, scanning speed and layer thickness of 240 W, 300 mm/s and 0.05 mm were used, respectively, to produce the test specimens. It was reported that the in-situ formed TiB reinforcements were in a form of needle-like shaped and were distributed within α-matrix. Furthermore, the microstructure of the composite was composed of parallel strips architecture with TiB rich in some regions and learn in other regions. The size of the TiB reinforcements was observed to become wider as the TiB2 content was increased. The authors reported that presence of the needle-like TiB particles enhanced the hardness from 4.38 to 6.00 GPa.

A study by Popoola et al. [24] investigated the properties of in-situ TiB/Ti6Al4V composite manufactured with LMD technique. During deposition, the Ti6Al4V powder was used as matrix, while the TiB2 content was varied from 5, 10, 15 and 20 wt.%, respectively. Specimens with dimension of 70 x 70 x 5 mm³ were manufactured on a Ti6Al4V substrate, using laser power of 750 W, scanning speed 10 mm/s and beam diameter 2 mm as process parameters. It was reported that only TiB whiskers were observed on the microstructure with the TiB/Ti6Al4V which formed according to the in-situ exothermic reaction between Ti and TiB2 (Ti+TiB2→TiB). The authors reported an increase in corrosion and wear resistance as TiB2 volume percentage was increased, and this was attributed to the formation of TiB whiskers. Moreover, the presence of TiB whiskers was confirmed to have played a significant role in increasing hardness values. In another study, Meng et al. [25] employed LMD process to manufacture a hybrid (TiC+TiB)/Ti6Al4V composite, using Ti6Al4V and B4C powders as the starting materials. Specimens with dimension 160 x 160 x 15 mm³ were produced using laser power 1500 W and scanning speed 10 m/s. Their microstructural analysis showed the presence of both TiC and TiB whisker in the Ti matrix. Furthermore, it was found that addition of B4C particles refined the grain size remarkably. The yield strength, tensile strength elastic modulus and elongation of the produced composite were significantly strengthened by the addition of the B4C particles.

Despite all work that has been conducted on AM of several ceramic to manufacture reinforced TMCs, investigations on in-situ reinforced TiB/Ti6Al4V on the microstructure with LMD technique are limited. This implies that there is still a need of robust understanding on the microstructure and mechanical properties LMD manufactured TiB/Ti6Al4V composite. Hence, this study investigated the microstructural evolution and hardness properties of TiB/Ti6Al4V composite produced via LMD technique.

II. METHODOLOGY

A. Materials

A grade 23, pre-alloyed Ti6Al4V extra low interstitial (ELI) powder with particle size distribution in the range 20-60 µm (supplied by TSL Technik GmbH & Co, Bitterfeld, Germany) was used as the matrix. A TiB2 powder with particle size in the range -140-325 mesh (supplied by Stanford Advance Material) was used as a reinforcing material. The samples were deposited on a Ti6Al4V base plate, which was used as the substrate.

B. Methods

All samples were manufactured on an (Ire-Polar-Group) IPG fibre laser (1073 nm wavelength) processing system which was integrated with a KUKA robot and a three-way nozzle. A GTV powder system (D-57629), equipped with two powder feed hoppers was used was used to deliver the Ti6Al4V and TiB2 powders through the carrier gas during deposition. The volume flow rate for Ti6Al4V was fixed at 5 rpm, while TiB2 was varied between 1.0 rpm, 1.2 rpm, 1.4 rpm, 1.6 rpm, 1.8 rpm and 2.0 rpm, respectively. The powder
carrier gas was blown at 1.5 l/min during the deposition process. Argon gas was used as a shielding gas to prevent oxidation on the manufactured samples. Laser power of 1500 W, scanning speed of 0.5 m/min, gas flow rate of 12 l/min and beam diameter of 0.5 mm were used as the processing parameters during deposition for all the samples. The Ti6Al4V base plate was subjected to sand blasting to prepare it for deposition. Before the deposition process, the Ti6Al4V base plate was heated on a heating stage to a temperature of 400°C. The heating stage was equipped with an element that was used to heat the base plate. The temperature of the base plate was measured and monitored by measuring the temperature on the base plate before each deposition process using a pyrometer. Long single line track of approximately 40 mm were deposited for every deposition. Post manufacturing, all samples were left to cool inside the heating stage and were removed when the heating stage was at room temperature.

The deposited samples were cut in perpendicular to the deposition direction on a Struers Labotom-5 cutting machine using a Struers high quality titanium cutoff wheel (20S25). The samples were then mounted using an AMP 50 automatic mounting press machine. AKA Resin Phenolic SEM black conductive resin was used to mount all samples. The mounted samples were mechanically ground with Struers Tetrapol-25 grinding and polishing machine. Silicon carbide (SiC) grinding papers with grit sizes of 80, 320, 1200 and 4000 were used for grinding the samples which were later surface finished by polishing to a mirror finish using Diaprep MD-Mol 3µm diamond suspension and colloidal silica 0.04µm OP-S suspension for 3 minutes. The specimens were etched with Kroll’s reagent, a solution containing 100ml H2O, 1-3ml HF and 2-6ml HNO3. The metallographically prepared and etched samples were observed for microstructure using an Olympus BX51M Optical microscope and Joel JSM-6010PLUS/LA SEM. To observe full view of the microstructure, microstructural images were taken using various magnifications. Hardness measurements were performed using Matsuzawa Seiko Vickers model MHT-1 micro-hardness machine. All measurements were done using a diamond type of indenter and applying a force of 0.3 kgf and dwell time of 10 seconds. For all samples, three hardness patterns were measured, and the average was calculated as the hardness of the material.

III. RESULTS AND DISCUSSION

A. Microstructures

Optical Figure 2 shows the morphologies of the Ti6Al4V and TiB2 powders.

The Ti6Al4V ELI showed spherical and smooth particles, with no porosity as can be seen in Figure 2(a). Spherically shaped and smooth Ti6Al4V ELI particles were reported in other studies [23,26]. On the other hand, the TiB2 powder revealed fine irregular shaped particles. Irregular shaped particles of TiB2 were also reported in other studies [13,14].

Optical images of the deposited single track clad are presented in Figure 3.

![Optical micrographs of the samples.](image)

No cracks were found on the interface of the clads and the substrate as presented in Figure 3. Moreover, a good metallurgical bond between the clads and substrate was obtained on all samples, indicating an enhanced interfacial compatibility by the in-situ reaction [26]. The absence of cracks could be attributed to the pre-heating temperature of 400°C that was used. Figure 3(a) shows that volume flow rate of 1.0 rpm resulted in the formation of un-melted TiB2 particles that were distributed in some regions on the sample. According to Sayat et al. [27], the presence of un-melted particle is due to incomplete in-situ reaction between Ti and TiB2 (Ti+TiB2 →2TiB).

When the TiB2 volume flow rate was increased 1.2 rpm, the number of un-melted TiB2 particles was slightly increased (Figure 3b). In addition, a single large spherical pore was observed on the microstructure of this sample as can be seen in Figure 3(b). Formation of the pore could be due to gas entrapment in the melt pool during LMD process. In contrast, Cai et al. [14] reported similar type of pores and categorised them as inter-layer micropores and were attributed to short lifespan of the melt pool during laser processing.

The number of un-melted TiB2 particles was observed to have remained the same as the volume flow rate was increased to 1.4 rpm. However, the number of spherical pores (porosity) increased to three as can be seen in Figure 3(c). When the volume flow rate was increase to 1.6 rpm, porosity remained the same (Figure 3d), whilst the number of un-melted TiB2 particles was slightly increased. Depositing of TiB2 at volume flow rate of 2.0 rpm resulted in an increase in the size of the reaction-induced pores, with a slight increase in the number of un-melted particles (Figure 3f). It is important to note that all the formed pores were spherical and were found close to the interface of the clads and substrate. To study further the microstructures in-depth and in detail, the samples were analysed using SEM. The obtained SEM micrographs are presented in Figure 4.
The 22nd Annual International RAPDASA Conference

Digital Manufacturing: Industrialising Africa

Figure 4(a) shows that the microstructure of the sample that was deposited at volume flow rate of 1.0 rpm consisted of a brighter region and dark particles that were clustered and closely packed across the sample. According to literature, the brighter region is identified as the Ti matrix, whereas the dark particles are characterised as in-situ synthesized TiB particles and precipitates [1,14,20]. To confirm these phases, XRD analysis was conducted on the sample that was produced with powder flow rate of 2.0 rpm. The resulting XRD pattern of the composite is presented in Figure 5.

The XRD results shows the presence of three phases, namely Ti, TiB and Ti$_3$B$_4$. This was confirmation of the microstructural analysis. Similar type of results was reported in literature [22,24]. During LMD of Ti6Al4V ELI and TiB$_2$, an exothermic reaction between Ti and TiB$_2$ take place to form TiB (Ti+TiB$_2$→2TiB), which explain the formation of the TiB particles and TiB precipitates on the microstructure in Figure 5(a). The microstructure also showed that the in-situ synthesized TiB particles presented three types of morphologies, namely elongated needle-like whiskers, small circular particles, small of precipitates as can be seen in Figure 4(a). It is important to note that these TiB particles were densely packed and distributed throughout the microstructure of the sample. The average length of the long needle-like whiskers was measured to be ~26.1 µm, while the diameter of the small circular particles measured ~5.3 µm. Similar types of whiskers on AM manufactured TiB/Ti6Al4V composite were reported in other studies [24,28]. It is well known that Ti6Al4V manufactured with LMD process exhibit a fully martensitic α' microstructure due to high cooling rates [6,28,29]. It is important to note that no martensite α' phase was observed on the microstructure of the sample. It is understood that absence of the martensite α' was due to the formation of the TiB particles, whiskers and precipitates which inhibited the formation of the martensite phase [20].

The microstructure presented in Figure 4(b) showed that when the TiB$_2$ volume flow rate was increased to 1.2 rpm, a slight decrease clustering of the TiB whiskers and precipitates. It seemed as the TiB particles were becoming loosely packed. The increase in volume was also followed by an increase in the size of the TiB whiskers. This was a clear indication of grain growth which was confirmed by an increase in length and diameter of the elongated needle-like and small circular whiskers to 50.3 µm and 12.1 µm, respectively. When the volume flow rate was increased to 1.4 rpm, further grain growth was evident as can be seen in Figure 4(c). This observation was attributed to increase in length and thickness of the needle-like and small circular TiB whiskers, respectively. The average lengths of the long needle-like and short circular whiskers were calculated as 63.3 µm and 16.1 µm, respectively. The clustering of the TiB whiskers was reduced, with number of TiB precipitates decreasing and becoming finer as presented in Figure 4(c). There was no major microstructural change that was observed when the volume flow rate was increase to 1.6 rpm. However, deposition at volume flow rate of 1.6 rpm resulted in a slightly coarser microstructure (Figure 4c) compared to the sample that was deposited at volume flow rate of 1.4 rpm (Figure 4d). The length and diameter of the needle-like and small circular whisker were measured as 50.7 µm and 7.9 µm, respectively.

A major microstructural change was observed when the volume flow rate was increased to 1.8 rpm as can be seen in Figure 4(e). The clustering of the TiB particles and precipitates was markedly reduced. Moreover, TiB whiskers were properly arranged, and their length and diameters of the whiskers was remarkably increased, with the long needle-like TiB whiskers measuring an average length of 111.8 µm, while the circular whisker measured a diameter of 16.2 µm. Increasing the volume flow rate to 2.0 rpm produced a similar microstructure to the 1.8 rpm sample. However, it was followed by a slight decrease in size of the TiB whiskers. The decrease in size was confirmed by the decrease in average length of needle-like and circular whiskers to 105.1 µm and 7.02 µm, respectively after deposition at powder flow rate of 2.0 rpm. In summary, the microstructural analysis showed the formation three types of TiB with different morphologies during LMD process through in-situ reaction between Ti6Al4V and TiB$_2$. These TiB particles appeared as packed and clustered particles, whiskers and precipitates. The clustering of the TiB was found to decrease with increasing volume of TiB$_2$. Furthermore, the size of the TiB whiskers was found to increase with increasing volume of TiB$_2$. The
microstructural results also showed distinctively different microstructure when volumes 1.8 rpm (Figure 4c) and 2.0 rpm (Figure 4f) were used compared to the other samples. However, the latter samples showed similar microstructural characteristics to some degree. A study by Sahay et al. [27] reported that besides the starting proportions of Ti6Al4V and TiB2, the variation in morphology, phases and whiskers depend on the diffusion of B during the LMD process. The growth of the TiB whiskers was reported and attributed to a one-way diffusion of B along [010] direction. It is understood that this is due to the higher density of strong B-B bond in the same [010] direction, which implies favourable axial growth rate of TiB whiskers in the Ti matrix.

B. Hardness

The graph of hardness profiles and average hardness of the sample are presented in Figure 6 and Table 1.

![Graph of hardness profiles](image)

**TABLE 1: Average hardness of the samples.**

<table>
<thead>
<tr>
<th>Sample (rpm)</th>
<th>Hardness (HV&lt;sub&gt;S&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>570 ± 18</td>
</tr>
<tr>
<td>1.2</td>
<td>598 ± 23</td>
</tr>
<tr>
<td>1.4</td>
<td>649 ± 22</td>
</tr>
<tr>
<td>1.6</td>
<td>678 ± 22</td>
</tr>
<tr>
<td>1.8</td>
<td>701 ± 18</td>
</tr>
<tr>
<td>2.0</td>
<td>736 ± 30</td>
</tr>
</tbody>
</table>

It can be seen from Figure 6 and Table 1 that volume of 1.0 rpm gave the lowest hardness profile and hardness value of 570 ± 18 HV. Obviously, the lower hardness was attributed to smaller size of TiB2 whiskers that was observed on the microstructure of the sample in Figure 4(a). The hardness was noticeably increased to 598 ± 23 HV when the volume was increase to 1.2 rpm. The increase in hardness was attributed to the increase in TiB whiskers that was observed on the microstructure of the sample (Figure 4b). When the volume was increased to 1.4 rpm and 1.6 rpm, the hardness increased to 649 ± 22 HV and 678 ± 22 HV, respectively. The sample that was produced with the highest volume of 2.0 rpm gave the highest hardness of 736 ± 30 HV. From the results, hardness increased with increasing TiB2 volume. In connection with the microstructure, this trend was associated with the growth of the TiB whiskers and reduction of TiB precipitates that was observed as the TiB2 volume was increased.

IV. CONCLUSION

In this this study, TiB/Ti6Al4V composite was manufactured using LMD technique through in-situ reaction of Ti6Al4V ELI and TiB2 powders. The effect of TiB2 volume flow rate on microstructural formation and hardness was evident. The following conclusions were made:

- LMD of Ti6Al4V ELI and TiB2 result in the formation of TiB whiskers of different shapes and TiB precipitates.
- The clustering of the TiB whiskers decreases with increasing volume flow rate of TiB2.
- The size of the TiB whiskers also increase with increasing TiB2 volume flow rate up to 1.8 rpm, and then slightly decrease at 2.0 rpm.

ACKNOWLEDGMENT

The Council for Scientific and Industrial Research is thanked for laboratory equipment support.

REFERENCES


Rapid Sand Casting
Assessment of the Financial Feasibility for Rapid Sand-casting Process using the Payback Period Method

Anazo Msani  
Department of Engineering Metallurgy  
University of Johannesburg  
Johannesburg, South Africa  
anazo.majoka.m@gmail.com

Didier Nyembwe  
Department of Engineering Metallurgy  
University of Johannesburg  
Johannesburg, South Africa  
dnyembwe@uj.ac.za

Malan van Tonder  
Department of Technology Transfer and Innovation  
Vaal University of Technology  
Vanderbijlpark, South Africa  
malanvt@vut.ac.za

Abstract—The additive manufacturing (AM) of sand moulds and cores for foundry applications is also referred to as rapid sand casting. Due to skepticism as a result of the newness of the technology and its high cost, additive manufacturing has not yet been adopted by the local foundry industry in South Africa. The existing literature on additive manufacturing has demonstrated that rapid sand casting is more cost-effective and has a shorter lead time than traditional manufacturing processes. However, the literature has not demonstrated if it will be financially viable for the foundry industry to adopt this technology. Using the capital budgeting technique of payback period and based on the purchase of a new additive manufacturing machine easily available in South Africa, the recovery of the initial investment was calculated over a five-year period. Both an annuity and a mixed-stream cash flow were used. It was determined that, due to the speed and economy of rapid sand casting, the initial capital outlay could be recovered within five years and that rapid sand casting is economically feasible for the local foundry industry.

Keywords—additive manufacturing, rapid sand casting, economic feasibility, payback period.

I. INTRODUCTION

Additive manufacturing (AM) is one of the modern technologies that is part of the Fourth Industrial Revolution (4IR) [1] that can be applied to foundry processes. Additive manufacturing produces a component using a consecutive layering process [2]. Additive manufacturing is used across many different industries to produce many different products. This technology is well suited to the production of moulds and cores in the foundry industry as it utilizes three-dimensional (3D) design to create and build products [3]. Compared to traditional methods of mould making, rapid sand casting is easier, faster and cheaper because no expensive pattern is required for the production of the moulds. Not only is the production time and lead time involved in making the moulds and cores reduced because fewer steps are involved, but complex parts are more easily produced.

Additive manufacturing, as part of the Fourth Industrial Revolution, integrates intelligent production systems and information technologies [8]. Additive manufacturing plays a significant role in improving economic competitiveness as well as contributing to the sustainability of the environment compared to traditional manufacturing. The Fourth Industrial Revolution involves generation of computer product design and three dimensional printing which can fabricate solid parts by building consecutive layers of materials which fits in additive manufacturing technologies [1]. Due to its low cost and short production lead time, this technology has been
Adopted in various industries in most countries, including South Africa [9].

A. Additive Manufacturing in South Africa

Additive manufacturing technologies were introduced to South Africa in 1991 as rapid prototyping, and adoption of this technology started to grow over the years through collaboration between research institutes, universities and government, often through workshops [10]. As a result, industries have shown interest in adopting this technology due to its ability to manufacture very complex structures with less tooling and without the need to assemble parts in order to create the product [11]. These advantages over traditional methods of manufacturing should encourage the South African manufacturing industry to adopt this technology. Various additive manufacturing machines are available in South Africa at some universities and research institutes. They include three-dimensional printing, also known as binder jetting, selective laser sintering, fused deposition modelling and stereolithography apparatus.

B. Rapid Sand Casting

Moulds and cores of high quality have a significant impact on the quality, functionality and application of the final casting produced. It is, therefore, important to control mould properties of sand used for moulds and cores before printing process start [12]. Traditional sand-casting processes usually require more time and tooling to ensure high quality of moulds, which incurs more cost. Once parts have been produced, further processes are incorporated to ensure the high quality of the final product [13]. Rapid sand casting is a process of producing moulds and cores for foundry industry using additive manufacturing technologies. There are currently seven additive manufacturing technologies which are classified according to the raw material used and the solidification process. Two of these technologies may be used for rapid sand casting, namely binder jetting technology and powder bed fusing [14]. These technologies can now be adopted by the local foundry industry as they take less time to fabricate moulds and cores than the traditional methods. Adoption of this technology by South African foundries can also assist in improving global competitiveness in the market, rejuvenate tooling and improve foundries’ performance [11]. The other advantage of rapid sand casting is that it can fabricate complex moulds or cores with high dimensional accuracy. Due to extensive research conducted over the past years, additive manufacturing is maturing and can be adopted by the local foundry industry.

III. Investing in Additive Manufacturing

Investment in rapid sand casting is important for the foundry industry and long-term feasibility studies need to be considered when adopting this technology. Increasing demand for complex foundry parts will lead to economic growth in the market which will result in increased investment [15]. To improve the global competitiveness of South African manufacturing industry, the government started to invest in additive manufacturing technology researches in the early 1990’s, which aimed at studying additive manufacturing technologies needed by the manufacturing industry [11]. According to Wohlers report, additive manufacturing showed a significant increase in revenue over the past years [6]. This proves that the adoption of additive manufacturing is steadily increasing and is turning industries throughout the world on their heads. In evaluating the economic feasibility of rapid sand casting, a Payback period was adopted as one of the processes that can be applied by the local foundry industry for basic investment decisions. For the evaluation process, the prices of printers named as Printer A and Printer B machine were considered, and the cash flow generated over a period of five years, based on the gross profit, was also incorporated. These machines, Printer A and Printer B, were assumed to be adopting binder jetting technology for rapid sand casting process.

IV. METHODOLOGY

This study is based on a cylindrical shape of a sand core with the following characteristics:
- Geometrical shape: cylindrical
- Volume: 58118480.58 mm³
- Weight: 70.90 kg
- Average selling price: R13 008.24
- Material used: Furan alcohol based binder and sulfonic acid coated silica sand

The geometrical shape is based on the customers’ requirements while the volume and the weight of the sand core is calculated by Magix software during preparation of printing the sand core. The average price is the selling price of the core which is calculated based on the volume of the sand core, the quantity of consumables that will be used during printing process and the time it will take to print the sand core.

This study is based on the Financial Payback period method. Payback period is one of the capital budgeting techniques that calculates the number of years it will take for an investment to recover its initial money from cash flows generated annually by a project [3]. This method included three important components, namely the initial investment, the cashflow of the project and the payback period. The formula of the Payback period is shown in equation 1. Each component of the proposed method is explained in detail in section A to C.

\[
\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Cash Flow}}
\]

A. Initial Investment

Initial investment is defined as a price of purchasing a machine and the prices of these machines may differ due to different manufactures and the slight difference in the size of the machines. Average price of printing machines with the size between 1000 x 600 x 500 mm and 800 x 500 x 400 mm range between R15 200 000 and R12 200 000. These prices are quoted based on the building space, additional job box, unpacking stations, etc. This study assumed that Printer A machine price is R15 200 000 with 1000 x 600 x 500 mm as a building platform, while Printer B machine price is R12 200 000 with 800 x 500 x 400 mm as a building platform.
B. Cash Flows

Cash flow is the amount of money that is generated and received from the operational activities of the firm after investing in a project or process. Cash flow can be studied on a monthly or yearly basis. This study used cash flows over a yearly period for 5 years in order to obtain the most accurate results of payback period and with the assumption that investments in machinery have long life and can last up to more than 5 years [16].

Income statement was generated in calculating gross profit cash flows for payback period analysis as illustrated in Appendix A. Gross profit cash flows means that only the direct costs incurred in production of this cylindrical shape of sand core were considered, mainly the raw materials. The price of the mould and cost of producing the core were considered in calculating the revenues and cost of goods sold. Cost of goods sold was calculated by subtracting revenues from gross profit. Subsequently the gross profit cash flows for this specific sand core were calculated from gross profit margin and revenues. Gross profit margins were based on benchmarking for manufacturing industry [16], which illustrates the profitability of an investment at its most basic level as percentages.

This study also assumes full operational capacity of the machine of 260 operational days (excluding weekends and holidays) with at least 3 cores produced per day in a year over 5 years, the number of cores produced per day depends on the time it will take to produce a core. Table I and Table II illustrates gross profit cash flows operational data for Printer A and the Printer B machine calculated from the income statement. Year 0 is the initial investment outlay, which is the price of purchasing each machine, and from year 1 until year 5 are the generated gross profit cash flow from producing the cylindrical resin bonded sand. The gross profit cash flows for both machines are the same because they were based on the same study with the sand core of the same characteristics.

C. Payback Period

In this case study the Payback period was calculated from two methods that is the annuity cash flows and the mixed stream cash flows for both the Printer A machine and the Printer B machine as shown in Table I and Table II.

Annuity cash flows assume that the constant cash flows are generated each year while mixed stream cash flows assume escalated annual cash flows are generated based on inflation rate. Payback period 1 and 3 are for the annuity cash flows 1 and Payback period 2 and 4 are for the mixed stream cash flow 2. Due to the difference in generation of annuity and mixed stream cash flows the calculation of Payback period is also different. The shorter the time to recover the initial investment, the more appealing is the project.

Table III shows previous benchmarking for the past five years and assumptions of year 2021, 2022 and 2023 on the income statement were based on average of the year 2019 and 2020.

![Table III: Gross Profit Margins [16]](image)

**Printer A payback period from Table I cash flows**

1) **Payback period (annuity cash flow 1)**

\[ \text{Payback period} = \frac{\text{Initial investment}}{\text{Annual cash flow}} \]

\[ = \frac{R15 200 000}{R 4 048 424.60} \]

\[ = 3.75 \text{ years.} \]

2) **Payback period (mixed stream cash flow 2)**

- **In year 1**, R4 048 424.60 will be recovered from the R15 200 000 initial investment.
- **In year 2**, R8 288 616.68 will be recovered (R4 048 424.60 from year 1 and R4 240 192.08 from year 2).
- **In year 3**, R12 729 631.93 will be recovered (R4 048 424.60 from year 1, R 4 240 192.08 from year 2 and R 4 441 015.25 from year 3).
- R2 470 368.07 still needs to be recovered.
- **At the end of year 4** R2 470 368.07 would have been recovered, only 52.98% (R2 470 368.07 ÷ R4 663 066.01 = 0.52977) of the year 4 cash flow of R4 663 066.01 will be needed to complete the Payback of the initial R15 200 000.
Payback period for the mixed stream of cash flow = 3.53 years.

**Printed B**

Payback period from Table II cash flows

3) Payback period (annuity cash flow 1) = Initial investment ÷ Annual cash flow

= R 12 200 000 ÷ R 4 048 424.60

= 3.01 years

4) Payback period (mixed stream cash flow 2)

- In year 1, R 4 048 424.60 will be recovered from the R12 200 000 initial investment.
- In year 2, R 288 616.68 will be recovered (R 4 048 424.60 from year 1 and R 240 192.08 from year 2).
- At the end of year 3 R 3 911 383.32 would have been recovered, only 88% (R 3 911 383.32 ÷ R 4 441 015.25 = 0.88) of the year 3 cash flow of R 4 441 015.25 will be needed to complete the Payback of the initial R12 200 000.
- Payback period for the mixed stream of cash flow = 2.88 years.

For both cash flow methods of these machines, rapid sand casting is shown to be economically feasible because the initial investments are covered within the 5 years period. Printer A machine has shorter Payback period on the mixed initial investment of R15 200 000 recovered before the end of year 4. Printer B machine also has shorter Payback period on the mixed stream cash flow compared to the annuity cash flow with the initial investment of R12 200 000 recovered before the end of year 3 and year 4, respectively. These Payback period results show good efficiency of material and resources usage for the rapid sand-casting process at the most fundamental level of the process for both the machines with only the gross profit cash flow incorporated in the calculation. In comparison with both the machines, Printer B machine has shorter Payback period for both cash flows as compared to Printer A machine as shown in Figure 3. This is because Printer A has smaller initial investment than Printer B.

V. CONCLUSION

The Payback period method is one of the capital budgeting techniques that is used by firms to evaluate the feasibility of a project by looking at how long it will take to recover the initial investment. The paper has illustrated how the financial technique could be applied to the rapid sand casting for the production of a basic cylindrical resin bonded sand mould. In the case study, evaluation of rapid sand casting using the Payback period was shown to be economically feasible for adoption by the local foundry industry. The Payback period is easy to calculate and understand by non-financial managers and can be applied by the local foundry industry as a first step in evaluating additive manufacturing for rapid sand casting process.

VI. REFERENCES


### APPENDIX A

#### Income Statement (Printer A)

<table>
<thead>
<tr>
<th>Years</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenues</td>
<td>R10 146 427,56</td>
<td>R10 653 748,94</td>
<td>R11 186 436,39</td>
<td>R11 745 758,21</td>
<td>R12 333 046,12</td>
<td></td>
</tr>
<tr>
<td>Price of the core</td>
<td>R13 008,24</td>
<td>R13 658,65</td>
<td>R14 341,59</td>
<td>R15 058,66</td>
<td>R15 811,60</td>
<td></td>
</tr>
<tr>
<td>Cost of goods sold</td>
<td>R6 098 002,97</td>
<td>R6 415 556,86</td>
<td>R6 745 421,14</td>
<td>R7 082 692,20</td>
<td>R7 436 826,81</td>
<td></td>
</tr>
<tr>
<td>Gross Profit</td>
<td>R4 048 424,60</td>
<td>R4 240 192,08</td>
<td>R4 441 015,25</td>
<td>R4 663 066,01</td>
<td>R4 896 219,31</td>
<td></td>
</tr>
<tr>
<td>Gross Profit Margin</td>
<td>39,90%</td>
<td>39,80%</td>
<td>39,70%</td>
<td>39,70%</td>
<td>39,70%</td>
<td></td>
</tr>
<tr>
<td>Project Evaluation from Gross Profit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed stream cash flow</td>
<td>-R15 200 000,00</td>
<td>R4 048 424,60</td>
<td>R4 240 192,08</td>
<td>R4 441 015,25</td>
<td>R4 663 066,01</td>
<td>R4 896 219,31</td>
</tr>
<tr>
<td>Annuity cash flows</td>
<td>-R15 200 000,00</td>
<td>R4 048 424,60</td>
<td>R4 048 424,60</td>
<td>R4 048 424,60</td>
<td>R4 048 424,60</td>
<td></td>
</tr>
</tbody>
</table>

#### Income Statement (Printer B)

<table>
<thead>
<tr>
<th>Years</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenues</td>
<td>R10 146 427,56</td>
<td>R10 653 748,94</td>
<td>R11 186 436,39</td>
<td>R11 745 758,21</td>
<td>R12 333 046,12</td>
<td></td>
</tr>
<tr>
<td>Price of the core</td>
<td>R13 008,24</td>
<td>R13 658,65</td>
<td>R14 341,59</td>
<td>R15 058,66</td>
<td>R15 811,60</td>
<td></td>
</tr>
<tr>
<td>Cost of goods sold</td>
<td>R6 098 002,97</td>
<td>R6 415 556,86</td>
<td>R6 745 421,14</td>
<td>R7 082 692,20</td>
<td>R7 436 826,81</td>
<td></td>
</tr>
<tr>
<td>Gross Profit</td>
<td>R4 048 424,60</td>
<td>R4 240 192,08</td>
<td>R4 441 015,25</td>
<td>R4 663 066,01</td>
<td>R4 896 219,31</td>
<td></td>
</tr>
<tr>
<td>Gross Profit Margin</td>
<td>39,90%</td>
<td>39,80%</td>
<td>39,70%</td>
<td>39,70%</td>
<td>39,70%</td>
<td></td>
</tr>
<tr>
<td>Project Evaluation from Gross Profit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed stream cash flow</td>
<td>-R12 200 000,00</td>
<td>R4 048 424,60</td>
<td>R4 240 192,08</td>
<td>R4 441 015,25</td>
<td>R4 663 066,01</td>
<td>R4 896 219,31</td>
</tr>
<tr>
<td>Annuity cash flows</td>
<td>-R12 200 000,00</td>
<td>R4 048 424,60</td>
<td>R4 048 424,60</td>
<td>R4 048 424,60</td>
<td>R4 048 424,60</td>
<td></td>
</tr>
</tbody>
</table>
Abstract—Appreciable quantities of waste sand are generated during the manufacturing of sand parts using additive manufacturing processes. In line with environmental regulations and, considering the increasing value of sand, the reuse of waste sand has become imperative in the rapid sand-casting process. This paper investigates the properties of waste sand generated from the additive manufacturing of sand parts using the Voxeljet process. The characterization results suggest that the waste sand could be recycled for the production of sand cores and moulds using both the traditional method and the modern method of additive manufacturing.

Keywords—sand, reused sand, sand core, additive manufacturing process, rapid sand-casting process, sand grain

I. INTRODUCTION
Three-dimensional printing (3D Printing) is an additive manufacturing technique for producing a wide range of structures and complex geometries using three-dimensional model data [1]. It involves fabricating an object of any shape from a digital model and applying successive layers of the printing material to create the geometry from this application, a refractory material is used [2]. A refractory material is a material that resists decomposition by heat, pressure, or chemical attack, and retains strength at high temperatures. Silica sand that is made up of silicon dioxide (SiO2) is the most common refractory material used in foundries [3]. For sand moulds and cores, three rapid sand-casting techniques are available, namely selective laser sintering, binder jetting and patternless casting manufacturing technique [4]. Three-dimensional printing technologies for rapid sand casting include ZCast, ExOne and Voxeljet; these are just some of the most visible examples on the market that are used to produce sand moulds and cores using binder jetting technology [5].

Voxeljet and ExOne are the leaders in three-dimensional printing of sand parts [6]. Both use a similar printing process, the only difference being the materials with which they can print. Voxeljet uses two different types of plastic and one type of sand. While ExOne uses two different types of sand, five types of metals, with seven different finishes, and a soda lime glass that's available in three different finishes [6]. The Vaal University of Technology (VUT) Science and Technology Park currently houses a Voxeljet VX1000 platform, which runs on the furan process.

The Voxeljet VX1000 printer uses a self-hardening two-part furan binder system. The hardening mechanism involves the addition of furfuryl alcohol resin and sulphonic acid catalyst, which acts as an activator and triggers an exothermic poly-condensation reaction which bonds the sand particles together. The curing rate is specifically relative to the acid concentration [7].

The condition of the sand used has a significant impact on the quality of the printed sand cores and moulds. As such, understanding the influence of sand properties such as sand purity, particle size, acid requirement, refractoriness, and grain shape is essential. Table 1 summarizes the important physical classifications to consider when selecting sand for traditional core and mould production, as well as for Three-Dimensional Printing method.

Table 1: Silica sand properties required for Three-dimensional printing (Van Tander: 2019).

<table>
<thead>
<tr>
<th>Property</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFS GFN</td>
<td>50 – 60 (if not differently specified)</td>
</tr>
<tr>
<td>Sand distribution</td>
<td>3 – 5 sieves</td>
</tr>
<tr>
<td>Grain shape</td>
<td>Rounded to sub-rounded</td>
</tr>
<tr>
<td>AFS clay content</td>
<td>&lt; 0.3 %</td>
</tr>
<tr>
<td>Acid Demand Value</td>
<td>≤ 6 ml</td>
</tr>
<tr>
<td>Moisture</td>
<td>&lt; 0.2 %</td>
</tr>
<tr>
<td>Sintering temperature</td>
<td>≥ 1450°C</td>
</tr>
<tr>
<td>Coating ratio</td>
<td>0.3 % BOS ±0.1%</td>
</tr>
<tr>
<td>Angle of repose</td>
<td>≤ 45°</td>
</tr>
</tbody>
</table>
During the printing of the furan-bonded sand cores using the Voxeljet VX1000 printer, waste sand is produced. The printing process selectively deposits the furan binder layer by layer on precoated sulphonic acid sand. As summarised in Figure 1, the process starts with the application of sand on the building platform by means of a recoater. Afterwards, the print head applies the binder selectively in the areas that correlate with the CAD layer geometry. After the entire layer is printed, the building platform is lowered, and the following layer is applied [8]. The recoating and printing steps are repeated until the entire part is printed. After the removal of the printed part, the remaining unprinted sand, consisting of both non-activated and semi-activated sand, is considered to be waste [9].

The amount of waste sand generated per cycle, which depends on the size of the part being printed, is referred to as the nesting density i.e., the percentage of utilized sand verses unutilized sand [9]. One other factor that determines the amount of waste sand produced is the part’s surface area. The surface area will determine the ratio of non-activated to semi-activated sand, as the sand near the part is semi-activated due to the binder fumes that partially activate the sand.

Both thermal and mechanical methods are available to reclaim the waste foundry sand. However, if the sand is to be reclaimed successfully, the reclamation process must not only restore the condition of the sand, but the process must also enable the sand to be reused by recoating the sand with sulphonic acid [10]. Washing off previously added acid is one way to reclaim the sand; however, the waste water will need to be treated in accordance with strict safety and health regulations before it is disposed in the local water system. Once the acid has been removed, other processes, such as drying, need to be implemented to ensure the sand is able to be reused.

The Vaal University of Technology (VUT) currently stores the waste foundry sand for a maximum of one month. This is because a longer storage period may lead to moisture pick up in the sand, which will affect the strength of the furan bonded sand parts when reused. Up to 40% of the waste sand generated can be reused but that amount can be less if the strength of the sand parts is not within the required specifications [9].

The characterisation of the sand will assist in ascertaining if the material has properties that align with the literature. The American Foundry Society (AFS) Grain Fineness Number (GFN), between 50 and 60, is the most used and is acceptable for silica sand. This range gives a good surface finish and requires low levels of binder. Rounded and sub-rounded sand grains offer good flowability and permeability with high strength at low binder additions. Sand distribution with 95% spread over 4-5 screens offers good packing and minimises expansion defects [11].

South Africa, as a developing country, is moving towards seeking greener solutions that will effectively preserve the environment; therefore, the management of industrial waste is becoming an imperative area of study. The advantage of sand reclamation is that it results in economical utilization of sand, self-sufficiency, no freight and delay, and no necessity for a bulk inventory [12].

Up to approximately 25,000 tons of hazardous waste sand are generated each year by the South African foundry industry [13]. Hazardous waste sand is regarded as a material that contains heavy metals (e.g. Chrome) and is acidic in nature. The leachate obtained from that material may contain a hazardous substance, which may affect the environment. Understanding the leachate characteristics of the used sand is essential in its disposal and the environmental impact [14]. This phenomenon is well-known in mining operational and referred to as an acid mine drainage.

Waste furan sand generated from additive manufacturing brought an interest in investigating the possible reuse of the sand. Currently, large volumes of waste foundry sand are discarded on local municipal waste landfills. Foundry silica sand costs approximately R754 – R5278/1000Kg [15]. This makes it essential for the metal manufacturing industries to recovery and reuse waste sand in order to reduce manufacturing costs while minimizing waste.

This paper is aimed at investigating the properties of foundry waste sand generated from the additive manufacturing of sand parts using the Voxeljet process. Armed with the knowledge of the sand properties, it will be possible to suggest the reuse routes of the waste furan bonded sand in the traditional foundry industry, rapid sand casting or the construction industry.
II. METHODOLOGY

Three types of Silica sand samples were collected from Vaal University of Technology, and were identified as follows:

- Virgin silica sand
- Used sand 1
- Used sand 2

The virgin silica sand was precoated with sulphonic acid and fed into the system, however, it had not been used to print any sand parts. Used sand 1 and Used sand 2 is excess waste sand which was generated during the printing of the furan bonded sand cores using the Voxeljet VX1000 printer. It is important to note that Used sand 1 and Used Sand 2 are from different suppliers. The actual virgin sand and the Used sand 1 at the time of the sample collection were from the same supplier. Figure 2 below illustrates the condition of the collected waste sand and the location site in which it was collected.

![Figure 2: Sand sampling classification.](image)

The virgin silica sand was sand that was precoated with sulphonic acid and fed into the system, but not used to print anything. Used sand 1 and Used sand 2 were waste sand generated during the printing of the furan-bonded sand cores using the Voxeljet VX1000 printer as shown in Figure 3.

![Figure 3: Used sand 1 stored in the sand silo (left), collecting virgin silica sand from the Voxeljet VX1000 printer (right).](image)

Used sand 1 was collected directly from the storage silo hopper, while Used sand 2 was collected from a stockpile of sand kept in a bulk bag and virgin silica sand was collected from the sand box located on the Voxeljet VX1000 printer. Figure 3 shows where Used sand 1 and virgin sand were collected. The sand samples were transferred into two litre plastic buckets. Figure 4 show how the sand was handled and tested.

![Figure 4: Sample handling and sand characterization testing.](image)

The following tests were performed to characterise the collected sand samples. The tests were conducted according to the American Foundry Society (AFS) [16]

2.1. Sieve Analysis

One hundred grams of the sample was screened through a series of sieves with progressively smaller meshes. Particle size distribution was determined by weighing the material retained in each of the sieves and dividing these weights by the total weight of the sample to obtain the sand AFS and %fines.

2.2. Determination of pH

Twenty-five grams of silica sand was mixed with 100 ml distilled water and stirred for 5 minutes, after which the pH of the sample material was measured. The pH of the sand determines the strength of the printed parts.

2.3. Loss on Ignition (LOI)

Ten grams of the sample was subjected to 1000 °C in a muffle furnace for 4 hours. The sample was then removed from the muffle furnace and allowed to cool to room temperature and
weighed to obtain the Loss on Ignition content. The weight loss is a result of the volatilization of organic substances.

2.4. SEM and XRF Analysis

A scanning electron microscope (SEM) equipped with Energy Dispersive X-Ray Spectroscopy (EDS), sometimes referred to as EDAX or EDX was used to provide high-resolution, three-dimensional images which supplied topographical morphological and compositional information. A macroscopic analysis was also conducted to assess other parameters of the material such as grain size, texture, and nature of fractures. An X-ray diffraction analysis was conducted to identify the crystalline phases present in the silica sand samples and from that the chemical composition of the samples.

III. RESULTS AND DISCUSSION

3.1. Sand Grain Distribution:

Virgin silica sand appeared to be considerably finer than both Used sands 1 and 2, showing an AFS of 87.79 and a fines content of 11.60% as summarized in Figure 5 and Figure 6. Used sand 1 showed an AFS of 80.35 and fines content 10.04%, which was much higher than Used sand 2 with an AFS of 68.05 and fines content of 7.79%.

![Figure 5: Sand AFS number of virgin silica sand, Used sand 1 and 2.](image)

![Figure 6: Sand fines (%) of virgin silica sand, Used sand 1 and 2.](image)

The grain size distribution of Used sand 2 was spread more widely than that of the virgin sand and Used sand 1 which were both spread narrowly. Due to the higher AFS in the virgin silica sand as well as in Used sand 1, the sand cores produced form these sand types are expected to have a much higher density, lower permeability smoother surface finish than sand cores produced with Used sand 2.

3.2. Sand pH

The pH of virgin sand was found to be 2.86, indicating the presence of sulphonic acid with no contaminants. The pH of both Used sands 1 and 2 was found to be 3.03 and 3.29 respectively. This suggests that the sulphonic acid with which they had been coated had been utilized.

3.3. Loss on Ignition (LOI)

Used sand 1 and virgin silica sand had a loss on ignition content of 0.54% and 0.57% respectively, which was higher than that of Used sand 2 which was found to be 0.33%. As far as the same supplier sand samples, the results suggest that the Used sand was contaminated by excess resin.

3.4. SEM and XRF Analysis

The scanning electron microscope revealed some morphological features of the sand samples. Virgin silica sand grains were observed to be angular to sub-angular with a medium to low sphericity, therefore the flowability and packing of the sand grains was expected to be low. Used sand 2 grains were observed to be sub-rounded with a medium sphericity with Used sand 1 being angular to sub-angular with a medium sphericity. The results indicate that the printing process abrades the grains to a more rounded shape.
The 22nd Annual International RAPDASA Conference

Digital Manufacturing: Industrialising Africa

The X-ray diffraction images show some peaks which are high with a narrow intensity, see Figures 11-13. This indicates that there is more regularity than the other directions. Low peaks are an indication of crystals that are arranged in a random order, known as an amorphous crystal structure.

All three sand samples showed a high purity of silica content ranging from 87.9% to 93. The purity of used sand samples has decreased to 87.9 and 89.5 respectively from used sand 1 and used sand 2. This also suggests some form of contamination during the additive manufacturing process. However, the silica content is still high enough to ensure the
refractoriness of the sand. Traces of Al₂O₃, SO₃, Fe₂O₃ and ZrO₂ were also found, as shown in Table 2.

<table>
<thead>
<tr>
<th>Component</th>
<th>Virgin Silica Sand</th>
<th>Used Sand 1</th>
<th>Used Sand 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>1.04</td>
<td>1.02</td>
<td>0.74</td>
</tr>
<tr>
<td>SiO₂</td>
<td>87.89</td>
<td>89.54</td>
<td>93.14</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.14</td>
<td>2.08</td>
<td>1.15</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.32</td>
<td>1.12</td>
<td>1.04</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>3.63</td>
<td>2.65</td>
<td>1.55</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.09</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.31</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>CaO</td>
<td>0.13</td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.78</td>
<td>2.44</td>
<td>1.70</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.10</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>MgO</td>
<td>0.14</td>
<td>0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>Nb₂O₅</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

From the preliminary test results of the sand characterisation, it appears that the used sand samples have changed in properties and morphology from the virgin sand due to the additive manufacturing process. However, the properties of the used sand still offers a potential for further reuse during additive manufacturing due to the size distribution, silica content and grain shape still close to the virgin sand.

IV. CONCLUSION

This paper investigated the properties of waste sand generated from the additive manufacturing of sand parts using the Voxeljet process and reviewed the potential reuse of waste sand in order to reduce the costs of purchasing new sand and transporting waste sand to landfills. The investigation has shown that waste sand generated from additive manufacturing has the potential to be reused for rapid sand casting in that the properties investigated still meet the 3D printing specifications. In addition the XRF test results indicate that these used sand samples might not be hazardous because they do not contain heavy metals such Chrome.

Future work will primarily focus on treating the recovered waste sand through thermal and mechanical methods of sand reclamation to reduce the residual binder concentrations without significantly altering the sand's physical condition, and to reuse in applications such as foundry core and mould making as well as in construction.

Future work will also involve assessing the used sand for additional properties, including moulding properties such as strength, flowability and resistance to mould erosion. The reclamation of sand will also be an important aspect of any future investigation to optimise the reuse of used sand generated from additive manufacturing processes.

REFERENCES

Assessment of Moulding Properties of Local Chromite Sand for Rapid Sand Casting Applications

Julieth Languhati Chauke  
Department of Mining and Metallurgy  
University of Johannesburg  
South Africa  
201419371@student.uj.ac.za

Kasongo Didier Nyembwe  
Department of Mining and Metallurgy  
University of Johannesburg  
South Africa  
dinyebwe@uj.ac.za

PJM van Tonder  
Southern Gauteng Science and Technology Park  
Vaal University of technology  
malanvti@vut.ac.za

Abstract—Rapid sand casting is a three-dimensional printing technique that directly manufactures sand moulds and cores without the use of patterns or coreboxes. Pattern and corebox making is a very complex and time-consuming process, therefore eliminating such steps improves the overall speed of the process and agility. Traditionally, silica sand has been the refractory material of choice in rapid sand casting applications due to availability, cost and regional local supply. However, silica sand is associated with few non-negligible disadvantages, including its low refactoriness and high linear thermal expansion coefficient. Chromite sand is generally identified as a suitable refractory material to address the shortcomings of silica sand. The use of chrome sand in rapid sand casting applications is considered in this investigation and could produce better quality castings in specialized applications. This study analyses the mechanical properties of various local chromite sand for rapid sand casting applications. Voxeljet resin and catalyst was used to manufacture Tensile, Friability and Bend testing specimen. The analysis of results lead to a conclusion that South African Chromite sand can be considered for rapid sand casting applications. This study will show the suitability of South African Chromite sand for rapid sand casting applications.

Keywords—Rapid sand casting, Three-dimensional printing, Chromite sand, Mechanical properties

I. INTRODUCTION

Three dimensional printing (3D Printing) or additive manufacturing (AM) is a process of fabricating physical objects through direct layer by layer deposition of material using a computer aided design (CAD) model (1). There are various applications of three-dimensional printing in many sectors, e.g. medical, manufacturing, and education. The application of three-dimensional printing in sand casting in the foundry industry is known as rapid sand casting, which uses binder jetting technology. The binder jetting process involves the deposition of a layer of powder in which in Voxeljet the sand should be catalyst-coated prior, followed by spraying liquid resin which fuses the powder by means of a chemical bond (2). Rapid sand casting creates moulds without utilizing patterns (3). Pattern making is a slow process and requires extremely high-quality materials and skills. As an alternative to traditional moulding, rapid sand casting eliminates the pattern making process thus improving the productivity of the casting process by reducing the lead time, however it produces low volumes of castings.

Most moulds and cores are based on silica sand because of its great abundance and low cost (4). However, silica sand is known to have high thermal expansion which can cause casting defects with high melting-point alloys and low thermal conductivity that could lead to unsound castings. Chromite sand has a much lower thermal expansion and high resistance to penetration of liquid metal (5). Its high thermal conductivity offers fast cooling thus minimizing the casting chilling effect (6).

Research shows that most studies investigated the suitability of silica sand for rapid sand-casting applications. By comparing the mechanical properties of the imported silica sand recommended for Voxeljet VX1000 3D printer and local silica sand, Nyembwe et.al (7) discovered that South African silica sand is suitable for use in rapid sand casting. Nyembwe then made castings with the moulds made from the South African silica sand to test for defects (3). In 2019 Sama et al. (8) conducted different case studies, they discovered that rapid sand casting could resolve shrinkage-related porosity, reduce lead time by nesting multiple cast parts within a single mould as well as offering the unique advantage of design freedom. The only limitation observed was the higher surface roughness. As most rapid sand-casting studies were conducted using silica sand, there is little to no literature on the suitability of South African chromite sand for rapid sand-casting applications.

The Voxeljet VX1000 process requires the sand to be coated prior to printing. The process typically applies the Furun No Bake (FNB) casting process. The FNB process is a self-hardening bonding system using a furan resin and liquid catalyst to cure the resin, in this case sulphonic acid (9). Curing characteristics of sand mixtures are mainly affected by the sand’s Acid Demand Value (ADV), moisture, temperature and resin reactivity as well as addition proportions. Sand with high ADV increases the resin and catalyst additions in order to effectively bond the sand. Moisture and temperature of the sand is directly proportional to the curing rate. High catalyst addition causes the resin to become brittle resulting in a decrease in the cohesiveness of mould and core. Too little catalyst results in longer curing time which then affects the cohesiveness of the mould or core (2).

In traditional moulding, the sand is rammed into the pattern and the pattern is stripped off after a few minutes of curing and allowed to self-cure. The curing time can be decreased by heating the mould in an oven. During rapid sand-casting sand falls freely on the printing bed. A recoater is used to apply a layer of sand on the print bed. Flowability is one of the vital properties in rapid sand-casting as it allows for easy flow of the sand (10). The angle of repose should be less or equal to 45° and the resting period for the coated sand...
should be a minimum of two days to allow for acid evaporation and improved flowability.

The amount of catalyst added is inversely proportional to sand flowability and if the amount is incorrect, can cause the recoater/feed system to clog. Therefore, the catalyst coating should be carefully controlled to ensure the reliability of the printing process. The rapid sand-casting coating ratio is between 0.3% and 0.1% based on the weight of sand. The required bend strength based on voxeljet specification is 220 N/cm². Previous study involved characterization of the sand to ensure the samples complied with rapid sand-casting specifications. Unfortunately, some of these sands did not comply with the required specifications. The specifications for rapid sand casting are in Table 1 below.

TABLE 1: VOXELJET SAND SPECIFICATION (2).

<table>
<thead>
<tr>
<th>Sand Property</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFS GFN</td>
<td>50 – 60</td>
</tr>
<tr>
<td>Grain size distribution</td>
<td>3 – 5 Sieves</td>
</tr>
<tr>
<td>Grain Morphology</td>
<td>Rounded – subrounded</td>
</tr>
<tr>
<td>Acid demand value</td>
<td>≤ 6ml</td>
</tr>
</tbody>
</table>

II. METHODOLOGY

The methodology followed was based on the previous work using silica sand (7) and is summarized in the schematic diagram shown in Figure 1. This section labels the raw materials followed by the experimental procedure in terms of the tests performed.

A. Raw Materials

The raw materials used included four different chromite sand samples from different South African mines available commercially, resin (furfuryl alcohol) and catalyst (aryl sulphonic acid). The resin and catalyst chemicals were both the same as those used in the Voxeljet VX1000 3D printer.

B. Experimental Procedure

1) Flowability

Flowability measures the ability of sand to flow freely and is determined by the angle of repose. In rapid sand casting, the acceptable angle of repose is a maximum 45 degrees. The acceptable range is further broken down into different categories. Angle of repose between 25 and 30 degrees is regarded to as excellent flowability, 31 to 35 degrees is known as good flowability and 36 to 40 degrees is a fair flowability (2). Flowability plays a crucial role in the uniformity of the deposited layers during printing as well as ensuring the least variation in the mechanical motion during recoating of each layer (10).

Following the flowability procedure, sand was first coated with 0.3 wt% aryl sulphonic acid, and mixed for five minutes in a batch mixer or blender. The ASTM C1444 standard procedure for flowability testing was followed to determine the angle of repose of each of the four chromite sand samples. These tests were repeated after 24 and 48 hours as per Voxeljet recommendations to ensure better flowability.

2) Sand preparation and moulding

Traditional moulding processes were conducted to test the efficiency of the whole process before actual printing of sand samples on the Voxeljet VX1000. The sand was first coated with 0.3 wt% aryl sulphonic acid as catalyst, 4% furfuryl alcohol resin was then added and mixed for 5 minutes in a batch mixer/Blender. The mixture was then rammed into tensile, bend and friability patterns and allowed to cure for 10 minutes before stripping. The manufactured samples before stripping are shown in Figure 2. The patterns were then removed and the samples were allowed to self-set or cure for 24 hours. The samples were then heat cured in the oven at 110°C for two hours.

3) Mechanical sand testing

The mechanical tests performed were bend, tensile and friability. Tensile and bend strengths were tested in a universal strength tester to determine if the specimens met the minimum required strength of 220 N/cm². However the strength value as based on silica sand. The bulk density of chromite sand (2.6 g/cm³) is nearly twice the bulk density of silica sand (1.54 g/cm³), therefore the strength should be higher.

Friability measurements were performed following the AFS 248-00-S standard procedure. Two standard 50x50 cylindrical specimen were placed side by side in a rotary screen of the friability meter and it was ensured that the specimens are touching and their ends are in contact with the supporting plate. The machine was then started and allowed to run for 30 seconds while collecting the abraded sand from the surface of the specimens underneath and weighed. Friability measures the ability of the mould or core to resist abrasion during pouring and throughout the solidification process. Friability Percentage is calculated using the equation...
1 below. Good friability value must not exceed 11% otherwise the sand would have a tendency towards dirt defects and a loss of casting surface quality (12).

Loss on Ignition (LOI) indicates the percentage of combustible or gas forming materials in the sand. According to Hussein (11) the LOI content for bonded sand has to be 3% maximum. LOI is mainly affected by the chemical composition of the sand. Bonded sand from tested samples was used to perform the loss on ignition tests. Two samples were tested per sand making them eight LOI samples. The tests were performed according to the AFS 5100-00-S in order to determine the amount of volatile matter or if any gas-forming materials were in the sand. The process involved firing the measured weight of chemically bonded sand in the crucible at 982°C for two hours. The fired samples were then weighed and the difference in weight of the fired and unfired samples was calculated to determine the percentage of LOI. The equation used to calculate % LOI is shown below.

\[
\% \text{ LOI} = \left( \frac{B - C}{B - A} \right) \times 100
\]

Where: 
A = starting weight of empty crucibles 
B = Starting weight of crucible with material. 
C = Final weight of crucible with material after firing and subsequent cooling.

III. RESULTS AND DISCUSSION

This section presents the test results obtained from the four chromite sand samples. The tests performed were flowability, tensile, bend, friability and LOI.

A. Flowability

From the above flowability results in Figure 3, it appears that all tested chromite sand samples complied with the flowability requirement of an angle of repose of less than 45°. It can be seen that the angle of repose decreased as the storage time increased. This decrease was due to acid evaporation resulting from the increased storage time. The angle of repose differed between the sands. Sample B had the highest angle of repose throughout. In the previous characterization studies, it had the highest AFS GFN and bulk density which indicates finer sand. Finer sand increases the angle of repose resulting in poor flowability due to inter-particle cohesion. There was little difference in the grain shape and grain size distribution.

B. Loss on Ignition (LOI)

The LOI results are presented in figure 4. It appears that in all four samples, the LOI values were within the required specifications, of less that 3%.

The LOI values varied slightly with sample C having the highest percentage of 2.54, with fixed resin and catalyst auditions of 0.3 wt% of ary sulphonic acid, 4% furfuryl alcohol. X-ray fluorescent results revealed that sample C did not comply with the standard specifications, containing 43.96% Cr2O3 and 1.36% SiO2. Even though its LOI content was still within the acceptable range, sample C was regarded as low-quality sand as its LOI was close to the maximum permitted.

C. Mechanical Testing Results

The mechanical tests performed were tensile, bend and friability.

1) Tensile strength

...
The tensile strength results in Figure 5 above show that all samples met the voxeljet strength requirement mentioned above. Sample C had the highest strength whilst sample D had the lowest. The strength is mainly affected by the effectiveness of the bonding process which depends on the pH and ADV of the sand. The tensile strength did not differ much between the sands.

2) Bend Strength

Figure 6 above presents the bend strength results. The lowest strength was 353 N/cm² (Sample C) uncured and 460 N/cm² (Sample B) cured. The highest strength for both cured and uncured sands was Sample D with 577 N/cm² and 460 N/cm² respectively. All the samples met the strength requirement for rapid sand casting. The sand with high pH appeared to have low ADV and have the highest bend strength (Sample D).

3) Friability results

The friability results are shown in the graph in Figure 7.

IV. CONCLUSION

The aim of this study was to establish if South African chromite sand could be considered for rapid sand-casting applications using the Voxeljet VX1000 3D printer. Four chromite sand samples were purchased from different local chromite sand suppliers. The Voxeljet binder and activator was used to manufacture the sand specimens. Through sand characterization, it was found that they were of different qualities in terms of physical properties. Furthermore, the flowability behavior, which will be critical during additive manufacturing, showed a minor difference in the samples and all the samples met the flowability requirement for rapid sand casting. The sand samples tested also appear to comply with Voxeljet strength and friability requirement.

The next stage of this ongoing study will be to manufacture a test specimen on the 3D printer available in one of the local research institutions and test them for mechanical properties. Furthermore, the binder and catalyst ratios will also need to be optimized as chromite sand is heavier than silica sand and thus would require more binder and catalyst for the same volume of silica sand. These additional research aspects will finally determine the suitability of the South African chromite sand for rapid sand-casting applications. If successful there will be no need to import sand as it will be proven that our local sand could be used instead.

ACKNOWLEDGMENT

I would like to express my special gratitude to my Supervisor and Co-supervisor (K.D Nyembwe and P.J.M van Tonder) as well as VUT Science and Technology Park team.

REFERENCES

coated sand used in additive manufacturing technologies. North West University.


Assessment and Comparison of Local Silica Sands for Three Dimensional Printing Applications

Oyombo Dady
Metal Casting Technology Station
University of Johannesburg,
South Africa
oday@uj.ac.za

Didier Kasongo Nyembwe
Department of Metallurgy
University of Johannesburg,
South Africa
dnyembwe@uj.ac.za

Malan van Tonder
Technology Transfer and Innovation
Vaal University of Technology,
South Africa
malanvt@vut.ac.za

Abstract - Silica is extensively used as a refractory material due to its properties such as its low thermal expansion, low cost, and higher temperatures resistance. The fast moving of manufacturing technology has forced the implementation of the three-dimensional printing (3DP) into the metal casting industry to improve the product quality and to satisfy customer needs. Unfortunately, this 3DP technology for sand parts production can be successfully accomplished only with the use of specially imported sand. This situation makes the sand production expensive. Previous study was already initiated with the purpose of substituting the imported sand with the Atlantis silica sand which is mined in South Africa. The outcomes have proven that the Atlantis local sand could be successfully used as a substitute and led to the economic production of moulds. This paper is an extension of the previous study aiming to use Consol sand as an alternative material to substitute both the imported and Atlantis sands. Preliminary trials, with Consol sand, have already proven its performances and the outcomes show that these data are comparable to those of Atlantis sand in applications other than the 3DP. The new Consol sand will be first characterized, thereafter its characteristics will be compared to those of Atlantis sand and further determine its use for eventual 3DP application.

Keywords — Silica sand, three-dimensional printing.

I. INTRODUCTION

Three-Dimensional Printing (3DP) in the metal casting refers to the application of additive manufacturing (AM) to produce sand moulds and cores used for metal casting. This technology has become very popular in the 21st century with sophisticated three-dimensional printing (3DP) equipment for metal casting applications. These equipment are used in the production of sand parts such as moulds and cores. This application offers several benefits to foundrymen that include the elimination of tooling in the form of sand pattern and core boxes, the reduction of lead design time in the casting process and topology optimization of complex parts [1]. The 3DP methods used in the mould productions are centered on the resin bonded sand casting process such as the alkaline phenolic, croning and furan processes. Silica sand is locally mined and is one of the widely used refractory sands in metal casting applications. This is due to its large availability worldwide and low price compared to other specialized foundry sands such as chrome, olivine, and zircon sands. Silica sand foundry characteristics include size distribution, grain shape, chemical purity, refractoriness, and acidity level. The characteristics of silica sand ensure that the resin usage is diminished, the mould strength is adequate, and the final castings are well built and without defect [2]. The AM processes are free of sand dampening and mould jointing and squeezing. During the layer-by-layer construction of sand components, sand particles size distribution needs to be narrowed and the fabrication of strong objects are supported by the intrinsic features of silica sand with regards to tighter distribution, finer and spherical shape sand particles. Besides the above-mentioned properties being important, the variety in the sand choice is also a crucial factor in ensuring a cost-effective production of sand parts. For the same reason, the running cost of AM processes was found to be expensive because of the import of silica sand from overseas. In the quest for solving this problem, various studies and experiments have been conducted to prove that local sand could be considered for AM of sand moulds and cores using a 3DP in place of the expensive imported silica sand [2]. In the aim of addressing the above issue, this research expands its scope to find another local sand with better moulding properties besides the sand that was already identified in the previous research as an alternative material to the imported sand [3].

II. METHODOLOGY

Silica sand from various local mines have been the object of analysis in terms of moulding properties in a previous published project conducted on behalf of the National Foundry Network (NFTN) [4]. This publication is largely used as a reference document is South Africa (SA) foundries. In the present research, two of the silica sands in the above study are assessed once more and compared with the focus on their suitability to 3D printing applications. The first one, identified as Atlantis sand, was sourced from Vaal University of Technology-Technology Transfer and Innovation (VUT-TTI) center. Atlantis is the sand initially proven to be an alternative to the imported sand. The second sand is named Consol sand, also sourced from the same technology center and was selected because of its good reputation among other sands that were recently tested at the University of Johannesburg as part of a survey commissioned by the National Foundry Network (NFTN) agency [4]. And, this sand has proven to show good response during AM trials using a 3DP technology available at VUT-TTI center. It should be noted that the 3DP technology for sand parts production is a sophisticated binder jetting mechanism consisting of a liquid binder deposited successively on layer after layer of sand, pre-coated with a liquid catalyst [5]. Despite the constraint associated with the usage of high-quality sand such as Atlantis and Consol sands, nowadays the 3DP technology has found application in casting industry over the conventional method since it is considered to be a rapid process [3]. From previous studies specific sands used for 3DP are characterized by exceptional mechanical properties. For instance, Nyembwe et al 2016 described the...
mechanical properties (tensile [75 N/cm²] and transverse [240 N/cm²] strengths) for sand prompt to be used in a 3DP type Voxeljet VX1000 [3].

The experimental work was carried out in the characterization of refractory sands. Test procedures recommended in the American Foundry Society (AFS) handbook were followed during sand testing [6].

A. Characterisation of refractory sands
The two selected foundry sands were tested for the following properties:

- Size distribution
- Particle size distribution (AFS number and AGS)
- Loss on ignition
- pH
- Acid demand value (ADV)
- Sintering point
- Clay content
- Bulk density
- Specific gravity
- Silica content
- Grain morphology
- Moisture

In order to determine all the properties presented above, the American Foundry Society of mould and core testing procedures were carried out. Three runs were used in the current investigation to validate the quality of results. The grain shape or grain morphology and the chemical composition were determined using a X-ray fluorescence (XRF) and a scanning electron microscope (SEM). The refractory materials were received as already pre-coated with an acidic catalyst.

III. RESULTS

A. Grain Morphology
B. Particle distribution

![Particle size distribution graph]

![Grain morphology images]

Fig. 1: Grain morphology of the raw Atlantis sand on the left and raw Consol sand on the right. Particle size distribution. Both sands were captured at 25X.

Fig. 2: Particles distribution of both raw sands

C. Properties of silica sands

**TABLE 1 TABLE OF PROPERTIES OF RAW SANDS**

<table>
<thead>
<tr>
<th>Sand Properties</th>
<th>Consol sand</th>
<th>Atlantis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid Demand Value [ml]</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>AFS Grain Fineness</td>
<td>55</td>
<td>67</td>
</tr>
<tr>
<td>Average Grain Size [μm]</td>
<td>251</td>
<td>257</td>
</tr>
<tr>
<td>Bulk Density [g/ cm³]</td>
<td>1.62</td>
<td>1.69</td>
</tr>
<tr>
<td>Loss on Ignition [%]</td>
<td>0.60</td>
<td>0.40</td>
</tr>
<tr>
<td>pH</td>
<td>3.74</td>
<td>6.39</td>
</tr>
<tr>
<td>SiO₂ [%]</td>
<td>98.14</td>
<td>97.4</td>
</tr>
<tr>
<td>Sinter Point [°C]</td>
<td>1600</td>
<td>1600</td>
</tr>
<tr>
<td>Specific Gravity [g/cc]</td>
<td>2.65</td>
<td>2.59</td>
</tr>
<tr>
<td>Total Clay Content [%]</td>
<td>0.46</td>
<td>0.78</td>
</tr>
<tr>
<td>Moisture [%]</td>
<td>0.24</td>
<td>0.1</td>
</tr>
</tbody>
</table>
D. Sand properties evaluation

<table>
<thead>
<tr>
<th>Sand Properties</th>
<th>Consol sand</th>
<th>Atlantis sand</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid Demand Value [ml]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFS Grain Fineness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Grain Size [µm]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Density [g/ cm³]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss on Ignition [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂ [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinter Point [°C]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Gravity [g/cc]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Clay Content [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 shows various refractory sand properties. Noticeable and appreciable differences between the two silica sands can be observed regarding these characteristics. A comparative approach using symbols ‘high’ and ‘low’ are used in Table 2 to differentiate the level of each property between these two moulding aggregates. Since foundry sand is at the heart of the sand casting process, these properties ensure in one way or another that the moulding sand holds a shape well and captures the fine details of a casting, provide enough permeability to allow gas escape during casting, smooth mould or core surface and strength that allows the sand part to maintain its integrity during casting operation [7].

4. DISCUSSION

The stereo microscope grain morphology images of both Consol and Imported sand sands are presented in Figure 1. Ideal sand in terms of grain morphology is sand with rounder particles than sand with angular particles. Generally, sand with round or spherical crystals packs better than angular and elongated sand grain shape sands. The former type of sand will generally produce much denser and strong moulds than the latter type of sand [8].

The particle size distribution of the sands describes the spread of sand particles. Figure 2 shows the distribution of the particles of both refractory materials portraying wider normal distributions. For 3D applications, a narrower spread is preferable over the wider one. The latter distribution could possibly prevent sand particles segregation during 3D printing and negatively impacting the sand parts quality [9].

The loss on ignition property of silica sand provides an indication of combustible substances or impurities present in the bulk sand. This characteristic is ideal when sand yields a low value of LOI preventing excess gas generation during casting that could cause gas-related defects which will affect the quality of the final casting [10].

Both the pH and ADV measure the level of acidity or basicity in the sand. Although they measure the same thing, the nuance between these two properties is that water-soluble impurities will change the pH more than the ADV and the insoluble contaminants in the sand may have a larger impact on the ADV. The change in these two properties in the sand certainly impacts the performance of the binder system being used in the mould and core production [11]. An increase in ADV suggests that the sand contains a higher amount of alkaline impurities which will react with the catalyst of cold-setting, acid-catalysed binders. Moulding aggregate with higher ADV is preferable in the alkaline resin binder system. In the acid binder system such as furan, a lower ADV is therefore adequate. An improper combination between ADV and the pH of the sand leads to a neutralization reaction hence bonding of sand will not be achieved [12].

Particle size distribution (PSD) and the average grain size (AGS) give an indication of sand particles size. Although PSD and AGS are all useful, the choice of refractory sand is mostly based on the PSD, as the size distribution affects the quality and properties of casting produced. Mould permeability and surface smoothness are the properties the most affected by the PSD. The higher the PSD the coarser the moulds with finer crystals is highly preferred to prevent jamming of the 3D printer re-coater. In the case of 3D printing of sand moulds and cores sand with finer crystals is highly preferred to prevent jamming of the 3D printer re-coater.
The specific gravity of sand is considered to be a measure of the strength or quality of the material. The specific gravity helps in the identification of sand. Specific gravity is important for several reasons. Some deleterious particles are lighter than the good aggregate. Tracking specific gravity can sometimes indicate a change of material or possible contamination. The difference in specific gravity may be used during production to separate the deleterious particles from the good using a media liquid. Specific Gravity is the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water. Low specific gravity explains the presence of air voids in the bulk sand and these voids determine the level resin absorption during moulding [15].

Curing of and strip characteristics depend on factors as ADV, binder reactivity, amount of resin, the temperature of components, and moisture content, humidity, and water content in the resin and catalyst. Moisture in the sand dilutes the acid catalyst and slows the condensation-type curing reaction. Sand with a higher amount of moisture conceivably slows the cure rate, lowers cured strength, decreases flowability, and produces inferior through-cure property [16]. For these reasons, the amount of moisture in the refractory sand should maintain as low as possible.

The clay content test measures the percentage of fine particles in the refractory sand. These particles are generally of clay types in silica sands. The presence of fine particles in the sand decreases the sand refractoriness, permeability and increases the chemical binder requirements. It is therefore important to limit or lower the amount of clay content to a lower level [17].

IV. CONCLUSION

The aim of any manufacturing operation is to produce good products, affordable at relatively low production costs. The production of sand parts such as moulds and cores, raw materials such as silica has to meet specifies foundry requirements to assure smooth and successful operation. These sand properties affect in one way or another the sand behavior either in the foundry traditional production method or in the additive manufacturing using 3D printing to produce sand parts. There is no single property superior to another one, in fact, all these properties or characteristics are crucial in the material selection. Looking into the properties’ evaluation data and the influence of each property for a possible 3D applications success, Consol sand appears to have superiority over Atlantis sand. This does not imply that Atlantis sand is presently a poor-quality material. An absolute conclusion on the superiority of one sand over another can only be drawn once sand components are printed from both sands and physical assessment carried thereafter.

REFERENCES

Additive Manufacturing Post Processing and Qualification
Dimensional Error Testing of 3D Printed Samples after Sterilization for Orthopedic Surgery

Leon Kotze  
Institute for Biomedical Engineering (IBE)  
Stellenbosch University (SU)  
Stellenbosch, South Africa  
20008392@sun.ac.za

Johan van der Merwe  
Institute for Biomedical Engineering (IBE)  
Stellenbosch University (SU)  
Stellenbosch, South Africa  
jovdmerwe@sun.ac.za

Rudolph Grobler Venter  
Division of Orthopedic Surgery  
Stellenbosch University (SU)  
Stellenbosch, South Africa  
rvgventer@sun.ac.za

Abstract — The purpose of this study was to investigate the dimensional accuracy of 3D printed samples after ethylene oxide (EtO) or autoclave sterilization to show material and sterilization compatibility for 3D anatomical models used as intraoperative references in a public healthcare system. Samples were 3D printed in acrylonitrile butadiene styrene (ABS), nylon, and polylactic acid (PLA), and sterilized using EtO and autoclave sterilization. Afterward, samples were measured with a digital vernier caliper for dimensional error testing. EtO sterilization had a minimal effect on nylon (0.012 ± 0.126 cm³) as opposed to PLA (-0.089 ± 0.193 cm³) and ABS (-0.085 ± 0.102 cm³), which both shrunk in mean volume differences. PLA (-0.219 ± 0.224 cm³) was the most affected by autoclave sterilization whereas ABS (-0.081 ± 0.398 cm³) and nylon (-0.055 ± 0.159 cm³) showed less shrinkage in mean volume differences. Therefore, nylon may be a suitable material to use in both EtO (preferably) and autoclave sterilization techniques as opposed to ABS and PLA materials.

Keywords — additive manufacturing, dimensional accuracy testing, ethylene oxide, autoclave, intraoperative references (keywords)

I. INTRODUCTION

A. Background

Orthopedic surgeons generally use visual perception to interpret conventional imaging modalities such as X-ray (two-dimensional) and computed tomography (CT) or magnetic resonance imaging (MRI) scans (three-dimensional) to pre-operatively plan surgical procedures. However, haptic perception (sense of touch), plays an important role in how orthopedic surgeons diagnose and evaluate their patient’s bone anatomy or pathology of interest [1].

The use of three-dimensional printing (3DP) provides orthopedic surgeons with a direct three-dimensional (3D) representation of their patient’s musculoskeletal disorders and trauma by allowing haptics to complement visual sources of information such as CT or MRI scans [1]. Additive manufacturing (AM) creates a physical 3D object by adding material layer-by-layer from virtual 3D models [2], [3]. The use of AM technologies has become more prevalent in various medical specialties, especially in the field of orthopedics [4].

Image processing software packages and 3DP technologies to extract and create 3D anatomical models have become very affordable and more user-friendly for use in orthopedic applications [5]. Biomedical engineers and surgeons frequently use volumetric imaging data (CT/MRI scans) to virtually segment 3D anatomical models with image processing software packages such as 3D Slicer (Slicer Community) and Rhino3DMedical (Mirrakoi SA, Switzerland). Furthermore, the segmented region of interest (ROI) is used to design patient-specific instruments (PSIs), e.g. surgical cutting guides (SGC), drill templates or jigs, and implants or prostheses with AM, reverse engineering (RE), and computer-aided design (CAD) software packages, which can then be 3D printed by utilizing AM technologies [6].

The Advanced Orthopedic Training Centre (AOTC) is a world-class orthopedics training facility that hosts the Division of Orthopedic Surgery at Tygerberg Hospital, South Africa. An orthopedic 3DP laboratory is situated at the AOTC, which includes image processing software packages and Fused Filament Fabrication (FFF) 3D printers to segment and fabricate 3D anatomical models from volumetric imaging data (CT/MRI scans) for use in pre-surgical rehearsal.

Orthopedic surgeons at the division have identified numerous ways in which medical 3DP and the use of 3D printed anatomical models can improve traditional visual-only surgical planning techniques by adding haptic perception to their pre-operative planning process. Therefore, surgeons can rehearse complex surgical procedures with the actual implants or prostheses on life-size reproductions of their patient’s bone anatomy or pathology with no patient morbidity [7].

B. Motivation

Orthopedic surgeons may require sterilized 3D anatomical models for use as intraoperative references to guide surgeons during surgery. 3D printed anatomical models are used to improve precise implant or prosthesis placement [8] and better surgical outcomes in orthopedic surgery [6].

For use in an operating room environment, 3D printed anatomical models need to be adequately sterilized. However, there exists minimal knowledge on the use of various sterilization techniques, e.g. Ethylene Oxide (EtO) and autoclave sterilization, on 3DP filament materials used to fabricate 3D anatomical models, which may affect and transform the 3D geometrical shape of these models [9].

C. Aim

This study aimed to investigate the dimensional accuracy of samples 3D printed in ABS, nylon, and PLA filaments, after EtO or autoclave sterilization to show material and sterilization compatibility for 3D anatomical models used as intraoperative references during orthopedic surgery.
II. METHODOLOGY

A. Dimensional Error Testing Apparatus and Technique

Autodesk Inventor (Autodesk Inc., San Rafael, CA, USA) was used to design various 3D objects, including a solid cube, a modified cube with rectangular indents on each of its faces, a solid elliptical cylinder, and a thin-walled, hollow elliptical cylinder, with dimensions shown in Figures 1 to 4. The part files were subsequently converted to the stereolithography (STL) file format before being uploaded into slicing software packages, e.g. Z-Suite (Zortrax, Poland) and Simplify3D (Simplify3D, Ohio, USA). The software selected was specific to the 3D printer that was chosen to prepare a unique set of printing instructions (code), to print the samples. In each case, a 50% interior infill percentage was specified. Samples were 3D printed in ABS, nylon, and PLA filament, each with their associated FFF 3D printer, namely the Zortrax M200 and Zortrax M300 Dual (Zortrax SA, Olsztyn, Poland), and Leapfrog Bolt Pro (Leapfrog Co., Alphen aan den Rijn, Netherlands), respectively. In total, two sets of eighteen samples of each type of 3D object were printed from ABS, PLA, and nylon.

After printing, dimensional error testing was performed by using a digital vernier caliper to measure the dimensions of each sample as shown in Figures 1 to 4 to estimate their volume in cubic centimeters (cm³). After the first set of measurements were performed, the 3D printed samples were sent to the Central Sterilization Service Department (CSSD) of Tygerberg Hospital for sterilization. Eighteen samples of each type of 3D object were sterilized using low-pressure EtO and autoclave sterilization respectively, according to the parameters shown in Table 1. Afterward, the 3D printed samples were retrieved and measurements were repeated to obtain post-sterilization volume estimates. Figure 5 summarizes the method for dimensional error testing.

<table>
<thead>
<tr>
<th>Type of sterilization</th>
<th>EtO sterilization</th>
<th>Autoclave sterilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-pressure (cold cycle) temperatures and duration.</td>
<td>45 °C for 8 hours.</td>
<td>121 °C for 15 mins. (1 cycle = 45 – 55 mins).</td>
</tr>
<tr>
<td>Aeration duration.</td>
<td>3 – 4 hours.</td>
<td></td>
</tr>
<tr>
<td>Cooling duration.</td>
<td>10 – 20 mins.</td>
<td></td>
</tr>
</tbody>
</table>

B. Ethylene Oxide (EtO) Sterilization Technique

Prior to EtO sterilization, each 3D printed sample was individually wrapped by placing it in a vacuum chamber and packed separately in a labeled sterilization bag. The EtO sterilization bags were loaded loosely at full capacity in the EtO sterilizer to facilitate air removal, humidification, EtO circulation, and penetration of all 3D printed surfaces. Each EtO sterilization bag with its associated 3D printed samples was sterilized by using the cold cycle method at 45 °C for 8 hours.
A. Ethylene Oxide (EtO) Sterilization Dimensional Error Testing

Table 2 shows the changes in estimated volume after 3D printed samples made from ABS, nylon, and PLA filaments were exposed to low-pressure EtO sterilization. The volume difference of the aggregate ABS sample group after sterilization was $-0.085 \pm 0.102$ cm$^3$, while the mean absolute percentage error was 1.811 $\pm$ 1.675%. For the nylon group, the mean volume difference and absolute percentage error were $0.012 \pm 0.126$ cm$^3$ and $1.616 \pm 2.149\%$, respectively. The PLA group showed a mean volume difference of $-0.089 \pm 0.193$ cm$^3$ and an absolute percentage error of 2.703 $\pm$ 4.157%. All samples from the ABS object types exhibited significant changes in volume after sterilization.

### TABLE III. CHANGE IN ESTIMATED VOLUME AFTER AUTOCLAVE STERILIZATION.

<table>
<thead>
<tr>
<th>Object Type</th>
<th>Volume Difference (cm$^3$)</th>
<th>Percent Error (%)</th>
<th>Volume Difference (cm$^3$)</th>
<th>Percent Error (%)</th>
<th>Volume Difference (cm$^3$)</th>
<th>Percent Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>-0.041</td>
<td>0.073</td>
<td>0.038</td>
<td>0.545</td>
<td>0.048</td>
<td>0.475</td>
</tr>
<tr>
<td>Cube</td>
<td>-0.064*</td>
<td>0.624</td>
<td>0.054*</td>
<td>0.475</td>
<td>-0.057</td>
<td>1.290</td>
</tr>
<tr>
<td>Modified</td>
<td>-0.113</td>
<td>2.090</td>
<td>0.013</td>
<td>1.507</td>
<td>-0.069</td>
<td>2.037</td>
</tr>
<tr>
<td>Cube</td>
<td>0.070*</td>
<td>1.286</td>
<td>0.124</td>
<td>1.496</td>
<td>0.170</td>
<td>2.067</td>
</tr>
<tr>
<td>Solid</td>
<td>-0.112</td>
<td>4.906</td>
<td>-0.003</td>
<td>1.011</td>
<td>-0.151</td>
<td>1.754</td>
</tr>
<tr>
<td>Elliptical Cylinder</td>
<td>-0.125*</td>
<td>0.961</td>
<td>0.116</td>
<td>1.023</td>
<td>0.111*</td>
<td>0.966</td>
</tr>
<tr>
<td>Hollow</td>
<td>-0.076</td>
<td>2.931</td>
<td>-0.003</td>
<td>3.298</td>
<td>-0.077</td>
<td>3.742</td>
</tr>
<tr>
<td>Elliptical Cylinder</td>
<td>0.113*</td>
<td>2.469</td>
<td>0.167</td>
<td>3.374</td>
<td>0.310</td>
<td>7.085</td>
</tr>
<tr>
<td>Grouped</td>
<td>-0.085</td>
<td>1.811</td>
<td>0.012</td>
<td>1.616</td>
<td>-0.009</td>
<td>2.703</td>
</tr>
<tr>
<td>Distrib.</td>
<td>0.102</td>
<td>1.675</td>
<td>0.126</td>
<td>2.149</td>
<td>0.190</td>
<td>5.175</td>
</tr>
</tbody>
</table>

*p < 0.05

B. Autoclave Sterilization Dimensional Error Testing

The changes in estimated volume after low-pressure autoclave sterilization are shown in Table 3. The mean volume difference of the ABS group was $-0.081 \pm 0.398$ cm$^3$, with an absolute percentage error of 4.624 $\pm$ 8.524%. The grouped distribution of the nylon objects exhibited a mean volume difference of $-0.055 \pm 0.159$ cm$^3$ and an absolute percentage error of 2.319 $\pm$ 2.664%, respectively. The PLA group showed a mean volume difference of $-0.219 \pm 0.224$ cm$^3$ and an absolute percentage error of 4.341 $\pm$ 4.622% after autoclave sterilization. All samples from the individual object types manufactured from PLA showed significant changes in volume.

### TABLE II. CHANGE IN ESTIMATED VOLUME AFTER ET0 STERILIZATION.

<table>
<thead>
<tr>
<th>Object Type</th>
<th>Volume Difference (cm$^3$)</th>
<th>Percent Error (%)</th>
<th>Volume Difference (cm$^3$)</th>
<th>Percent Error (%)</th>
<th>Volume Difference (cm$^3$)</th>
<th>Percent Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>-0.035</td>
<td>1.590</td>
<td>0.021</td>
<td>0.301</td>
<td>-0.140</td>
<td>1.844</td>
</tr>
<tr>
<td>Cube</td>
<td>-0.021</td>
<td>0.217</td>
<td>0.131</td>
<td>0.926</td>
<td>0.070*</td>
<td>0.896</td>
</tr>
<tr>
<td>Modified</td>
<td>0.020*</td>
<td>1.559</td>
<td>-0.070</td>
<td>1.813</td>
<td>-0.104</td>
<td>2.578</td>
</tr>
<tr>
<td>Cube</td>
<td>0.009</td>
<td>0.756</td>
<td>0.164</td>
<td>2.296</td>
<td>0.113*</td>
<td>1.905</td>
</tr>
<tr>
<td>Solid</td>
<td>-0.422</td>
<td>1.767</td>
<td>-0.003</td>
<td>1.080</td>
<td>-0.408*</td>
<td>4.440</td>
</tr>
<tr>
<td>Elliptical Cylinder</td>
<td>0.407*</td>
<td>3.184</td>
<td>0.096*</td>
<td>0.782</td>
<td>0.090*</td>
<td>1.036</td>
</tr>
<tr>
<td>Hollow</td>
<td>-0.160</td>
<td>11.576</td>
<td>-0.096</td>
<td>5.853</td>
<td>-0.216</td>
<td>8.440</td>
</tr>
<tr>
<td>Elliptical Cylinder</td>
<td>0.623</td>
<td>14.110</td>
<td>0.203</td>
<td>3.437</td>
<td>0.346*</td>
<td>7.570</td>
</tr>
<tr>
<td>Grouped</td>
<td>-0.081</td>
<td>4.624</td>
<td>-0.055</td>
<td>2.319</td>
<td>-0.219</td>
<td>4.341</td>
</tr>
<tr>
<td>Distrib.</td>
<td>0.398</td>
<td>6.524</td>
<td>0.159</td>
<td>2.664</td>
<td>0.224</td>
<td>4.452</td>
</tr>
</tbody>
</table>

*p < 0.05

Afterward, the operator used heat-resistant gloves to unload and safely transfer the EtO sterilization bags from the EtO sterilizer to the aeration cabinet to remove any cumulative EtO absorption or residual from the 3D printed samples. Aeration parameters such as temperature and time depended on the amount, size, thickness, arrangement, and weight of the 3D printed samples. Each sterilization bag with its associated 3D printed samples was aerated approximately for 3 – 4 hours.

The operator ensured that the 3D printed samples were adequatly aerated until excess and toxic EtO residues were removed. The EtO sterilization bags were allowed to cool for 10 – 20 minutes before storage or dispensing. Afterward, the EtO sterilization bags were retrieved for further dimensional accuracy testing.

### C. Autoclave Sterilization Technique

During autoclave sterilization, 3D printed samples were exposed to more or less the same sterilization procedure but underwent low-pressure autoclave (steam heat) sterilization. Each 3D printed sample was individually wrapped and packed separately in a labeled autoclave sterilization bag. Afterward, the autoclave sterilization bags were loaded loosely into the autoclave sterilizer to facilitate air removal and ensure steam heat penetration of all 3D printed surfaces. Each sterilization bag with its associated 3D printed samples was sterilized by using the cold cycle method at 121 $^\circ$C for 15 minutes (1 cycle = 45 – 55 minutes). Afterward, the operator used heat-resistant gloves to unload and safely transfer the autoclave sterilization bags from the autoclave sterilizer to the aeration cabinet to remove any cumulative autoclave absorption or residual from the printed samples.

Each autoclave sterilization bag with its associated 3D printed samples was aerated approximately for 3 – 4 hours. The operator ensured that the 3D printed samples were adequatly aerated until excess autoclave residues were removed. Afterward, the autoclave sterilization bags were allowed to cool for 10 – 20 minutes, before the bags were retrieved for dimensional accuracy testing.

### D. Analysis

To determine the morphological changes after low-pressure EtO or autoclave sterilization, the difference in volume was calculated by subtracting the volume estimate of each post-printed sample from its sterilized volume estimate. In this way, negative values indicate shrinkage of the samples after sterilization. Furthermore, the percentage error was determined based on the absolute volume difference, normalized against the post-printed volume.

The measured values of the samples were categorized according to their object type and material. One sample t-tests were performed on the volume differences of each category, assuming a mean error of zero with a probability value of 0.05. The means and standard deviations (SD) for each sample group were determined for both the volume differences and percent errors. Finally, the means and standard deviations were also determined for the aggregate volume differences and percent errors of all samples manufactured from a single material. The results for EtO and autoclave sterilization are shown in Tables 2 and 3, respectively.
IV. Discussion

EtO sterilization had a minimal effect on nylon (0.012 ± 0.126 cm³) as opposed to PLA (-0.089 ± 0.193 cm³) and ABS (-0.085 ± 0.102 cm³), which both shrank in mean volume differences, as shown in Table 2. Furthermore, all ABS object types exhibited significant changes in volume. PLA (-0.219 ± 0.224 cm³) was the most affected by autoclave sterilization whereas ABS (-0.081 ± 0.398 cm³) and nylon (-0.055 ± 0.159 cm³) showed less shrinkage in mean volume differences, as shown in Table 3. All PLA object types experienced significant changes in volume. Nylon was the least affected by either low-pressure EtO or autoclave sterilization, which showed decreased shrinkage and fewer significant differences in mean volume differences. This study investigated the dimensional accuracy of 3D printed objects manufactured from ABS, nylon, and PLA, after EtO and autoclave sterilization.

Popescu et al [10] used low-pressure hydrogen peroxide (H₂O₂) plasma to sterilize a 3D part printed in ABS for surgical use. The study reported a predominantly positive deviation of their non-sterilized ABS test part’s aggregate dimensions with a range of ±0.27 mm when compared to the nominal CAD dimensions. After H₂O₂ sterilization, the test part’s dimensions varied within a reduced range of ±0.20 mm, indicating some shrinkage, although not significant given the small changes. Similarly, while direct comparisons are difficult to make, our results show that the comparatively higher temperature autoclave sterilization process could have contributed to a higher overall change in volume in ABS samples as opposed to a lower temperature EtO sterilization process.

Oth et al [11] used low-pressure gas (H₂O₂) plasma and autoclave sterilization to sterilize SCGs 3D printed in PLA and polyethylene terephthalate glycol (PETG) for surgical use. The study reported that comparisons between the virtually 3D designed guide and 3D printed or sterilized guide, made from PLA and PETG, showed minimal morphological differences at less than 0.20 mm after H₂O₂ sterilization. In addition, they found that autoclave sterilization resulted in parts manufactured from both materials to melt during the higher temperature autoclave sterilization process. Similarly, during our study, PLA parts sterilized using autoclave sterilization resulted in significant volume differences and higher percent errors compared to the lower temperature EtO sterilization process.

In our study, PLA and ABS were the most affected by EtO and autoclave sterilization, which both exhibited shrinkage in mean volume differences. Similarly, previous studies indicate that ABS and PLA are more likely to deform after a higher temperature sterilization technique such as autoclave sterilization compared to a lower temperature sterilization technique such as H₂O₂ sterilization [9]–[11]. Although 3D printed samples showed less deformation after EtO sterilization compared to autoclave sterilization, the use of EtO sterilization may lead to the onset of molecular weight loss and changes in polymer structures which creates a toxic deposit on the surface of the object. Conversely, H₂O₂ sterilization has proved to be an effective and safe solution that does not produce toxic residues or requires aeration time [11], [12].

The authors are not aware of a similar comparative study between 3D objects printed from ABS, PLA, and nylon and subsequently sterilized via autoclave and EtO techniques in current literature. Therefore, this work aimed to contribute to the available literature in the field.

V. Conclusions

Autoclave sterilization affected ABS and PLA to a greater extent with regard to changes in volume compared to EtO sterilization. The volume of nylon objects was less affected regardless of the sterilization method. Therefore, nylon proved to be a suitable material to use for both low-pressure EtO and autoclave sterilization, as opposed to ABS and PLA materials, for 3D printed anatomical models intended to serve as intraoperative references.

Further research is still required to determine how 3D objects, using other materials such as high impact polystyrene sheet (HIPS), polyvinyl alcohol (PVA), PP (polypropylene), and ULTRAT (acrylonitrile-butadiene-styrene copolymer), are affected after high- and low-pressure autoclave, EtO, or H₂O₂ sterilization for intraoperative navigation and surgical use.

REFERENCES


Importance of Characterizing the Variability for Batch Production using Laser Powder Bed Fusion

Cindy Sithole  
Dept. Design, Production and Management  
University of Twente  
Enschede, Netherlands  
c.sithole@utwente.nl

Ian Gibson  
Dept. Design, Production and Management  
University of Twente  
Enschede, Netherlands  
i.gibson@utwente.nl

Sipke Hoekstra  
Dept. Design, Production and Management  
University of Twente  
Enschede, Netherlands  
s.hoekstra@utwente.nl

Abstract—Additive Manufacturing (AM) of metals is passing the research stage and finding application in the industrial environment as a manufacturing technology of choice. However, the quality of products fabricated using metal AM technology could be considered inferior when used in batch manufacturing. Quality is generally defined as conformance to specification and is inversely proportional to process variation. Variation in a process signifies the number of possible defects per million opportunities in a given production. This gives rise to the need to characterize process variation to improve quality. This paper explores the characterization of variability in laser powder bed fusion (LPBF) AM of metals to improve the quality of part production with specific focus on batches. It summarizes the factors that influence the variation and discusses the tools used to improve part quality.

Keywords—Laser powder bed fusion, Characterization, Variability, Batch Production

INTRODUCTION

Laser powder bed fusion (LPBF) is an additive manufacturing (AM) technology being increasingly adopted in highly regulated manufacturing sectors for metal fabrication [1]. LPBF for metal part production presents many benefits among which is small batch production of customized and complex shapes without the need for additional tooling. Components produced using LPBF are expected to have increased quality from the production stage due to the capability of the technology to produce near-net shape products [2]. However, due to the current limitations of LPBF, which are influenced by the complexity of the production systems and the interaction of the machine, processing parameters and the material properties can be produced with unacceptable amounts of variability. Though the technology is proficient to manufacture products with high accuracy and the process parameters can be optimized to improve the consistency and quality of the resultant products, it is still difficult to produce components without any form of disparity [3,4].

One of the definitions of quality is “fitness for use” [5]. It is obtained and validated by the collection and measurement of product features and characteristics that contribute to their ability to meet the stated requirements for the intended application [5],[6]. Different techniques are used to measure and characterize the quality of manufactured products. These techniques are applied to identify variability in the resultant product features and characteristics. Variability in manufacturing is defined as the discrepancy between an actual measure of specific features (characteristics) and the target measure of the characteristic of the product [7,8]. This is also known as the characterization of variability. Although every process has the inherent nature of variation, it must be controlled and kept minimal. The amount of variation in manufacturing is related to the possible defects per million opportunities existing in a given process [6] and, for this reason, variation is related to quality. According to Yang et al. [9], variability in a production environment is inversely related to product quality and in AM is mostly observed in components that are built at the same time from the same CAD model; also known as batch production.

Batch production in AM refers to the production of components in one run. They can be components of similar and or different geometries. As stated by Yang et al. [9], AM components exhibit high variability even though they are built from the same machine with the same conditions. This is identified as one of the challenges of AM technology for batch production. Figure 1 shows a batch production of similar components in a build.

Batch production is a significant industrial application of AM technology that is likely to increase in the future. The quality of the resultant products in metal additive manufacturing is influenced by the commonly complex AM geometries and the many process parameters. The number of process parameters in laser powder bed fusion is approximately 130 [10,11]. These include powder characteristics, build chamber settings, laser characteristics and the melt pool variables. The processing parameters in LPBF have a great influence on product quality, so process parameter optimization and control is used in AM part qualification [12]. Optimal component properties can be achieved by adequately adjusting the processing parameters based around energy density and understanding the melt pool [4]. Variability in LPBF produced components can be observed in surface roughness, geometry and dimensional inaccuracies and microstructures. Understanding and characterizing the process variation in LPBF could assist in finding the sources of discrepancies and eliminating some of

Funded by the National Research Foundation of South Africa (Grant Number: 111611)
the factors that affect product quality and consequently improve technological performance.

This work has studied the effect of characterizing process variability for quality improvement in LPBF technology. It reviewed work that explored the sources of variability in AM, strategies employed to measure variability and deviations in AM technology’s resultant products. It subsequently outlines the tools to demonstrate how variability could be characterized to improve product quality. It further describes the effect of characterizing variability in AM technology.

I. LASER POWDER BED FUSION PROCESS

The most widely used AM technology for metal fabrication is currently LPBF. It produces metal components layer by layer from 3D computer-aided design (CAD) software descriptions. CAD models are transformed into a STL file in the form of a triangular surface mesh appearance suitable for the LPBF machine. The AM machine has slicing software and a building platform with hardware controls. The STL file is sliced by the machine software into ultrathin layers in conjunction with commands custom-made to the specific AM machine [13]. This transformation of the CAD model into a machine-readable file is one of the features of the process which involves the choice of the slicing step and the algorithm for making the layers. The LPBF process is simply defined in figure 2. After slicing, fabrication occurs in the machine chamber where the ultrathin layers of the part are deposited as a powder onto a build plate (a substrate for parts fabrication) which is selectively melted by a high energy laser to make a solid component.

LPBF technology comprises powder delivery and energy delivery systems. The powder delivery system contains a powder supply piston, a recoater to spread the powder layers and another piston that holds the manufactured part in place until the end of the process [11]. During manufacturing, the piston that holds the parts in place goes down and the powder supply piston goes up at a similar distance to the layer thickness. The recoater deposits the new layer of powder across the bed in the build chamber [14,15]. Figure 3 shows a typical LPBF process. The energy delivery system has a laser scanner with optics within the build platform that permits the delivery of focused energy to all points as defined by the STL file [11]. This energy system is responsible for selectively scanning the powder and forming a melt pool that rapidly solidifies.

During production, gas is passed over the powder bed to protect the parts from oxidation, reduce the effect of spattering and disperse fumes that occur during production [11,16]. The powder delivery system needs to maximize the flow of the powder, reduce particle cloud formation in the build chamber and minimize shear forces over previous layers during production [15]. Interactions between these systems take place in the machine build chamber. Although these systems must be individually explained, they also need to be understood synergistically to understand their influence on product quality. The previously defined components serve as fundamental elements in every commercial LPBF system. Moreover, outlining these systems, in general, provides a basis for understanding and drawing knowledge of the process. This process knowledge is needed for defining and correlating process parameters with part quality.

LPBF for metal production has many process parameters. However, the most critical are laser power, scan speed, scanning strategy, hatch-spacing (distance between the laser tracks) and the thickness of the powder layers [2,11]. These process parameters affect the mechanical and physical properties of the resulting metal parts, including their densities and the level of residual stress formed during manufacturing. The above-mentioned process parameters somehow control the interactions of the systems and are critically involved in the complex physics of the process such as absorption and transmission of the laser energy, causing rapid melting and cooling [17]. Most literature has focused on the understanding of the process parameters through correlation studies, while others have looked at defects formation and influencing process parameters [17,18,19]. Process parameter definition and understanding in manufacturing is a critical factor towards maximizing the quality of the resultant products. The LPBF process can be characterized by the morphology and particle size distribution of the material used [15], the machine parameters and the energy source characteristics. The energy source, including how it is applied, influences the characteristics of the melt pool [13]. The definition and characterization of the process parameters may be different for each machine type due to specific features and applied software. Moreover, understanding the interactions within these systems increases control of the whole process. Defects in LPBF could be characterized by location, size and nature of the occurrence.

Fig. 2. The general AM process modified from [13]

Fig. 3. The LPBF production system [15]
II. DEFECTS IN LASER POWDER BED FUSION

Defects and discrepancies in LPBF technology occur either during manufacturing or following the post-processing of products [18] and are only observed after fabrication. They can be initiated at any stage of the process depending on the production layout and part designs. The identification of defects occurring in LPBF could potentially assist in classifying which defect occurs and how they occur during fabrication and which ones arise after post-processing. This knowledge is significant for improving the manufacturing technology and the quality of the product in general.

Some defects in LPBF occur due to the nature of production such as residual stresses which can be managed by controlling the properties of the material to be fabricated, the heat transfer between the material layers and the chamber atmospheric conditions [20]. Defect formation and its mechanisms can never be studied enough due to the availability of diverse LPBF machines with different features that control the process parameters [16, 17, 21]. Table 1 summarizes defects observed in metal AM technology and their categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Defect</th>
<th>Contributing parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical and dimensional</td>
<td>Shrinkage defect, size distortions</td>
<td>Staircase effect Machine parameter, building direction</td>
</tr>
<tr>
<td>Surface quality</td>
<td>Balling effect Surface roughness.</td>
<td>Laser power, scan speed, layer thickness.</td>
</tr>
<tr>
<td>Microstructural defects</td>
<td>Porosity, Lack of fusion and cracks</td>
<td>Laser power, scan speed and scanning strategy</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td>Cracks, holes, low strength etc.</td>
<td>Laser power, Scan speed and scanning strategy</td>
</tr>
</tbody>
</table>

The geometrical and dimensional defects in LPBF are attributed to the staircase effect and machine parameters, shrinkage, building direction, microstructural distortion and gas flow [11, 17]. The staircase effect occurs due to the geometrical approximation of a curved surface [18], which is observed in the process as the layer offset, resulting in a rough product surface. The staircase effect is influenced by the layer thickness and the geometrical orientation before production.

The cyclic heating that occurs during LPBF also leads to thermal shrinkage, which affects the dimensional accuracy of resulting AM parts. The surface quality is affected by the original powder, the balling effect during melting and surface distortion. Various process parameters influence these defects in powder bed fusion including laser power, scan speed and strategy, layer thickness and powder deposition defined by the layer thickness. The balling defect results due to the capillary instability of the melt pool and can lead to increased surface roughness and porosity [14,11]. The rapid heating, melting and cooling of the LPBF process together with the defined process parameters affect the microstructure which consequently affects the quality of resultant parts.

Microstructural defects can be described in terms of porosity, lack of fusion and cracks [16,17]. Porosity is the main defect affecting the microstructure and influences the initiation spot for material failure and a fracture point. Inappropriate selection of processing parameters affects the microstructure and influences porosity [22]. Some industries require parts with a specified level of porosity. However, due to the challenges in LPBF technology, it is at times not easy to achieve that level. According to Kim and Moylan [22], porosity in AM parts can be characterized as a defect or intentionally induced, based on the part’s application. For the context of this paper, porosity is characterized as a defect occurring due to variability in the production technology. Figure 4 shows a microstructure of Ti-6Al-4V manufactured using LPBF with porosity.

![Fig. 4. Ti-6Al-4v Microstructure with porosity obtained using SEM](image)

The porosity shown in Figure 4 consists of small, spherical pores and is influenced by the packing density of the powder and the melt pool temperature [16]. Process parameters such as hatch spacing, laser spot size, scan speed and laser power can also result in microstructural defects [21]. Other discrepancies observed in LPBF relate to mechanical properties resulting from lack of fusion which can be observed as holes, insufficient bonding between the layers, low strength and porosity [13,17]. It is imperative to be able to accurately characterize between microstructural defects and mechanical defects to adjust the process parameters accordingly. Quantitative methodologies can be applied to analyze the effect of the characterized variability in LPBF technology.

III. CHARACTERIZATION OF VARIABILITY IN LPBF

The characterization of discrepancies in LPBF is critical for process improvement and quality control. Due to the application of AM technology in highly regulated industries, AM parts are often manufactured based on defined tolerances governed by manufacturing standards. Standards are made to safeguard manufactured products and to ensure that they meet the required quality as defined by the industry. Tolerances are used to define the design intent and to prevent misrepresentation of the product [23]. To validate that manufactured parts are fit for use, products are measured against those defined tolerance limits [24]. According to Thompson et al [24], tolerance limits are specified values of part characteristics and they include upper and lower limits. Products that do not meet the specified limits are either
reworked through post-processing or discarded based on the degree of variability.

The selection of the measurement system and the characterization technique gives an insight into the capability of the production technology and the quality of the resultant products. Different measurement techniques and tools are applied for characterizing variability and discrepancies in the modern manufacturing environment and advanced tools are developed for AM part analysis [22].

The production of complex and freeform shapes enabled by AM technology at times imposes challenges for quality control. However, in recent years many tools have been developed for AM parts measurement. Measurement techniques such as X-ray computed tomography (XCT), digital image correlation (DIC) and scanning electron microscopy (SEM) have been used to characterize the microstructure and mechanical properties of LPBF parts [22,24]. These techniques can account for the complexity of AM parts and can effectively access internal features better than conventional part measurement systems.

XCT is a measurement technique that captures x-ray images around an axis of rotation and forms a three dimensional (3D) representation of the actual object [24]. This technique uses algorithms to reconstruct a 3D model by scanning the part and moves over a full 360° to acquire data for the whole object [24]. XCT can be used to measure internal and external disparities such as porosity, surface roughness and dimensional deviation for LPBF parts [24,25,26]. The use of XCT scans for characterization is one of the efficient and economic methods since data is collected without damaging the part.

DIC is a non-contact measurement method that involves acquiring images of an object and conducts image analysis to extract information about the shape, deformation and displacement of the object [27]. During measurement analysis, DIC tracks the movement of the surface pattern by analyzing its displacement within the facet elements of the image [26,27]. DIC can be used for characterizing thermal expansion, general material deformation and mechanical properties [28].

SEM is a widely used measurement technique for characterizing material surfaces. It assists to visualize distortions and material defects including their location in the microstructures. SEM involves a source of electrons and electromagnetic optical lenses, electron detectors and a sample chamber including a movable stage and computers to display sample images during measurement [29,30]. During characterization, the electron beam passes through a combination of lenses and open spaces to produce an acceptable beam of electrons. The electron beam comes in contact with the surface of the sample under a vacuum. The sample surface is scanned by moving the electron-beam coils [29].

Product analysis using SEM is subject to sampling as a representation of the total number of produced parts and samples are often sectioned [30]. Once sectioned they can no longer be used. This technique can be considered ineffective economically and not sustainable since the tested sample cannot be used again. The application of these techniques has indicated how the process is performing and which process parameters are affecting the technology’s productivity.

These measurement tools provide the size, location and nature of variability in LPBF parts. This information is then correlated to assess which parameters in the process are responsible for the variability. This is one of the important techniques for improving AM parts qualification and the technology at large. Geometrical and dimensional measurement techniques such as Coordinate Measurement Machine (CMM) and Three-dimensional scanners (3D scans) and other techniques such as digital Vernier’s are being used to characterize geometrical and dimensional variability [31]. Although probing measurement machines are slow, they can provide maximum measurement accuracy [31].

Variability characterization has a pivotal role in batch production (production of more than one part at the same time) and quality improvement as a whole. Although the characterization of variability can be performed in any production environment, it is more visible in batch production. In batch production, variability can easily be characterized from part to part and/or batch to batch and so could lead to process improvement. The focus of characterizing variability is to identify and distinguish it due to the inherent nature of the process based on the special factors within the production technology [26,32]. Variability due to the inherent nature of production can only be reduced by redesigning the process [33], while variability due to special factors can be better understood and reduced by applying statistical process control (SPC) methods. It is also important to note that variability due to process design and technology is minimal when compared to variability due to special factors within the process.

IV. CONCLUSION

Process variability is related to accuracy and product quality. Quality is one of the key factors driving productivity, efficiency and competitive advantage. Variability measurement and characterization are some of the techniques used to measure the capability of the processor technology to produce products with adequate quality and to initiate process improvement projects. This paper presented a theoretical work focusing on the significance of characterizing variability in LPBF AM technology. It described the common discrepancies in LPBF as a result of variability and the characterization techniques that can be employed to measure the quality of resultant parts. Variability in LPBF should be kept minimal and be monitored.

Although this paper listed some of the tools used to characterize the microstructural and mechanical properties, future work will include the implementation of the described characterization techniques for components manufactured using LPBF technology. Design of experiments will be employed for process parameter optimization. The results obtained after characterization will be correlated to the process parameters to outline the overall quality of the products and how the process parameters affect that quality. The future work will also look at characterizing the geometrical and dimensional accuracy of products in LPBF due to the ease of in-process measurement techniques such as CMM.

ACKNOWLEDGEMENT

This work is based on the research supported by the Department of Design, Production and Management at the University of Twente in the Netherlands.
REFERENCES


Industry’s Adoption of Additive Manufacturing of Spare Parts

Mr. Duwan Bester  
National Laser Centre  
Council for Scientific and Industrial Research  
South Africa  
dbester@csir.co.za

Dr. Lerato Tshabalalala  
National Laser Centre  
Council for Scientific and Industrial Research  
South Africa  
lthabalalal1@csir.co.za

Abstract—The adoption of Additive manufacturing (AM) in South Africa has grown significantly, with more industries investing and investigating the possibility of adoption to their operations. Some of these industries are the railway and mining industries, following the wider demands in the aerospace markets. This paper demonstrates some of the developments that has happened recently, what these industries are investigating, how they go about it, and how they can possibly benefit from adopting the technology. The paper concludes that there are many advantages in using AM in the production of spare parts and that with more work, it be economically feasible to adopt this approach.

Keywords—Additive Manufacturing, spare parts supply, Industry case studies

I. INTRODUCTION

The early adopters of Additive Manufacturing (AM) technology have been the medical and aerospace industries sector. Centres such as the CRPM at Central University of Technology in Free State, began commercializing medical prototypes in plastics and metals. The focus is finally starting to shift from research to implementation in other industries such as the railway and mining industries [1, 2, 3, 4]. These industries are enormous and their adoption of the technology could begin to revolutionize the demand and manufacturing capabilities of South Africa.

Many aircraft manufacturers are already using AM technology to produce high-cost, long lead-time, metallic components. AM has begun to change the conventional configuration of the aircraft spare parts supply chain to achieve safety inventory reduction; thus cutting inventory holding cost across the entire supply chain [5]. Literature has demonstrated that the centralized AM supply chain is however more suitable for parts with low average demand, relatively high demand fluctuation and longer manufacturing lead time.

Globally, adaptability has typically been slow in sectors such as rail and mining maintenance systems with advances in design and technology delayed in filtering through to operators. Research, however, continues to grow on how the introduction of alternative manufacturing methods such as AM might assist these industries with design and production optimization, as well as the maintenance of various internal components. Companies such as Alstom are adopting light rail and heavy rail compatible assets that can be interchanged, in order to better adapt to changing demands [4, 6]. Deutsche Bahn have 3D printed parts for their older fleets, the first generations of ICE high-speed trains, which are no longer in large-scale production [6].

Companies want to understand the quantitative impact to understand what it means for their business, and make decisions to improve their operational efficiency and provide better service offerings. They are looking at a different approach in using AM, to minimize maintenance costs, down-time and to increase efficiency. AM has also proved to be beneficial in the production of spare parts, with opportunities for increasing localization of production and consumption goods to create employment. In the case of the mines, the reasoning is not necessarily to produce the parts at a cheaper price, but rather to, for instance, possibly empower and benefit the communities around them.

Since 2014, market research continue to project that adoption of 3D Printing would dramatically alter the supply chains, but most provide qualitative and quantitative descriptions of what that impact may be. Analyses suggest that 3D Printing will reduce the total supply chains cost by 50-90% as production will move from make-to-stock in offshore/low-cost locations to make-on-demand closer to the final customer with major reductions coming from transportation and inventory costs [7].

In this paper, the multiple case study was used to generate the framework for implementation of AM for on-demand manufacturing of spare parts, especially those in metallic materials such as steels.

II. METHODOLOGY

This research studies a holistic view on the impacts of AM across different phases, the structure illustrated in Fig. 1 will be exploited. The adopted framework encompasses the main processes that a given manufacturing company deals with across the various stages of AM technology impact evaluation.

![Fig. 1: Holistic view of AM technology impact][1]

Two case studies were carried out in companies operating in different industrial sectors. The first case study, in the rail context, shows the potential of AM, especially in the design phase, allowing for product customization. The second one, performed in the mining sector, shows the use...
of different techniques to demonstrate the impact of production and supply chain phase, on inbound logistics. The approach is to cover some of the opportunities and barriers towards the implementation of AM to South African industries.

Two different approaches were taken in each case study. The one used in case study 1 was to do a complete redesign, using Design for Additive Manufacturing (DfAM) tools, of an identified component. The other approach use in case study 2 was candidate identification from data collection and analysis.

Fig. 2: Process flow of case study 1 - Railway industry approach

The candidates were then taken through the DfAM process. The DfAM process was done to obtain CAD models of the components, which was then used to determine cost and the correct method to additively manufacture.

A. Case study 1

In this case study, the knuckle in the coupler system was identified as the potential candidate. The coupler is used in the railway industry, where it is used to link the locomotive and carriages to one another. The knuckle (grey part in Figure 5) is the part that interlocks and bears most of the load.

A comparison was then made between the topology optimized and the original organic (due to potential IP issues, just used as Proof of Concept) CAD model with regards to strength and weight. The comparison was made to determine if the topology-optimized part would be able to handle the required loads, while being significantly lighter than the original part.

B. Case study 2

The second case study describes an approach taken towards AM by a company operating in the mining sector. The study includes an analysis of company’s inventory of spare parts, such as impellers for pumps, shaft sleeves, gasket bonnet valves, and mining rock drill bits, exploring the impact of adopting a digitally distributed supply chain, and then digitizing, locally producing and testing these parts for operations in South Africa.

This case study took a much different approach to case study 1 and forms part of the first phase of the project, which is to investigate the use of AM in the production of on-demand spare parts. Data was collected from the company’s Supply Chain department on the inventory that can be candidates for digital distribution and local on-demand manufacturing model. The data consisted of stock count, lead-time, minimum order quantity, material price, etc.

The candidate impellers were identified, procured and sent for reverse engineering to obtain their CAD models. The reverse engineering consisted of 3D scanning the impellers, importing the point cloud data into a CAD package and creating a model that fits the point cloud data exactly. Possible methods of manufacturing each impeller were identified, as well as the estimated costs for each method.

III. Results

A. Case study 1

The topology-optimized part is shown in Fig. 3. When analyzing the results shown in TABLE I, it seems that the optimized design’s stresses are much higher than the original design and that the optimized design will not be suitable for the application. Figure 4, however show high stress can be attributed to stress concentration in the part.

Fig. 3: Topology-optimized part

Fig. 4: Von Mises stress analysis of optimized part

TABLE I: ORIGINAL PART VS OPTIMIZED DESIGN

<table>
<thead>
<tr>
<th></th>
<th>Original part</th>
<th>Optimized design</th>
<th>% reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design weight</td>
<td>44.967</td>
<td>24.876</td>
<td>44.68</td>
</tr>
<tr>
<td>Part volume</td>
<td>5728</td>
<td>3169</td>
<td></td>
</tr>
<tr>
<td>Von mises stress</td>
<td>±246</td>
<td>±870</td>
<td></td>
</tr>
</tbody>
</table>
According to information received, the cost of one of these knuckles is R6,000.00, excluding Value Added Tax (VAT) and the freight charges, which significantly increases the cost. The major bottleneck has been the lead-time of up to six months and replacement happens every 4 to 5 years. The next step for this case study would be to determine a manufacturing process that would make the on-demand supply of these knuckles viable. The company has been inclined to invest in AM for several reasons among which, the following common goals can be mentioned:

- redesigning their products to fully exploit novel concepts introduced by AM,
- improving the production processes by cutting back on wastes and optimizing their resources,
- enhancing performance of their final products in the use phase.

By avoiding time-consuming steps spent for creating molds or tools, companies could test multiple working prototypes in just a few days; something that would otherwise take a couple of weeks (or even months) to be delivered by their external suppliers. Thus, for those products and sectors where high performance is not a key competence, the main aim behind introducing AM is not related to the possibility to customize products and increase their functionalities, but rather to the opportunity to reach their target market faster and reply to market changes with higher agility [7].

B. Case study 2

The preliminary investigation provided data from supply chain of three business units within the South African mining company. The data categorized items and the total spent for the year 2020 as presented in Fig. 7. The components identified as candidate parts were impellers that account to over $4 million of the total spent for 2020. The following are the reasons why impellers were chosen as the candidate parts over pumps and valves:

- They can be quite expensive, which would make AM a good option.
- Their geometry is complex enough to eliminate many traditional manufacturing methods.
- They need to be replaced after a certain number of working hours or if wear is observed during a maintenance check.
- They are used in pumps and compressors, and along with bearings is the most commonly replaced in these systems.
- Valves do not have components as complex as impellers.
Fig. 9: Build simulation results for Stainless Steel impeller

<table>
<thead>
<tr>
<th>TABLE II: CANDIDATE STEEL IMPELLERS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Traditional Manufacturing</strong></td>
</tr>
<tr>
<td>Method</td>
</tr>
<tr>
<td>Part Cost</td>
</tr>
<tr>
<td>Lead time (Days)</td>
</tr>
</tbody>
</table>

The two identified manufacturing processes for this impeller were LPBF and AM assisted investment casting. LPBF is a process that utilizes a laser to melt the cross-sections of a part, layer-by-layer. AM assisted investment casting is where a sacrificial model of the part is manufactured through an AM process, like binder jetting, in order to create an investment casting mold for the part. When looking at the costs presented in TABLE II, it seems that LPBF is much more expensive than the current method of procurement. However, the cost could be reduced by for instance doing a batch build of the impeller instead of just one at a time. Even though the cost of AM assisted investment casting is not shown, early predictions show that it might be a more viable option. Another possible production method is rapid sand casting, which could be similarly priced to the AM assisted investment casting.

IV. DISCUSSION

The results from the case studies presented in TABLE II presents a resume of the framework for a holistic view of the impact/change across supply chain processes and stages. AM impact the rail industry in the design phase, while leaving no significant impacts in the final use phase. The increases in unit production costs, and reduction of lead times in the production phase amount to conflicting results in the overall evaluation especially for the parts selected for the mining industry. However, if the final production cost is the only criterion for making a decision, it can be said that AM in this case may perform worse than the conventional process.

It can be argued that AM shows a dual impact in this case. On one hand, there is a positive impact on inbound logistics and pre-production phase, resulting in reduction of inventory level, lowering tool utilizations, and shortening the lead time from 4 weeks to 1 week.

TABLE III: HOLISTIC FRAMEWORK

<table>
<thead>
<tr>
<th>Holistic supply chain framework</th>
<th>Rail</th>
<th>Mining</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td>Changing</td>
<td>No change</td>
</tr>
<tr>
<td><strong>Production &amp; Supply Chain</strong></td>
<td>Changing</td>
<td>Changing</td>
</tr>
<tr>
<td><strong>Outbound logistics</strong></td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td><strong>End Use</strong></td>
<td>Utilization Efficiency</td>
<td>No change</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>No change</td>
</tr>
<tr>
<td></td>
<td>End-of-life</td>
<td>No change</td>
</tr>
</tbody>
</table>

V. CONCLUSION

A. Case study 1

As mentioned in the results, the high stress results are caused by stress concentrations. These stress concentrations can be eliminated by redesigning these areas, which will not have a major effect on the part’s volume. It can be concluded that the topology-optimized part could help achieve the goal of increasing payload, by achieving a weight saving of 45%. The refinement of the topology optimized design was not done due to the case study only being used to prove the concept and thus will be done in future work.

B. Case study 2

The research in the mining sector continues through interviews and literature searches, a "top-down" approach was applied to a develop cost-benefit model to identify and evaluate potential spare parts for AM from the current spare parts portfolio. The results were evaluated as promising for several of the spare parts in terms of reduced manufacturing, procurement, tool cost, and lead-time reduction, which results in increased uptime for mining business units. There is also great potential for reducing the costs for warehousing, where spare parts of low demand can have their stocks reduced or eliminated by securing supply through on-demand manufacturing.
C. Overall conclusion

Exciting times lay ahead for AM in South Africa now that large industries such as the mining and railway industry are investigating the use of AM in their operations. When weighing the different options, one has to look at the bigger picture and not just at the cost. Some of the aspects, that also has to play a role in the decision-making, are as follows:

- Local investment and economy growth
- Storage costs/space
- Carbon footprint (e.g. shipping vs. locally manufactured)

The supply chain managers can reduce their inventories to virtually zero while still maintaining 100% item fill rate from OEM manufacturers. While they are projected to lose revenue on the freight business this can be an opportunity to transform their service offerings and forge partnerships with end-users to provide integrated manufacturing and supply chain services.

The holistic assessment of the two industry sectors on the implementation of AM technologies demonstrate would have to cut across the manufacturing supply chain. Businesses have to go collect qualitative and quantitative data derived from real industrial cases. This preliminary study showed that industrial applications are beyond the limited number of cost related aspects that companies usually investigate. A series of changes and disruptive concepts across supply chain would consequently imply that AM adoption could be accelerated though digitized on-demand manufacturing using advanced AM technologies.

ACKNOWLEDGMENT

The authors would like to acknowledge Transnet and Anglo American for their involvement and support in these projects.

REFERENCES

Framework for Cemented Tungsten Carbide Drill Bit Prototype Fabrication using Laser Engineered Net Shaping

Brandon Davoren
Department of Industrial Engineering & DSI-NRF Centre of Excellence in Strong Materials
Stellenbosch University
Stellenbosch, South Africa
brandond@sun.ac.za

Natasha Sacks
Department of Industrial Engineering & DSI-NRF Centre of Excellence in Strong Materials
Stellenbosch University
Stellenbosch, South Africa
natachasacks@sun.ac.za

Maritha Theron
National Laser Centre
Council for Scientific and Industrial Research
Pretoria, South Africa
mtheron@csir.co.za

Abstract—The interest in additive manufacturing and its unique applications has increased significantly over recent years. This has resulted in the need for alloys and composites to be optimized for these processes. In this study a multiphase parameter refinement framework was developed to guide optimization, and a cemented tungsten carbide alloy was used as a means of validation. Laser engineered net shaping (LENS™) was used to fabricate thin walls, cubes, and a functional prototype, namely a drill bit. The circularity, depth and diameter of the drilled holes were benchmarked against a commercially available drill bit, and finite element modelling simulations were performed to illustrate regions of high stress and simulate possible fracture zones. The circularity of the resultant holes was found to be consistent for the respective drill bits except when the drill bit tip failed and tore material from the walls of the hole. The depth and diameter of the drilled holes varied across the tests and the depth was significantly less for the fabricated drill bits compared to the commercial drill bit. The framework allowed for the functional prototype to be fabricated in 23.5 hours of active laser time, whereas the purchased drill bit comprised of the cemented carbide whereas the shank of the purchased drill bit is fabricated from steel and only the tip region from WC-based materials. The entire drill bit comprised of the cemented carbide could lead to improved drilling performance and will be considered in future studies.

Keywords—laser engineered net shaping, framework, cemented tungsten carbide, drill bit, design of experiments

I. INTRODUCTION

Limited commercialization, including research, has been done using the DED process to manufacture cemented tungsten carbides, with only cobalt (Co) being utilized as a binder phase [1]. Since DED has been used to develop, prototype and produce specialized surgical prosthetics [2] it therefore has the potential to fabricate precision drilling tools. If additive manufacturing (AM) methods can be utilized to fabricate drill bits then custom bits can be printed on demand for specialized applications without the need to mass produce, as is the case with modern commercial manufacturing methods. Furthermore, if a drill bit becomes worn or fractures, it could potentially be rebuilt or repaired using an AM process instead of purchasing a new drill bit. Thus, the focus of the current study was to produce cemented tungsten carbide drill bit prototypes using the DED process, and to compare initial drilling performance against a commercially available drill bit.

To produce successful AM prototypes an optimized manufacturing framework is required. In literature an AM component is generally fabricated using an optimal set of parameters with limited information provided on how these parameters were obtained [3], [4]. Attempts to duplicate the component are often only feasible if there is an abundance of information available regarding the process parameter optimization process which was followed for successful material deposition, which is only the case for commonly printed materials such as titanium based alloys [5]. However, there is not always published parameters or manufacturing frameworks to aid the deposition process when novel alloys or binders are considered, or even when AM is considered as an alternative production process for an existing material such as cemented tungsten carbide. A framework which allows for rapid parameter optimization is required for these instances, or a critical simulation study can be undertaken. Researchers have used a design of experiments matrix to develop the optimization process [6], although a basic framework for parameter optimization using an iterative deposition approach is not readily available, which would also assist researchers new to the field of additive manufacturing as well as in the development of novel alloys.

Therefore, based on the high number of depositions required and the absence of a published basic optimization framework, a simple framework was designed in this study which used multiple simple cubic geometries to determine an optimal parameter set which could be used for the deposition of a functional prototype. It also determined whether parameters obtained for various geometries could be simply translated across designs. The LENS™ fabricated WC-9.2wt%Monel400 drill bits were tested against a commercially available product to determine whether the additively manufactured prototype was comparable. Here the entire drill bit comprised of the cemented carbide whereas the shank of the purchased drill bit is fabricated from steel and only the tip region from WC-based materials. The study aimed to achieve these results by using the least number of depositions and total laser time. The framework can be utilised in any experimental setup where a novel material combination is required to be optimised.

Funded by the Department of Science and Innovation and the National Research Foundation in South Africa (Grant Nos: 41292 & 129313).
II. FRAMEWORK FOR PROTOTYPING DRILL BITS

Design of experiments (DoE) and statistical based approaches have been used by numerous researchers [7]–[9] to provide valuable information for the generation of numerical models, machine learning parameter optimizers and finite element analysis models. The framework developed in this study was based on these approaches with adaptations made to the optimization process to produce a functional prototype. It is also provided in a simple layout such that it can be applied in any iterative parameter testing situation. The proposed framework is shown in Fig. 1 and can be used to optimize the parameters for the deposition of a functional prototype, by starting with thin walls and then optimizing through small-scale samples. The framework is divided into several phases which are discussed in more detail thereby providing a general overview and the approach used in this study.

A. Development phase

1) Design for AM

Design for Additive Manufacturing (DfAM) has the highest impact for production parts and the lowest for a prototype since the time spent optimizing a production part will be justified in the reduction of batch material waste and time reduction. The design process is therefore a crucial stage in additive manufacturing and has been explored by multiple authors [10], [11]. The design stage undergoes an iterative approach [12] until the model meets the desired requirements which could include reduction of build material and localized stresses, by using generative design, appropriate angular structures or the addition of support structures. The conceptualization of the component needs to accommodate the limitations of the additive manufacturing technology to be used as well as maintain the desired features without extensive compromise. Salonitis and Zarban [12] presented a simple and definitive hierarchical and multi-criteria decision making design for choosing an optimized design. The drill bit prototypes, in this study, were modelled using the commercial drill bit as a template since the benchmarking was performed against the commercial bit.

B. Experimentation phase

1) Design of experiments

Design of experiments have been used by multiple researchers to perform optimization experiments [6], [13]. Many experimental design templates are available within statistical software and are calibrated using the desired outcomes of the study. Two examples of widely used design of experiments are Factorial and Taguchi designs. Factorial based designs consider all possible interactions that occur for each of the input factors which results in large experimental sets. Factorial designs allow for interactions between parameters to be determined although one pitfall is that some interactions may be confounded and if not considered can lead to highly erroneous conclusions. Taguchi designs are based on fractional factorial designs as well as factorial designs with multiple factors being tested. With Taguchi designs, the most significant interactions need to be hypothesized before the experimental processes commence. A design of experiments allows for analysis of variance (ANOVA) to be applied to the obtained experimental data and provide results which pertain to the experimental range employed. Any variable sets which are beyond the scope of the study can be extrapolated although this assumes that the mathematical nature of the results is consistent over any variable set, which is not necessarily true. When a novel material is the subject of the research and no defined literature is available, then other materials which have been used for the intended application or the major alloying constituents can provide a guideline as to how the material may react and provide beneficial properties such as hardness, strength and layer thickness in determining feasible initial parameter sets.

For this study, a 3x3 full factorial DoE was used including star points. The range which was chosen was hypothesized to contain a local “optimized” set which cannot be defined as a globally “optimized” set due to the restrictive nature of the design of experiments. Only three important parameters were considered in the design of experiments as not all parameters can be tested due to the exponential effect an additional parameter has on the number of depositions required. The laser beam power, traverse speed and powder flow rate were selected since literature has identified these as the main deposition parameters [14]. Three values / settings at a low, medium and high level, relative to the maximum and minimum of the machine, for each parameter yields a 3x3 matrix. Three levels provide more information about the interactions of the parameters and the inclusion of star points provides more information about the parameter sets around the “central” values of the design matrix. The values in Table I, along with the 6-star points resulted in 33 depositions.

<table>
<thead>
<tr>
<th>Deposition Parameters</th>
<th>Laser beam power (W)</th>
<th>Traverse Speed (mm/s)</th>
<th>Powder flow rate (g/min)</th>
<th>z-increment (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150, 250, 350</td>
<td>2, 3, 4</td>
<td>5, 7, 10</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Thin walls provide an ideal deposition design for rapid variable set determination due to low deposition times. The thin walls were 20 mm in length, 25 layers high and on a...
single deposition track. A schematic of the thin wall depositions is shown in Fig. 2 (a).

![Fig. 2: General schematic for a) design of experiments thin walls b) cubic and cylindrical structures](image)

2) **Thin wall analysis**

Once the thin walls have been deposited analysis needs to be performed such that feasible parameters can be obtained for the optimization phase. If there are any visible cracks, agglomerated particles causing surface roughness, poor adherence to the base plate or insufficient build height in the depositions then the parameter sets should be excluded. The properties of interest should be recorded, such as height, width or porosity for each parameter set so that an analysis of variance can be performed and the effect of each parameter as well as parameter interactions can be determined for the desired property. The desired parameter set is then used in the optimization phase with small-scale depositions.

The height, width and hardness were analysed and recorded for the 33 DoE trials. The theoretical height and width of the thin walls were calculated using the z-increment and beam spot size, respectively. An ANOVA regression and the resultant quadratic function was used to determine the most feasible parameter set, for the optimization phase. The parameter contributions and interactions in yielding a specific height, width and hardness were also analysed.

C. **Optimization phase**

1) **Small-scale samples**

Small-scale samples can now be used to test the best parameter sets obtained from the experimentation phase. Small cubes or cylinders, as in Fig. 2(b), can be deposited and have been used in multiple publications as an optimization standard and many researchers use these as a base to subtractively machine tensile components [15]. The samples are now larger than thin walls and filled with a rastering pattern which introduces different thermal gradients and cooling rates during deposition which allows for the parameter sets to be refined further. The set which performed best on the thin walls may not be the best solution for filled geometries but provide a feasible starting point. The optimized parameter set obtained from the thin wall depositions can now be applied to the validation phase. If the relative dimensions of the final component are the same as the small-scale sample, then the final CAD design can be applied in the optimization phase and optimized accordingly, or the CAD for the final product can be applied in this validation phase. The final component is however generally larger than the small-scale samples utilized in the optimization stage, which will affect the resultant cooling rates and thermal gradients during the deposition process [20]. It is important to monitor the first component print process to determine whether in-situ parameter adjustments are required to prevent the damage of the equipment, such as the deposition nozzle colliding with the build. These altered parameters can then be applied to the successive deposition process. According to Equation 1, the laser power and traverse speed directly affect the energy density. By lowering the laser power, the powder being fed may not melt adequately and result in lack of fusion porosity, whereas the higher traverse speed will yield less time at each successive point and may also develop porosity. A higher traverse speed is favourable over a lower laser power since this aids in faster printing, limiting layer thickness and reduces the alterations required to other parameters [21].

\[
P/\nu D = E \quad (1)
\]

where \(P\) is the laser power (W or J/s), \(\nu\) is the scanning speed (mm/s) of the operating head, \(D\) is the diameter (mm) of the laser spot and \(E\) is the energy density (J/mm²).
Based on the quality control minor changes can be made to the deposition parameters to improve the final product through the same iterative process used in the optimization phase. Additional post processing techniques can be employed such as Hot Isostatic Pressing (HIP) to reduce the porosity, surface finishing techniques to improve surface roughness or machining processes to enhance features of the final design. If none of these processes show a beneficial change or cause the product cost to elevate excessively then a new alloy should be examined for the process or a different manufacturing process or application should be investigated. The CAD of the drill bit for this study and an as-printed drill bit example is shown in Fig. 3(a) and Fig. 3(b) respectively, as was deposited using the process parameters recorded in Table II, along with a fixed powder feed rate of 11.9 g/min. The traverse speed was the only parameter altered to accommodate for the varied thermal properties and two drill bits were built on a heated stage to determine the effect on the deposition process. All drill bits except DB4 underwent mild sharpening after fabrication. Post processing is required to provide final products.

### TABLE II. PRINTING PARAMETERS FOR DRILL BITS

<table>
<thead>
<tr>
<th>Drill bit</th>
<th>Power (W)</th>
<th>Traverse speed (mm/s)</th>
<th>Substrate</th>
<th>Fabrication time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>220</td>
<td>8.2</td>
<td>Heated 450°C</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>220</td>
<td>10.25</td>
<td>Heated 450°C</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>220</td>
<td>20.50</td>
<td>Not heated</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>220</td>
<td>10.25</td>
<td>Not heated</td>
<td>40</td>
</tr>
</tbody>
</table>

2) Quality control

The component which is fabricated can be observed for any external anomalies such as insufficient build height, irregular surface agglomerates, high surface roughness, diminished components resolution or visible cracks. The samples can also be examined for porosity, micro cracks, hardness and various microstructural characteristics if necessary. Various failure criterion simulations can be applied to determine possible fracture sites and yield properties, such as Von Mises stresses [22].

The drill bits were printed without an iterative refinement step or post processing techniques such that the performance of the as-deposited prototype could be determined.

### E. Feasibility phase

This is concerned with the volume that needs to be printed, the time to print each component and the cost of the final part. After validation a full cost analysis needs to be applied to the final product to determine whether additive manufacturing is in fact the most cost efficient and suitable method for part production. Additive manufacturing has its strengths in low volume, highly customizable components, prototyping and concept validation. If high volume is required, then additive manufacturing can be used to design a mould which will allow for rapid manufacturing thereafter using injection moulding or metal casting. When accurate features and surface finish is required, a subtractive manufacturing process may be more suitable or even a different type of additive manufacturing process such as metal binder jetting.

The drilled hole quality was used for comparison against a commercial product. The drill bits were tested on a turn-mill at a rotational speed of 2000 rpm, a penetration depth of 6 mm with a feed rate of 100 mm/min. The holes were drilled into 2011 aluminium alloy which has a hardness of 90-100 HV0.1. Drilled hole circularity was analysed using image analysis software.

### III. FRAMEWORK VALIDATION

The powders and LENS™ configuration described in a previous study by Davoren et al. [19] was used in the framework validation. The study considered the design of experiments and optimization phase of a WC-9.2wt%Monel alloy, where the power and powder feed rate had a positive effect on the build height whereas the traverse speed and square of the powder feed rate had a negative effect, with power and powder feed rate showing antagonistic property data. The calculated model was found to explain the experimental data with 91.7% accuracy [19]. When the width was considered, an increase in laser power deposited a wider wall whereas a higher traverse speed deposited a thinner wall. Laser power and traverse speed were found to have an antagonistic effect and the calculated model was found to explain the experimental data with 93.2% accuracy.

The design of experiment phase provided important interactions and based on the calculated models allowed for cubes to be produced in the optimization phase. A density of 94% was obtained for the first iteration of the optimization phase, with the second yielding a density of 97% [19]. The third iteration did not reduce the porosity to any greater degree. In the current study the validation phase was done and used to produce a drill bit prototype based on the parameter set that yielded the 97% density, which is slightly lower than commercial densities of about 99%.

When the deposition properties are considered, it is evident from Fig. 3 (b) that the surface finish of the drill bit was very rough when compared to the CAD design in Fig. 3(a), due to the WC particles which did not dissolve and merely cooled in the binder while protruding from the deposition. The size of the WC powder particles (±90 µm) meant that if two or three particles are solidified upon one another, the surface roughness would increase. The nature of the precursor powder is therefore extremely important in

![Fig. 3: a) CAD model of drill bit, b) DB4 as deposited.](image)

the finishing of the final product if no post fabrication machining is considered.

The deposition dimensions were larger than the CAD model with the tip diameter showing a 27-48 % increase in
dimensions than the CAD model while the shank was 11-22 % larger. The tip length was 2-30 % greater, the flute length 22-27 % less and the total drill bit length 7-8 % longer than the CAD model. The relatively large beam spot size of 1.35 mm meant that any features that were smaller or within 1.35 mm would have poor resolution and the high surface roughness had a more profound effect on the smaller geometry. By reducing the beam spot size, a better resolution will be obtained, but at the cost of longer printing times, hence more powder usage and more laser time. The LENS™ machine employed did not allow for simple alteration of the beam size, as it can only be done by manually adjusting the internal lens in the deposition head and testing the new beam spot size. Thus, a large beam size for the shank and a small spot size for the tip is not a viable solution. This indicates that a post processing procedure will be required in majority of cases to comply with strict quality standards.

The best performing drill bit, DB3 as in Table 2, was found to have a circularity and diameter which was within 5% of the commercial drill bit although the hole depth was only 38% of the commercial one. This large variance was due to tip fracture caused by lack of post processing surface smoothing. The von Mises simulations showed that in the designed CAD, Fig. 4(a), and the corrected CAD, Fig. 4(b)-(d), which models the shape of the deposited drill bit, that the highest stress is observed at the base of the tip region. The as-deposited drill bit has a less defined flute and tip which resulted in less of a boring action. A secondary high-stress point is at the top of the shank, due to stress concentrations caused by sharp angles in geometry.

The highest strain was observed in the tip region, due to the high loading stress, although the displacement is the top region of the tip while the stress is in the base of the tip. The twisted nature of the flute allows for the displacement to be distributed throughout the mass due to its torsional rigidity. The von Mises stress and strain simulations allow for the drill bits to be refined and modified to improve their design properties within the validation phase of the framework.

The manufacturing times were calculated for the experimental phase as well as the optimization phase. The thin walls took a total of 101 minutes of active printing time to complete. Aspects which added to this included the initiation of each new print, refilling the powder hoppers and selecting the next set of process parameters. Since the model for the thin walls remained the same there was no need to change the CAD model, only the process parameters. The three iterations of cubic samples used a total printing time of 22 hours, again without the additional setup and preparation stages. Thus it took approximately 23.5 hours of active printing time to obtain a parameter set which yielded a cube with a density of 97 % without any post printing processes.

The drill bit deposition times varied between 27 minutes and 100 minutes depending on the process parameters which shows that the refinement of parameters can produce time savings of up to 4 times. The cheapest fabricated drill bit was still 3.5 times more expensive than the purchased drill bit. This is due to the entire drill bit comprising of WC-9.2wt% Monel 400 whereas the shank of the purchased drill bit is fabricated from steel and only the tip region from WC based materials. To make the fabricated drill bit competitive the shank should comprise of Monel 400 or steel which is then tipped with a WC-based material, possibly even a functional grading from the steel shank into the tip to remove any adhesion problems between the two dissimilar materials.

**IV. CONCLUSION**

An iterative, multi-phase parameter manufacturing framework was successfully developed and applied to a tungsten carbide alloy having a Monel 400 binder yielding reproducible functional drill bit prototypes after 23.5 hours of active laser time, using the laser engineered net shaping process. The framework provided a systematic process to follow and reduced the need for excessive parameter refinement in attempting to achieve the highest density and production of a component. The framework can be utilised in any experimental setup where a novel material combination is required to be optimised.

The geometries of the fabricated drill bits were larger in every dimension due to the high surface roughness and large spot size used for deposition. The best deposited drill bit produced hole circularity and diameters which were within 5% of the commercial drill bit but was unable to achieve the desired depth due to tip fracture from high stresses and microstructural properties. With suitable post processing machining, the dimensions can be customized and the drill bit performance improved by refining the surface properties by for example heat treatment. The cost of the AM drill bit still greatly exceeds the current conventionally produced commercial product but has its strength in being highly customizable and having short lead times if there is a local additive manufacturing distributor. Although the
commercial drill bit outperformed the prototype bits, the deposition of a competitive drill bit may be possible with a second iteration of parameter refinement, and/or by employing a different geometry.

ACKNOWLEDGEMENT

The National Laser Centre (NLC) at the Council for Scientific and Industrial Research (CSIR) is acknowledged for use of the LENS® machine as well as technical support (Grant No: LREPA25). Mr. Rodney Gurney is acknowledged for assistance with CNC operation during drill bit testing. Opinions expressed and conclusions arrived at are those of the authors and are not necessarily to be attributed to the funders.

REFERENCES


Directed Energy Deposition of a Cemented Tungsten Carbide Rotary Burr Prototype

Emma Molobi
School of Chemical and Metallurgical Engineering & DSI-NRF Centre of Excellence in Strong Materials
University of the Witwatersrand
Johannesburg, South Africa
emma.molobi@transnet.net

Natasha Sacks
Department of Industrial Engineering & DSI-NRF Centre of Excellence in Strong Materials
Stellenbosch University
Stellenbosch, South Africa
natashasacks@sun.ac.za

Maritha Theron
National Laser Centre
Council for Scientific and Industrial Research
Pretoria, South Africa
mtheron@csir.co.za

Abstract—In this study a cemented tungsten carbide rotary burr prototype was fabricated using directed energy deposition based on an optimal parameter set which was previously derived from a full factorial design of experiments matrix approach. Finite element analysis under static conditions was carried out on the burr to understand the possible geometric stress raisers and stresses during assimilated operation. Initial field tests were done to assess the functional performance of the prototype, and comparisons were made against a conventionally manufactured burr.

Keywords—directed energy deposition, cemented tungsten carbide, stress, rotary Burr

I. INTRODUCTION

Directed energy deposition (DED) is an additive manufacturing (AM) process which directs energy from a laser or electron beam heat source into a narrow, focused region to melt the feedstock powder as it is deposited onto the substrate [1], [2]. Laser engineered net shaping (LENS®) is a DED process which has been successfully used in the fabrication of a range of materials such as stainless steels, nickel alloys, composites and graded materials [3]. The LENS® process fabrlicates components by interpreting the STL file format of a computer aided design (CAD) model of the part to be manufactured. The CAD model is divided into thin orthogonal layers in the z-axis and the data for each layer is interpreted and translated into laser scanning paths to fabricate a single layer [4]. The layers are fabricated by first generating an outline of each feature and then the nozzle moves up by a z-increment in order to deposit more layers until fabrication is complete. The advantages of DED processes in comparison with conventional manufacturing processes such as sintering and subtractive manufacturing includes the production of near net shaped components, rapid production, limited usage of fixtures and no requirement for patterns [5].

There have been studies into the application of the LENS® technology in the fabrication of cemented tungsten carbide (WC) alloys. Xiong et al. [6], [7], [8] investigated its applicability in the fabrication of cobalt (Co) cemented WC while Davoren et al. [9] investigated the deposition of a WC-Monel alloy.

LENS® has also been successfully used in the repair of titanium manufactured components [10] and the fabrication of Inconel free forms [2]. However, the commercialization aspect of the LENS® fabrication of cemented WC does not appear to have been achieved yet. This study investigated the fabrication of an iron-based cemented WC rotary burr prototype using the LENS® process.

II. EXPERIMENTAL METHODS

A. Laser deposition

In preparation for deposition the prototype rotary burr was designed to have a shank diameter of 6 mm, burr diameter and length of 12 x 25 mm, and a total length of 65 mm. It was designed without a rotary end cut and all designs were based on DIN 8033 and the PFERD burr catalogue [11]. CAD models were made using Creo Parametrics which uses history based parametric modelling which entails building a 3D geometry, piece by piece by using 2D sketches. Once the CAD model was established it was saved as an STL format and then sliced along the z-axis into layers which translated into laser scanning paths.

An Optomec 850-R LENS® machine with a 1kW IPG fiber was used to manufacture two WC-10wt% FeCr cylindrical rotary burr prototypes at atmospheric conditions using the parameters shown in TABLE I which were derived in an earlier study. For the manufacture of one of the burrs the substrate was pre-heated prior to deposition. The burrs were sectioned from the substrate using a Struers Secotom-10 precision cutting machine, with a 12 cm diameter Struers diamond coated wheel at a cutting speed of 3500 rpm and a feed rate of 0.015 mm/s. The dimensions of the rotary burrs were measured using a Vernier calliper and compared to the dimensions of a conventionally manufactured burr to verify part accuracy.

<table>
<thead>
<tr>
<th>Process parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power (W)</td>
<td>200</td>
</tr>
<tr>
<td>Traverse speed (mm/s)</td>
<td>1.2</td>
</tr>
<tr>
<td>Powder feed rate (g/min)</td>
<td>12.2</td>
</tr>
<tr>
<td>Z-increment (mm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Stand-off distance (mm)</td>
<td>8</td>
</tr>
<tr>
<td>Laser spot size (mm)</td>
<td>1.4</td>
</tr>
</tbody>
</table>

TABLE I. Near optimum parameters for LENS® deposition

Funded by: Department of Science and Innovation and the National Research Foundation in South Africa (Grant Nos: 41292 and 129313).
B. Finite Element Analysis (FEA) and Benchmarking Tests

FEA analysis was done using MSC Patran® and Nastran® software at static conditions to verify the location of the largest von Mises stresses. A structural analysis using a first principle approach and a FEA linear static assessment were done. The performance matrix used for the analysis was a power tool with a rotational speed of 32000 rpm and a cutting speed of 600 m/min. Equations (1) to (4) show the calculations used for torque and maximum shear stress.

\[ \tau_{\text{max}} = k_{ts} \left( \frac{T}{J} \right) \]  
\[ T = \frac{P \times 30}{\pi \eta} \]  
\[ J = \frac{\pi (2r)^4}{32} \]  
\[ r = \frac{d}{2} \]

\( \tau_{\text{max}} \) is the maximum shear stress (MPa), \( k_{ts} \) is the stress concentration factor which is 1 for brittle materials [12], \( T \) is the torque, \( P \) is the power of the rotary tool, \( \eta \) is the rotational speed (rpm), \( J \) is the polar second moment of area, \( r \) is the radius of the burr shank (m), and \( d \) the diameter of the shank.

The finite element was meshed using a four node tetrahedral (TET4) element type mesh. The analysis boundary conditions was a fixed end at the burr shank. The properties of the burr used for the analysis was an elastic modulus (E) of 513 MPa [13], and a Poisson ratio (\( \nu \)) of 0.3 [14].

The rotary burr which was deposited on a preheated substrate fractured during removal from the substrate. Hence the prototype burr without substrate preheat was benchmarked against conventionally manufactured burrs in terms of removal of previously deposited weld material. A weld deposit made from AWS A5.1 E7018 -1 having a tensile strength of 490 – 550 MPa [15] was used for the test. The weld deposit was machined at one-minute intervals for a total time of five minutes using a handheld rotary tool with a cutting speed of 600m/min and rotational speed of 32000 rpm. The thickness of the weld deposit and substrate was measured using the Vernier calliper after each interval to record the amount of material removed by the burr. The burr which removed more material in the allocated time was selected as the better performing burr.

III. RESULTS AND DISCUSSION

A. CAD model and FEA analysis

Fig. 1 shows the CAD model of the rotary burr prototype.

Fig. 1. Side view of rotary burr

Fig. 2 shows the FEA model and the load/boundary conditions of the cylindrical rotary burr. The maximum shear stresses acting on the rotary burr prototype was calculated to be 6.84 MPa and the torque to be 0.29 Nm.

Fig. 2. Applied operational loads and boundary conditions

FEA showed that the fillet junction area which connects the shank and the burr head acts as a stress raiser and experienced the highest stress concentration (Fig. 3). Internal stresses will exist in sharp corners and fillet radii because of the abrupt change in shape. In order to mitigate this a large fillet radius should be incorporated in the 3D CAD model so that there is enough space for the distribution of the internal stresses. This analysis showed that if failure should occur, the area with the highest stress concentration would be the first to fail.

Fig. 3. Von Mises stress due to imposed load

B. Fabrication of the Prototype Burr

The rotary burr prototype was manufactured in a three-step process (Fig. 4) without the use of fixtures, compared to the nine-step conventional process (Fig. 5), which shows the benefits of using AM. The LENS® fabrication time per burr was 04h04min30sec in comparison to the conventional sintering cycles of 15-20 hours. The flutes on the burr were partially visible in comparison to the conventionally manufactured rotary burrs and this was due to the rougher surface finish imparted by the DED process. The powder utilization of this process was calculated to be 50.2% by weighing the initial amount of powder used for the deposition process and the amount of powder which was not deposited into the molten pool. The low powder efficiency of the LENS® process shows that feasibility of the process will depend on the ability to recycle the powder.
accurate dimensions, visible flutes and an acceptable surface finish. In addition the burr visually showed distortion in the form of a concave shape, this shape was in accordance to the CAD model which also showed a concave burr. Final machining will increase the number of production steps required before the burr can be deemed market-ready, however, the LENS® processes will then require 4 manufacturing steps which is still less than the conventional process.

<table>
<thead>
<tr>
<th>Table II. Dimensions of the LENS® fabricated and sintered WC burrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burr dimensions</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>CAD model</td>
</tr>
<tr>
<td>LENS® deposited WC-Co</td>
</tr>
<tr>
<td>Sintered WC-Co</td>
</tr>
</tbody>
</table>

### C. Field Testing of the Rotary Burr Prototype

The performance of the prototype burr was based on the removal of previously deposited welds. This was compared with conventionally manufactured cemented WC burrs. Fig. 8 shows the built-up weld requiring machining and Fig. 9 shows the performance of the prototype burr in comparison to the sintered burr in machining the weld surface. The prototype burr failed at the fillet junction as predicted by FEA after machining 0.22 mm of the weld in 2 minutes. The sintered burr did not fail and testing was stopped after 5 minutes.
During machining of the weld it was observed that the prototype burr vibrated extensively, which is believed to have contributed to failure of the burr. Fig. 10 shows the failed burr indicating a three-point brittle fracture with no evidence of plastic deformation. This indicates that only low fracture energy was required for the failure to occur.

IV. CONCLUSION

A WC-10wt% FeCr prototype cylindrical rotary burr was fabricated using the LENS® technology. FEA analyses predicted that the fillet junction area which connects the shank and the burr head would be a point of weakness as a stress raiser and would experience the highest stress concentration. This prediction was shown to be accurate when the burr failed at this junction area during machining tests. The conventionally manufactured cemented tungsten carbide cylindrical rotary burr outperformed the prototype. However, the prototype showed potential as it failed at the shank and not the burr head. One of the limitations of the prototype was the rough surface finish due to the DED process which possibly enhanced the vibrations experienced during machining of the weld thereby leading early failure. In addition to the rough surface finish the dimensional accuracy of the burr did not comply to the CAD model, hence final machining will be required in order to explore the feasibility of LENS® deposited cemented WC burrs.

ACKNOWLEDGEMENT

The National Laser Centre (NLC) at the Council for Scientific and Industrial Research (CSIR) is acknowledged for use of the LENS® machine as well as technical support (Grant No: LREPA25). Opinions expressed and conclusions arrived at are those of the authors and are not necessarily to be attributed to the funders.

REFERENCES

Combined Implicit and Explicit Techniques to
Create a Bespoke Optimized 3D Printed Lattice
Socket for a Prosthetic Hand

Jode Fourie
Department of Mechanical Engineering
Nelson Mandela University
Port Elizabeth, South Africa
s219170207@mandela.ac.za

Clive Hands
Department of Mechanical Engineering
Nelson Mandela University
Port Elizabeth, South Africa
Clive.Hands@mandela.ac.za

William Rall
Department of Mechanical Engineering
Nelson Mandela University
Port Elizabeth, South Africa
William.Rall@mandela.ac.za

Riaan Stopforth
Stopforth Mechatronics, Robotics and
Research Lab
University of KwaZulu-Natal
Durban, South Africa
stopforth.research@gmail.com

Abstract— A challenge for upper limb amputees is the
expense, fitment, weight, and usability issues of contemporary
prostheses which often sees the abandonment of the prosthesis
in day-to-day use and reliance on the remaining part of the limb
to carry out basic tasks. This paper includes the research,
design, manufacture and testing of a bespoke Additively
Manufactured prosthetic socket and protective arm sleeve for
lower arm amputations. The solution for this research was an
additively manufactured, Nylon PA650 socket with lattice
optimization and a ratchet-style adjustable fastening method.
The socket design utilized a combination of explicit and implicit
techniques with a reusable workflow to allow customization to
fit any arm shape and size. The advanced implicit latticeing
technique utilized, allowed a weight reduction of 80% compared
to other contemporary options on the market while maintaining
full structural integrity and increasing flexibility. Heat
dissipation analyses were conducted, and thermal plots were
generated to dictate the optimal lattice density, allowing
maximum breathability while maintaining stiffness in the
structure. The cost of the socket was 333.38 USD, which was less
than 10% of other typical entry-level options available on the
market.

Keywords—Additive manufacturing, Lattice optimization,
Lightweight, prosthetics

I. INTRODUCTION

The most important component of a prosthetic system is
the socket that secures the prosthetic device to the residual
limb [1], [2]. This research covered the conceptualization,
design, manufacture, and testing of a custom prosthetic socket
for the existing Touch Hand prosthetic device pioneered by
Stopforth Research Laboratory. This research focused on
creating a comfortable, lightweight, cost-effective prosthetic
socket that adds value to the users’ daily lives [3]. The socket
design utilized a combination of explicit and implicit design
techniques with a reusable workflow to allow customization
of the socket to fit any arm shape and size.

There are different levels and extents of arm amputations
and each one presents a different set of challenges to the
prosthetic designer. Factors such as sensitive scar tissue,
unusual skinfolds and bony protrusions in the residual limb
make each socket unique to the individual amputee [1].

Careful consideration to the above-mentioned factors needs to
be taken when designing a prosthetic socket to not injure or
cause discomfort to the amputee. This will certainly lead to
the prosthetic being abandoned as is typically the case in most
solutions [2]. It is crucial that the user feels as if the socket is
an extension and functional part of their body.

For this research, the amputee has a wrist disarticulation,
which means that most of his forearm is intact, and he has
fortunately also retained his forearm’s rotational
capability [3]. This type of amputation results in a longer
residual limb compared to other types of amputations [3],
which means that a prosthetic device would most likely result
in an uneven arm length compared to the other arm. The
design challenge was to minimize the space between the end
of the residual limb and the prosthetic device while keeping
the socket as lightweight and as comfortable as possible whilst
maintaining strength and integrity in the socket [3].

Existing prosthetic sockets for a wrist disarticulation
amputation include the “Figure-8 harness”, which provides
good stability but restricts free movement, also requires
assistance to put on and is bulky & uncomfortable for the
user [4]. Other less bulky options include the Munster and
vacuum style sockets, which rely on friction and a negative
pressure vacuum as suspension methods respectively [5].

The problem with these sockets is that they provide poor
suspension compared to the harness type, but they are less
bulky and can be used without assistance. The Munster
friction socket irritates the skin with extended use and the
vacuum socket causes discomfort as there is no ventilation
within the vacuum [5]. During daily wear, the vacuum seal
can weaken due to the residual limb shrinking and expanding
due to temperature changes and sweating [6]. A third socket
style called TRAC is an improved version of the Munster
socket, the difference being that suspension is achieved by
only compressing certain parts of the residual limb [2].
This reduces irritation and supports better blood flow but reduces the range of motion due to the socket extending over the elbow.

The research problem was to address the above challenges as well as to develop a new fastening method that would allow continuous adjustment of the socket throughout the day, as the residual limb shrinks and expands due to temperature changes. Finite element and heat dissipation simulation analyses were conducted, and thermal plots were generated to dictate the optimal lattice density allowing maximum breathability while maintaining stiffness in the structure.

The design method utilized state-of-the-art implicit modelling technology (the nTopology platform) to create a unique reusable workflow that can be modified easily to suit any arm amputee’s requirements [7]. The proposed design took inspiration from the above-mentioned socket styles with adjustments made to improve on their respective shortcomings. The product is a lightweight, adjustable, cost-effective prosthetic socket that can be used without assistance and adapted to fit many different arm shapes and aesthetic preferences.

The research contributions of this paper are:

- The design and development of a socket that allows periodic adjustment due to expansion of the residual limb due to temperature changes. Development of a reusable implicit workflow for designing prosthetic sockets. The lattice optimization of a prosthetic socket to reduce weight and improve breathability.

- An additively manufactured one-piece & supportless solution to the design.

II. DESIGN METHODOLOGY

The methodology of the research and development of the Touch Hand 4 socket is described in the sections indicated below [8].

A. Design Process

The design process shown in Fig. 1, started with the 3D Scanning of the amputee’s residual arm. The scan produced an STL mesh file which was then used as a base for the CAD model of the arm. This CAD model was then developed into an implicit format within the state-of-the-art nTopology platform and used to model the sock pattern, socket, and wrist attachment. The implicit model was then further manipulated within nTopology for lattice optimization, whereafter it was exported to a CAD platform (Autodesk Fusion 360) for assembly with the separately designed wrist attachment and suspension system [9]. The socket system was then ready for manufacturing and testing.

1) Scanning and model preparation

The scanning and model preparation process is shown in Fig. 2 and 3. A 3D surface scan was made of the amputee’s residual limb with him in a relaxed, seated position. The scan was made using a Creaform MetraScan 3D Scanner resulting in an STL output file which was sliced to only include the necessary portion of the forearm. The sliced output was then used as the base for the sock liner pattern and CAD modelling of the socket.

2) CAD modelling

The 3D Scan STL was imported into CAD as a base for the socket. The CAD body was shelled by 4 mm and then by a further 5 mm to represent the sock liner and socket respectively. This created 3 separate bodies. The outer 5 mm shell was then isolated for further CAD modelling.

a) First Iteration

The outer shell was divided into the three sections shown in the third image from the left in Fig. 4: The upper collar, middle section, and bottom collar. This was done so that the middle section could be isolated for lattice optimization without affecting the collars. The inner shell and original solid body were subtracted from the outer shell to create a hollow shell that was used to fit the amputee’s arm profile. The unique features of the end of the residual limb functioned as locating/orientating features for the socket and sock and thus it was separated from the main section of the forearm CAD body as shown in Fig. 5.
b) Second Iteration

For the second iteration of the socket, a new suspension method was introduced that required the socket to be more flexible to allow clamping onto the arm. Vertical slots, shown in Fig. 6 were introduced to allow the socket to flex when tightened. The trim lines of the socket were also improved by shortening the socket to allow more range of motion and reduce interference in the bend of the arm. A frame of 5 mm was created around the bottom half of the socket to serve as an endpoint for the lattice. The frame was shelled to create an internal channel around the circumference that covers and guides the suspension system wires.

c) Sock liner design

The sleeve design process was as follows and is shown in Fig. 7:

1. Slicing of the 3D Scan of the arm into the desirable size.
2. Generation of a surface mesh of the sliced scan.
3. Simplification of the mesh and conversion into a flat pattern using patterning software (ExactFlat) [10].

d) Suspension system

The suspension system shown in Fig. 8 and 9, was an FDM 3D Printed ratchet mechanism using ABS plastic. It consisted of a base, spool, pawl, engager/ratchet gear and cap. To tighten the socket the cap was pressed down to engage the pawl. The cap was joined to the engager mechanism with superglue. The cap was then turned clockwise which engaged the pawl and wrapped the wire around the spool. The pawl locked the spool in place and prevented the wire from unwinding. When the socket needed to be removed or loosened during the day, the cap was pulled up into the free position, which disengaged the pawl and allowed the spool to unwind freely. The system was held together by an embedded nut and bolt. The same bolt was used to hold the suspension system on the socket base.

3) Lattice optimization

For the lattice optimization aspect of the design, the following procedures were carried out:

a) First Iteration

The mid-section of the outer socket was isolated for focused lattice design whereas the wrist collar and elbow collar were maintained as solid entities for further design integration purposes. To maximize airflow and overcome the heating discomfort experienced by users with standard sockets, it was decided to employ a lattice configuration from the onset. This would not only aid heat dissipation, but the

Fig. 4 The initial socket development showing from left to right: The arm solid model, cross-section of the solid arm with 4mm shell and 5mm shell, the modelled socket.

Fig. 5 Locating features of the end of the arm

Fig. 6 Development of the second iteration socket base from left to right: Base solid socket, 5 mm frame generated on socket, solid frame isolated for integration with the lattice

Fig. 7 Development of the sock liner from left to right: The meshed arm scan, the split up flat pattern of the mesh, the flat pattern converted to a usable PDF pattern

Fig. 8 Assembly view of the ratchet suspension mechanism

Fig. 9 Section view of the ratchet suspension mechanism

Fig. 10 Development of the socket lattice from left to right: Mid-surface of socket solid, ramped points and mesh, generated lattice, solid model of lattice
inherent structural layout of the lattice structure would be naturally self-supporting. Furthermore, with the SLS-AM approach intended, wherein nylon powder particles are fused together layer by layer, this design enabled a support-free print and further staining to achieve the colour output requested by the user [11].

The design procedure required the setting up of a reusable workflow utilizing an imported input STL, converting this to an implicit format model and then applying multiple processes to this implicit model - this then created the desired design output to achieve a functional, unique, and aesthetically beautiful design, advised by organic contemporary designs. After many design iterations to hone the design into the desired outcome, the output was then exported to CAD format for further integration into the overall design flow.

b) Second iteration

The second iteration required increased flexibility and thus a variable density lattice was utilized, with the density decreasing to the point of maximum deflection and increasing to the point of the maximum required stiffness at the wrist. The lattice was split up into three parts, the main body and the two bottom sections.

CAD models of all the sections to be latticed were converted to mid-surfaces in order that the generated lattice could be thickened equally to the inside and outside. These mid-surfaces were imported into nTopology. The process for development of the base mesh followed a similar step-wise creation of a workflow for this new design, this again involved the conversion of the CAD files into implicit bodies based on fields. An initial surface mesh was generated on these mid-surfaces and was then used as a basis for ramping up the mesh spacing using scalar fields. Random points were generated on the ramped mesh, which caused the spacing between the points to be ramped according to the mesh spacing. The random points and ramped mesh were used to generate a lattice that was then thickened.

Again, the generated implicit body was iterated over multiple studies to achieve the desired configuration before finally being converted to a CAD body for export. This workflow, when designed correctly, is entirely reusable for any CAD surface body, and thus the process was repeated for the bottom sections. The process can be reused for future iterations by inputting different socket base surfaces.

III. STRENGTH AND FATIGUE CALCULATIONS

Structural strength and fatigue calculations were done on the ratchet system that fastens the socket to the residual arm. The wire that tightens around the socket created a torque on the ratchet as indicated with a blue arrow in Fig. 11. This induced a reaction force from the pawl indicated with red arrows on Fig. 11. The mechanical properties of the material used for the calculations are shown in Table 1 [12].

TABLE I. MECHANICAL PROPERTIES OF ABS PLASTIC USED FOR 3D PRINTING THE RATCHET MECHANISM

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>59 MPa</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>70 MPa</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>3.75 GPa</td>
</tr>
</tbody>
</table>

The distance between the wire and the center of the ratchet mechanism is 15 mm and the force in the wire is 3 kg.

\[
T = F \times d
\]

\[
T = \text{Torque (N.m)}
\]

\[
F = \text{Force (N)}
\]

\[
d = \text{Distance from wire to centre of mechanism (mm)}
\]

The distance from the center of the mechanism to the center of the pawl arm is 9.833 mm. From the torque, the reaction force on the pawl is calculated from (2).

\[
R = \frac{T}{d_2}
\]

\[
R = \text{Reaction force (N)}
\]

\[
d_2 = \text{Distance from centre of mechanism to centre of pawl arm}
\]

Reaction force on each pawl = \[\frac{441.45}{9.833} = 44.895 \text{ N}\]

A. Stresses on the pawl

The forces on the pawl are shown in Fig. 12. The cantilever beam, and cross section of the pawl are shown in Fig. 12 also.
The reaction forces on the pawl were determined from (2). The moment of inertia of the pawl was determined from (3).

\[ I = \frac{1}{12} \times w \times h^2 \tag{3} \]

The cross-sectional area of the pawl is calculated from (4).

\[ A = w \times h \tag{4} \]

The reaction force was broken up into its horizontal and vertical components from (5) and (6).

\[ F_h = R \times \sin(\theta) \tag{5} \]

\[ F_v = R \times \cos(\theta) \tag{6} \]

The distance from the applied force to the base of the cantilever is 5.9825 mm and the length of the cantilever is 7.17 mm. The reaction force on the ratchet is calculated using the deflection formula for a cantilever beam in (9).

\[ \Delta = \frac{6 \times P \times E \times l}{3 \times (w \times h)^2} \tag{9} \]

The reaction force from (7), reduces the effect of the bending moment to virtually zero. The maximum normal stress on the pawl is calculated from (8).

\[ \sigma_{\text{max}} = \frac{F_v}{A} \tag{8} \]

The deflection of the pawl was needed when tightening. The reaction force needed to deflect by 0.5 mm to allow the ratchet to turn when tightening the socket. The deflected pawl is indicated in Fig. 13 with a red line, and the original pawl position with a black line, showing the deflection distance. The force needed to deflect the pawl is indicated with a red arrow. The force needed to deflect the pawl is calculated from the deflection formula for a cantilever beam in (9).

\[ P = \frac{\Delta \times 6 \times E \times l}{(3 \times (w \times h)^2)} \tag{9} \]

The bending stress on the pawl due to the force from (9) is calculated from (10).

\[ \sigma_{\text{bending}} = \frac{M \times y}{I} \tag{10} \]

The equivalent stress on the pawl is calculated from (15).

\[ \sigma_{\text{eq}} = \frac{\sigma_{\text{bending}} + 3(t)^2}{2} = 56.356 \text{ MPa} \tag{15} \]

\[ \sigma_{\text{eq}} = \text{Equivalent stress (MPa)} \tag{15} \]

**C. Pawl Fatigue Calculations**

The reduction factors for a bending scenario follow, all reduction factors are from [13].

\[ \sigma_{\text{eq}} = \frac{\sigma_{\text{bending}} + 3(t)^2}{2} = 56.356 \text{ MPa} \tag{15} \]

Reliability factor = \( C_{\text{rel}} = 0.814 \) (assume reliability = 99%)

\[ C_{\text{surf}} = \text{Surface finish factor} = 1 \tag{16} \]

\[ D_e = \sqrt{\frac{A}{\pi}} \geq 2 \text{ mm} \tag{16} \]

\[ D_e = \text{Equivalent diameter of pawl (mm)} \tag{16} \]

Size factor = \( C_{\text{grad}} = 1 \) (values over 1 default to 1)

\[ \text{Overall reduction} = C_{\text{total}} = C_{\text{grad}} \times C_{\text{load}} \times C_{\text{temp}} \times C_{\text{surf}} \times C_{\text{grad}} = 0.814 \tag{17} \]

The stresses at 10^3 and 10^6 cycles are calculated from (18) and (20).

\[ s_{10^3} = 0.9 \times \sigma_{\text{fat}} = 63 \text{ MPa} \tag{18} \]

\[ s_{10^6} = 0.4 \times \sigma_{\text{fat}} = 20 \text{ MPa} \tag{19} \]

\[ s_{10^6} = 5n' \times C_{\text{grad}} = 22.792 \text{ MPa} \tag{20} \]

Using the Power law constants, a and b are calculated from (21) and (22).

\[ a = \frac{(s_{10^3})^2}{(s_{10^6})} = 174.14 \tag{21} \]

\[ b = -\frac{1}{2} \log \frac{s_{10^3}}{s_{10^6}} = -0.1472 \tag{22} \]
Stresses for loading cycle block 1 when the cables are being tightened are calculated from (15) and the fatigue life for this cycle block from (23) and (24).

\[ \sigma = \sigma_{eq} = 56.356 \text{ MPa from (15)} \]

\[ N = \sqrt{\frac{\sigma}{\sigma_{eq}}} = 2132.142 \text{ cycles} \]  

(23)

Days to failure if adjusted 4 times per day
\[ = 533 \text{ days [almost 1.5 years]} \]  

(24)

Stresses for loading cycle block 2 when the cables are holding the static load, are calculated from (8) and the fatigue life for this cycle block from (25).

\[ \sigma = \sigma_{y} = 7.683 \text{ MPa from (8)} \]

\[ N = \frac{1}{\sqrt{\frac{\sigma}{\sigma_{y}}} = 1.612 \times 10^{9} = \infty \text{ Cycles}} \]  

(25)

Fig. 14 shows the Goodman designer diagram for the loading of the ratchet mechanism. The blue line represents the yield line of ABS plastic, whilst the red line represents the Goodman line which connects the fatigue stress of 22.792 MPa at 10^6 cycles as calculated from equation 21, to the ultimate tensile stress of 70 MPa. The equivalent stress of 56.356 MPa from equation 16 is indicated on Fig. 14 by a red cross and it is evident that it is below the yield line, reassuring that the component will not fail due to yielding. Fig. 15 shows the S-N fatigue curve for the ratchet mechanism 3D printed using ABS plastic. The red line indicates an initial stress of 63 MPa at 10^4 cycles as per equation 19. The stress tapers down to 22.792 MPa at 10^6 cycles as per equation 21. The blue line indicates the point where the equivalent stress of 56.356 MPa cuts the red fatigue line. At this point the fatigue life expectancy due to the equivalent stress is 2100 cycles.

IV. FINITE ELEMENT ANALYSIS

Finite element analysis was conducted on the moving parts of the ratchet mechanism. The global triangular mesh had an element size of 0.8 mm, but discretization was applied at the point of interest as indicated in Fig. 16. The mesh size at this point was 0.2 mm. The point of interest was the fillet on the pawl arm, as this was expected to create a stress concentration. The pawl was constrained on the inside faces as it would be when the ratchet was assembled. There were two load cases, the first case being when the socket has been fastened and the ratchet is preventing the spool from unwinding and the second case when the socket is being fastened and the pawl must deflect to wind the spool.

For the first scenario, loads were applied to the outside gear teeth to simulate the tension that the wire would cause when the socket is fastened and holding the static load. The stress concentration raised the maximum stress to 17.962 MPa in the fillet area as shown in Fig. 18. The stress at the start of the pawl arm was 7.899 MPa based on the FEA. The calculated stress at this point according to equation 9 was 7.683 MPa. The error margin between these two values was 2.734% and was therefore acceptable and indicated a good correlation between simulation and calculation results.

For the second scenario, the same mesh setup was used as for scenario 1. The calculated reaction forces of 6.264 N were applied to each pawl arm as shown in Fig. 17. The maximum stress was again expected to be at the fillet of each arm. The maximum stress of 60.23 MPa was found at the fillet of each arm.
The calculated maximum stress was 56.356 MPa, the error margin between these two values was 6.4 \% which again indicated reasonable accuracy. Both maximum stress values from scenarios 1 and 2 were below the yield strength of ABS plastic of 70 MPa.

### TABLE II. COMPARISON BETWEEN CALCULATED AND SIMULATED STRESSES

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Finite element analysis results (MPa)</th>
<th>Calculated results (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First load scenario</td>
<td>7.899</td>
<td>7.683</td>
</tr>
<tr>
<td>Second load scenario</td>
<td>60.23</td>
<td>56.356</td>
</tr>
</tbody>
</table>

### V. THERMAL ANALYSIS

A comparative transient thermal analysis was conducted on the second iteration socket and a solid version of the same socket. The objective was to establish the latticed socket’s ability to keep the residual arm cool and allow proper ventilation to minimize perspiration. The analysis was done by setting the initial temperature of the arm to 36 °C [14] and the temperature of both sockets to ambient temperature 25 °C.

As this was a comparative study with conditions being the same in both cases, ambient convection was neglected to speed up computation. Therefore, only conduction between the arm and socket was considered. As seen in Fig. 20 and Fig. 21 the minimum arm temperature with the latticed socket was 23.696 °C compared to the minimum temperature of the arm with the solid socket being 33.445 °C. This proved that the latticed socket was more efficient in conducting the heat away from the arm than a solid socket of the same shape and material. The warmer part of the latticed socket arm was due to the increased lattice density, this was unavoidable as the increased density was needed to ensure adequate lattice stiffness at the wrist. The materials and their respective properties are shown in Table 3 [15], [16], [17].

### TABLE III. THERMAL PROPERTIES OF THE MATERIALS USED IN THE THERMAL ANALYSIS OF THE SOCKETS

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (W/m K)</th>
<th>Thermal expansion coefficient (1/K)</th>
<th>Specific heat (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neoprene</td>
<td>0.19</td>
<td>0.00014</td>
<td>2200</td>
</tr>
<tr>
<td>Nylon PA 650</td>
<td>0.243</td>
<td>0.000008</td>
<td>1527</td>
</tr>
</tbody>
</table>
VI. MANUFACTURE AND ASSEMBLY

The first iteration of the socket, shown on the left in Fig. 22, was 3D Printed support-free in PA 650 Nylon and did not require any further assembly to be able to function. It was attached to the Touch Hand device for successful use at the 2020 Global Cybathlon competition [18]. The second iteration, shown on the right in Fig. 22, would also be printed in PA 650 Nylon but has additional parts and required further assembly. After the socket is printed, the brass inserts would need to be inserted using a soldering iron to heat the inserts. Care should be taken to avoid misalignment when inserting the inserts in the printed holes. The wrist clamp can then be screwed onto the socket using the brass inserts and M3 cap screws. The ratchet mechanism is assembled separately and attached to the socket using a bolt and nut.

VII. TESTING AND RESULTS

The two iterations of the socket were compared to a carbon fibre socket of the same shape and a socket available on the market, in terms of weight and cost.

A. Specification Comparison

Table 4 shows a weight comparison of the first socket used in the 2020 Cybathlon race, the second iteration socket, a carbon fibre socket of similar shape to the 3D printed sockets discussed in this paper and the Touch Bionics iLimb socket which is a socket available on the market [19].

The first iteration socket was the lightest of all the sockets with a weight of 92 grams. The second iteration of the socket was heavier than the first, due to the increased lattice density and extra material to support the suspension mechanism. The weight of the second iteration lattice socket was on par with the weight of a carbon fibre socket of similar shape. Both these weights were significantly less than the weight of the Touch Bionics iLimb, which is a readily available socket. The increase in weight from the first iteration to the second iteration can be justified by the increased performance of the suspension mechanism and the fact that it still weighs significantly less than other options available on the market [20].

<table>
<thead>
<tr>
<th>TABLE IV. WEIGHT COMPARISON OF SOCKET ITERATIONS AND MARKET COMPETITOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of the socket without attachments (grams)</td>
</tr>
<tr>
<td>Cybathlon socket</td>
</tr>
<tr>
<td>Second Iteration</td>
</tr>
<tr>
<td>Carbon fibre socket</td>
</tr>
<tr>
<td>Touch Bionics iLimb</td>
</tr>
</tbody>
</table>

B. 2020 Cybathlon testing

The first iteration of the socket was used in the 2020 Global Cybathlon in the powered arm prosthetics race division as a socket for the Touch Hand prosthetic device. The race was an obstacle course, as shown in Fig. 23, where the obstacles ranged from very fine movements like inserting a credit card into a card slot to vigorous movements like driving a nail into a piece of wood using a hammer. This provided an excellent test for the practicality and functionality of the socket. During these races, it was found that the snap fit clips used for the wrist connection, in the first iteration of the socket, disengaged when the hand was bumped against an object in a lateral direction. The first iteration of the socket relied on the friction between the socket and sock liner to suspend the socket on the arm. It was found that the socket slipped off the arm after extended use. This was due to the residual arm shrinking due to water loss from sweat. The neoprene liner contributed largely to the increased sweating on the residual arm and thus the conclusion was drawn that a neoprene liner was not a viable option and needed to be replaced.

VIII. CONCLUSION

The unique design method followed in this research allows rapid prototyping of prosthetic sockets that fit any long residual arm shape. The reusable workflow used to design the socket reduces the time taken on model setup and preparation,
allowing faster manufacturing and therefore the amputee can receive the needed assistive device much faster.

From the stress calculations, the ratchet mechanism was modelled as a cantilever beam. It was shown that the maximum stress for both loading scenarios being 7.683 MPa for scenario 1 and 56.356 MPa for scenario 2 agreed with the FEA results. Both these maximum stresses were under the yield strength of 70 MPa. Fatigue calculations were done using the Modified Goodman formulation method and it was shown that if the socket was adjusted four times daily the pawl mechanism would need replacement after 1.5 years. This part is very affordable and easily replaced and thus it is a viable option for extended use in a real-life scenario. In table 4 it was shown that by using lattice optimization the weight of the socket is 90% less than the weight of other options available on the market. The weight of the socket described in this paper was 93 grams compared to other options on the market that weigh 895 grams.

At the 2020 Cybathlon competition testing, it was found that a neoprene liner does not work effectively and causes sweat build-up after extended use. It was also found that a snap-fit connection is ineffective for real-life applications and is not conducive to additive manufacturing. Due to this finding, the second iteration utilized a much more durable aluminum clamp instead of 3D printed snap-fit clips. It was found that the friction suspension method of the first iteration does not work effectively when compared to an active ratchet suspension system. Due to fluctuations in arm size during routine use, the friction socket starts to slip, but the ratchet system can be adjusted periodically, offsetting the change in arm size.

The transient thermal analysis showed that the lattice optimized socket allowed a much better heat dissipation and therefore better breathability when compared to a solid socket of the same shape. The latticed socket resulted in a final minimum arm temperature of 23.696 °C compared to an arm temperature of 33.445 °C using the solid socket.

The research contributions of this paper were achieved by:

- The design and development of a socket that allows periodic adjustment due to expansion of the residual limb due to temperature;
- the socket was designed, developed, manufactured, and successfully tested & used by an amputee pilot in the 2020 Cybathlon event.
- The development of a reusable implicit workflow for designing bespoke prosthetic sockets.
- The lattice optimization of a prosthetic socket to reduce weight and improve breathability was achieved.
- The optimized prosthetic socket showed breathability, with reduced swelling, when utilized in the 2020 Cybathlon event.

**ACKNOWLEDGMENTS**

Huge thanks & appreciation must go out to all these individuals for their completely selfless contribution to this project, be it for information, advice, their time, their contacts, their services, or whatever contribution they made, no matter how big or small. The team acknowledges Altair, Volkswagen South Africa, Jendamark, Prof Theo van Niekerk at Nelson Mandela University, eNtsA, Rapid3D, Axiology Labs, nTopology, Faulhaber, Altair, VWSA, Horne Technologies, Department of Science and Technology ROSSA programme, Embassy of Switzerland to South Africa, Dr Bryan Theunissen at Livingstone Hospital, Custom Works, Nicky Roote Physiotherapy, Sthuthi Varghese, Charl Rossouw, Zain Imran, Dr Zithulele Tshabalala, Axxess, BunnyCorp, Robotics Association of South Africa, Serendipity, Lungile Dick and Darren Hauptfleisch

**REFERENCES**


A Mobile and Portable Pre-ICU AM-produced BI-PAP Ventilator System in Response to COVID-19 Challenges

Zaahid Imran
Department of Mechanical Engineering
Nelson Mandela University
Port Elizabeth, South Africa
Zaahid.Imran@mandela.ac.za

William Rall
Department of Mechanical Engineering
Nelson Mandela University
Port Elizabeth, South Africa
William.Rall@mandela.ac.za

Clive Hands
Department of Mechanical Engineering
Nelson Mandela University
Port Elizabeth, South Africa
Clive.Hands@mandela.ac.za

Riaan Stopforth
Stopforth Mechatronics, Robotics and
Research Lab
University of KwaZulu-Natal
Durban, South Africa
stopforth.research@gmail.com

Abstract—The focus of this paper is to present the research,
design, manufacturing, and testing of the different iterations of
pusher arms on a custom mechanical ventilator using state-of-the-art additive manufacturing techniques and technologies,
which presents an affordable and local solution with rapid and
easily updatable manufacturing of the various components. The
ventilator parts were printed using Onyx® material providing
a significant increase in strength and fatigue-resistance than
standard Fused Filament Fabrication (FFF) materials typically
used. All components have been designed with the standards
CE0085 and CE0086 in mind, to complete and pass certification
processes. The cost of the ventilator in its current format was
US$850 whereas an equivalent imported machine costs a
minimum of US$2,500. Various computational analyses were
performed on the major components including dynamic motion
simulations, fatigue simulations and finite element analysis
(FEA) verification simulations, to confirm that each component
functions in a manner which represents the goals of the project
without resulting in failure due to yielding, fatigue loading and
static loading. The current design lays the foundation for future
development projects relating to the optimization of the
ventilator.

Keywords—AM, BI-PAP, Ventilator, COVID 19, Optimization, FEA.

I. INTRODUCTION
A ventilator is a machine that helps a patient breath if the
patient is unable to do so by themselves. The machine pushes
air and oxygen into and out of the lungs. These ventilators are
normally referred to as mechanical ventilators or respirators
and the main function is to take over the breathing system of
a patient using tubes and masks allowing the patient to breathe
while they are fighting off infection. A ventilator is essentially
a pump delivering air by positive pressure to the patient. For
the ventilator to know how much air it must administer into
the patient per breath, it must be controlled beforehand by
adjusting settings available. All the modes of control in a full-
blown ventilator are time controlled but are limited by volume
or pressure. Finally, the ventilator must also be activated by
the patient as to when starting delivery of oxygen, and this is
what is known as triggering [1].

An early challenge for first-responders was the availability
of both Continuous Positive Airway Pressure (CPAP) and
Bilevel Positive Airway Pressure (Bi-PAP) portable & easy-
to-implement ventilators en-route to ICU [2]. In response to
the shortage of ventilators in the early stages of the
coronavirus pandemic, the need for the design of a low-cost,
portable ventilator that automatically inflates and deflates an
Ambu-Bag, as per individual requirements, was initiated [3].

The ventilator is derived from the open-source MIT Bag
Valve Mask platform that meets international clinical
requirements for a medical respiratory device. Automating the
procedure of compression appeared to be the simplest strategy
to satisfy the need for low-cost mechanical ventilation, with
the ability to also be rapidly manufactured at scale, and
deployed quickly for first responders [4]. Producing this via
available local Additive Manufacturing (AM) resources
would also be substantially cheaper than the conventional
ventilator currently imported into the country at significant
cost.

A report in March 2020 by News24 argued that South
Africa (SA) appeared to be woefully underprepared for a
serious escalation of Covid-19 cases, with roughly 3,000 out
of about 7,000 critical care beds available between the public
and private healthcare sectors, according to best estimates [5].

The SA Managing Director (MD) of Draeger, a German
producer of ventilators worldwide, stated that there were
currently no manufacturers of ventilators in South Africa,
which relied completely on suppliers who import the
machines from various countries including the US, Germany,
and China [6].

The grim reality is that there was a global undersupply of
ventilators and Africa, and by extension South Africa, was not
currently on the top of supply lists. There were an estimated
4,000 ventilators in the private health sector, and about half
that number in the public sector [7].

Renai Moothilal, the executive director of the National
Association of Automotive Component and Allied
Manufacturers (NAACAM), who were also busy with a
ventilator project, stated that not all the ventilators in SA would be available to Covid-19 patients only since many were already in use [8]. Even if ventilators had become available from international sources, it would've been difficult to get these ventilators to SA since all international flights were suspended and no goods were allowed in and out of the country [9]. Hence the opportunity to urgently develop local, portable, and low-cost automated ventilators existed.

When a person’s lungs inhale and exhale air normally, oxygen is taken into the cells to survive and carbon dioxide is expelled. A patient suffering from covid-19 in severe cases has an inflamed airway which essentially causes the lungs to drown in fluids. A mechanical ventilator helps pump oxygen into the lungs at a rate required for normal breathing [10].

This design for this research paper contributes in the following manners:
- It provides a means for low-cost, portable ventilation
- A device that has a medically-approved interface with the patient
- Specifically a last resort device as an aid to give patients enough time to reach ICU

II. MECHANICAL AND ELECTRONIC DESIGN CONSIDERATIONS

The primary focus of the analysis is on the different design iterations of pusher arms and their dependent parts as seen in Fig. 1.

The articulation system started off with a single pusher arm that inflated and deflated the Ambu-bag as seen in Fig. 2. The pusher arm has a flat and large surface area to ensure maximum deflation. A major problem with this configuration of pusher arm was that, as the arm engaged the bag, the bag would fold into the base of the pusher arm making it harder to compress, therefore the pusher arm had to be redesigned as seen in Fig. 3. The next iteration of the pusher arm then consisted of a much finer rack and the arms have a more rounded contact-piece of material that bulges out of the top face of the arm. This eradicated the folding issue faced initially with the Ambu-bag. From this point onwards a series of shape optimization processes on the pusher arms were conducted until the pusher arm reached the stage as seen in Fig. 1. The ventilator in its final form consists of a two-pusher arm rack-and-pinion drive system, which is activated by a servo motor. The electronic system consists of a microcontroller and an HMI interface that allows the user to alter certain variables on the ventilator.

The following calculations have been utilised to determine the variables that will be used as a basis for the simulations that have been performed.

Calculation below will be assuming the worst-case scenario of the system being:
- Maximum pressure at airway: \( P_{\text{airway max}} = 40 \text{ cm } H_2O \) (pop off cracking pressure)
- Maximum respiration rate: \( RR_{\text{max}} = 40 \text{ BPM} \)
- Minimum inhale/exhale ration: \( I:E_{\text{ratio min}} = 4 \)
- Maximum volume output: \( V_{\text{max}} = 800 \text{ cm}^3 \)
This is the worst case the device needs to squeeze the bag at an air pressure of 40 cm H₂O in a 0.3 second \( t_{inhalе} \) sec / \( RR_{max} \) (1+E_{ratio min})

The volumetric flow rate needed in the worst case (peak) scenario is:

\[
Q_{airway} = \frac{v_{max}}{t_{inhalе}} = 0.0027m^3/s
\]  (1)

The power output in the form of pressurized volume flow in the airway is:

\[
P_{airway} = P_{airway max} \times Q_{airway} = 10.46W
\]  (2)

However, some of the power used to squeeze the bag is lost due to factors such as friction and bag deformation. Therefore, an estimate of 50% is converted to pressurized volume flow. Taking this efficiency into account the power required at the gripper is:

\[
P_{gripper} = 2P_{airway} = 20.92W
\]  (3)

The actual power needed from the motor will be higher depending on the mechanical and electrical system. Assuming half the power is lost due to mechanical and electrical efficiencies, the power output required by the motor is:

\[
P_{motor} = 2P_{gripper} = 41.84W
\]  (4)

Calculating the pressure, the Ambu bag exerts on the pusher arm:

Using the first iteration of the pusher arms as an example:

\[
P_{pusher} = \frac{F}{A}
\]  (5)

Where:

- \( P_{pusher} \) = Pressure acting on pusher arm pressure plate MPa
- \( F \) = Force acting on pusher arm pressure plate N
- \( A \) = Area of pusher arm pressure plate m²

Pusher arm 1

\[
P_{pusher} = \frac{13.483}{0.00124726} = 0.01081MPa
\]

To calculate the maximum force of the bag on one finger when fully squeezed using the same 50% pressure transmission efficiency as earlier the following equations can be used:

\[
F_{finger} = 2 \times A_{bag contact} \times P_{airway,max}
\]  (6)

\[
A_{bag contact} = 0.001718609m^2
\]

\[
P_{airway,max} = 3922.66Pa
\]

\[
∴ \ F_{finger} = 2 \times 0.001718609m^2 \times 3922.66Pa = 13.48N
\]

All the calculated data is depicted on the ventilator system in Fig. 4.

Fig. 4. Variables used for simulations

III. METHODOLOGY, RESULTS AND DISCUSSION

The following FEA verification tests were performed on all the different iterations of pusher arms. It is important to note down that the Pusher arms were additively manufactured in Onyx® which is a composite of Nylon (PA6) and chopped Carbon fibres [11]. The material properties can be seen in Table I as well as a stress-strain diagram in Fig. 5 to indicate the compressive properties of Onyx® [12]. Assumptions that were made when conducting these FEAs were the material properties being isotropic throughout the pusher arms, the pressure acting uniformly over the pressure plate of the pusher arms, and finally assuming that all the loading and boundary conditions were applied at the worst-case loading scenario.

<table>
<thead>
<tr>
<th>Composite Base</th>
<th>Test (ASTM)</th>
<th>Onyx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Modulus (GPa)</td>
<td>D638</td>
<td>2.4</td>
</tr>
<tr>
<td>Tensile Stress at Yield (MPa)</td>
<td>D638</td>
<td>40</td>
</tr>
<tr>
<td>Tensile Stress at Break (MPa)</td>
<td>D638</td>
<td>37</td>
</tr>
<tr>
<td>Tensile Stress at Break (%)</td>
<td>D638</td>
<td>25</td>
</tr>
<tr>
<td>Flexural Strength (MPa)</td>
<td>D790</td>
<td>71</td>
</tr>
<tr>
<td>Flexural Modulus (GPa)</td>
<td>D790</td>
<td>3.0</td>
</tr>
<tr>
<td>Heat Deflection Temp (℃)</td>
<td>D648 B</td>
<td>145</td>
</tr>
<tr>
<td>Flame Resistance</td>
<td>UL94</td>
<td>–</td>
</tr>
<tr>
<td>Izod Impact - notched (J/m)</td>
<td>D256-10</td>
<td>330</td>
</tr>
<tr>
<td>Surface Resistance (Ω)</td>
<td>ANSI/ESD STM11.11</td>
<td>–</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>–</td>
<td>1.2</td>
</tr>
</tbody>
</table>
A. FEA Verification on Iteration 1

The first iteration of the pusher arm was to indicate where the stress high spots were present as in Fig. 9. The FEA was performed with a standard mesh size with no refinement, as seen in Fig. 7, as this was used as the benchmark for an indication of hot spots as mentioned earlier. In subsequent iterations, fillets were included as well as localized discretization in specified areas to refine the mesh model. Linear static simulations were performed with the boundary conditions set at the worst case loading scenario the pusher arm will experience, as seen in Fig. 6. As shown, the pressure acts perpendicular to the pressure plates, the pusher arm has a sliding constraint on the railing and a constraint was placed on the meshing tooth which ensures that the pusher arm does not move away from the gear mesh. In Fig. 8 it can be clearly seen that the hot spot region occurred at the expected area where a stress concentration exists, and therefore explicit consideration in this area was necessary for subsequent iterations.
B. FEA Verification on Iteration 2

The second iteration pusher arm was a complete redesign from the first pusher arm - problems faced from the first simulation study were addressed firstly in the design of the second iteration, especially in the hot spots recognized from the first iteration. The same simulation methodology used for the base design iteration was applied to the subsequent design iterations. The boundary conditions for iteration 2 are shown in Figures 10 and 11. The simulation was run initially with a base global mesh size with additional discretization in the filleted areas, reducing down to an element size of 0.5mm as seen in Fig. 11. From there a convergence study was done in the high stress zone, which in this case is the fillet as seen in Fig. 12 and Fig. 13, to obtain more precise results - between all studies the error margin was within 5% therefore convergence was assumed to be achieved.

C. FEA Verification on Iteration 3

The third iteration took a different approach to the design. This pusher arm was designed to accommodate the possibility of injection moulding and, instead of having a fillet at the noted high stress zone, a rib was inserted. However the study confirmed that the hot spot was in the same region as the previous iterations as seen in Fig. 17. Further discretization of 0.5mm was performed on the filleted areas in tandem with a standard global mesh size as seen in Fig. 15. Again a convergence study was carried out in the high stress zone and all studies proved to be within a 5% error margin and thus convergence was assumed to be acceptable. The loading boundary conditions remained exactly the same as the previous iteration as seen in Fig. 14. All FEA verification simulations were performed as seen in Fig. 16.
The final iteration of the pusher arm was designed with the intent to remove as much stress concentration in hot spots previously encountered. In this scenario the high stress region can be seen in Fig. 21. The simulation study was then re-performed as seen in Fig. 20 using standard global mesh size of 0.5mm discretization in the high stress area as seen in Fig. 19. Again a convergence study was carried out and results were within 5% error margin as expected therefore convergence was acceptable. The loading boundary conditions remained exactly the same as the previous iterations as seen in Fig. 18.
IV. Tests and Results

All the data extracted from all the simulations performed above have been tabulated in Table II and various graphs have been plotted to compare data.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Von Mises Stress (MPa)</th>
<th>Displacement (mm)</th>
<th>Safety factor (Fatigue)</th>
<th>Compressive stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.690</td>
<td>0.100</td>
<td>57.987</td>
<td>0.539</td>
</tr>
<tr>
<td>2</td>
<td>2.280</td>
<td>0.420</td>
<td>17.547</td>
<td>1.537</td>
</tr>
<tr>
<td>3</td>
<td>3.232</td>
<td>0.456</td>
<td>12.377</td>
<td>1.318</td>
</tr>
<tr>
<td>4</td>
<td>1.117</td>
<td>0.229</td>
<td>27.882</td>
<td>0.857</td>
</tr>
</tbody>
</table>

The von Mises stress in the hot spots of all the pusher arms are shown in Fig. 22. Fig. 23 indicates the comparison of all the maximum deflections the different pusher arms experience at worst-case loading. Fig. 24 indicates the comparison of safety factors the different pusher arms exhibit and finally Fig. 25 indicates the comparison of compressive stresses in all the hotspots of all the pusher arms.
A. Costing and weight

The weightings and costing for the different iterations of the pusher arms are listed in Table III and compared to each other in Fig. 26. The costing is calculated based on the amount of material used and the time taken to print.

<table>
<thead>
<tr>
<th>Pusher Arm iteration</th>
<th>Weight (grams)</th>
<th>Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100.62</td>
<td>22.42</td>
</tr>
<tr>
<td>2</td>
<td>48.47</td>
<td>11.27</td>
</tr>
<tr>
<td>3</td>
<td>38.79</td>
<td>11.06</td>
</tr>
<tr>
<td>4</td>
<td>41.31</td>
<td>11.57</td>
</tr>
</tbody>
</table>

All the pusher arms were designed considering the design for additive manufacturing (DFAM) using Onyx® which is a composite material consisting of nylon and chopped carbon fibers. The pusher arms were all printed on a state-of-the-art Markforged desktop AM machine. Isotropic behavior of the material has been assumed considering the build orientation. It has been ensured that the build orientation is out of plane with the forces acting on the pusher arm to ensure shearing of the material does not occur as seen in Fig. 27. Furthermore Fig. 27 indicates that both the pusher arms for the ventilator can be printed in one batch with a possibility of adding duplicates to reduce the cost.
All the simulation studies conducted were computed assuming the worst case loading scenario to be static to simplify the analysis and ensure the design covered this scenario to inform the design. However all the loading boundary conditions were applied in such a way to imitate the real world scenario of the system. Most of the simulation studies were run with a standard global mesh size with further discretization carried out as required. Convergence studies were run on all iterations of pusher arms where fillets were present, and in all the error was within 5% variation of results and thus convergence was achieved. When conducting these simulation studies, reasonable assumptions were made to simplify analysis, such as the pressure acting uniformly over the pressure plates of the pusher arms. In the results, only subsequent iterations after the first iteration of the pusher arm were analysed and compared.

Looking at the comparisons in Fig. 22 to Fig. 25, it can be clearly seen that the most efficient and desirable pusher arm is the fourth iteration. This is due to the fact that the stresses that occur in the hot spots of this configuration are quite low in comparison to all the other iterations as seen in Fig. 22 and Fig. 25. We can see the maximum Von Mises stress on the pusher arm is 1.117 MPa while the maximum compressive stress that occurs is 0.857 MPa. It is important to note that the safety factor as depicted in Fig. 24 occurs in compression zone locations therefore fatigue failure is not an issue on this component. Moreover, the composite nature of the Onyx® material has built-in crack arrestors in the form of the short-fibre carbon whilst the Nylon PA6 matrix has recognized excellent fatigue and impact resistant properties too.

Furthermore this iteration of pusher arm has the least deflection of 0.229 mm off the original position and in a system like this an increase in deflection means a reduction in efficiency of airflow out of the Ambu-bag, therefore a more rigid structure is more desirable. Nonetheless, this deflection will not occur continuously in everyday usage, but only at the worst possible scenario which should never happen as the system has been programmed to never reach such a scenario.

Moreover we can see in Fig. 24 that this iteration of the pusher arm has a minimum safety factor of 27.882 at the high spot meaning that the possibility of failure at this location is minimal. The stresses are almost all occurring at locations where compressive stresses are dominant which influences the factor of safety results. Since compressive stresses do not result in fatigue failures, these compressive zones of failure are not important, and therefore do not have any significant design impact on the component.

Lastly, looking at Fig. 26 comparing the weights and costs of the different iterations of pusher arms, the third and fourth iteration have the least weight and cost with the third iteration weighing 38.79 grams and costing 11.06 USD and the fourth iteration weighing 41.31 grams and costing 11.57 USD. We can clearly see that the third iteration has the lower cost and weight, however the fourth iteration is still chosen for the assembly as a small sacrifice of weight and price can be quantifiable for a better and more efficient pusher arm. This is still around 50% of the initial benchmark’s mass, which further aids in light weighting and hence portability.

V. CONCLUSION

The results dictate that even under these over-conservative testing scenarios, the pusher arm will still perform optimally without failure under any reasonable circumstances. The initially selected concept design of pusher arm was adjusted during the design process to accommodate the standards of the industry to allow for a more dynamic, customisable design with further reaching applications. From all the tests, calculations and simulation studies, it has been proven that the fourth iteration of the pusher arm has more than adequate strength and therefore has passed all the necessary specifications needed to be used as a component in the ventilator assembly.

The pusher arms were designed on a basis of additive manufacturing using Onyx® on a state-of-the-art Markforged desktop AM machine. An extensive amount of research has been conducted on additive manufacturing and the materials used. The material properties have been studied and the impacts these properties have on the performance on all the applicable components has been conducted to ensure that all the additively manufactured parts will work successfully. Furthermore, research has been conducted on the Markforged to ensure that all components can be printed within one batch with the possibility of adding additional duplicates of components to reduce costs, and for quick service replacement should it be required.

Stiffness of the fourth iteration of the pusher arm is appropriate, achieving a maximum of 0.229 mm deflection under extremely conservative loading conditions. The safety factor of the pusher arm is also way more than adequate having a value of 27.882. Although it is worth noting that this value is achieved at the most critical scenario which in the real world will definitely not occur as programming constraints in the firmware of the ventilator ensures that this critical scenario will not occur. Furthermore, the minimum factor of safety only occurs at the locations that are in the compression zone therefore fatigue failure is not an issue on this component as fatigue is not affected by compression but only tension. This iteration experiences the least amount of stress as we can see the value of Von Mises stress and compressive stress are 1.117 MPa and 0.857 MPa respectively. Lastly an important factor that has been considered is the light weighting of the components to save costs on printing time and material and as seen in Fig. 26, the weight and cost-price of the component is within the range of the lowest compared to the other iterations, and very favourable compared to existing options available.

The contribution of the research was achieved in the following ways:

- The chosen pusher arm has a low cost which contributes to the total cost of the ventilator thus making the ventilator an affordable option.
- The pusher arm has enough strength and will aid in the medical certification process of the mechanical components
- A low cost ventilating system was designed and developed, which was constructed under a cost of US$ 850.00.
ACKNOWLEDGMENT

Huge thanks & appreciation must go out to all these individuals for their completely selfless contribution to this project, be it for information, advice, their time, their contacts, their services, or whatever contribution they made, no matter how big or small. The team acknowledges Altair, Rapid3D, Dr Liz van der Merwe at Livingstone Hospital and MerSETA.

REFERENCES

Geographical Education of the Visually Impaired
Using Braille System on Physical Models

Sanat Agrawal
Department of Mechanical Engineering
National Institute of Technology
Uttarakhand, India
sanata@nituk.ac.in

Vikas Khoj
Department of Mechanical Engineering
National Institute of Technology
Uttarakhand, India
vikaskhoj@gmail.com

Deon de Beer
Dept. of Mech. and Mechatronics
Engg
Central University of Technology
Free State, South Africa
ddebeer@cut.ac.za

Abstract—Education of the visually impaired has been a
challenge. Visually impaired persons, whether with complete or
partial impairment, require education for their social, economic
and day-to-day activities. There is a good amount of study
material available for them in the Braille system. However,
limited work has been done on representing maps, particularly
3D maps, for their education. The research presented here
reflects on the use of additive manufacturing (AM) of physical
models of some South African landscapes using GIS data.
Legends in Braille on the physical models of the Table
Mountain, Western Cape, and the Amphitheatre, KwaZulu-
Natal, are provided for geographical education of the visually
impaired.

Keywords—Additive Manufacturing, Braille, visually
challenged persons, GIS data, STL file format, physical maps.

I. INTRODUCTION

There have been significant advances in education of the
visually impaired since the development of Braille code, a
tactile writing system, by Louis Braille in 1824. There have
been several attempts in making maps for the blinds to assist
them in mobility and education. However, education of the
visually blind using tactile systems has been a challenge.
Education of geography for the visually impaired has been
particularly challenging where a person with vision can
understand geography by looking at a scaled down model or
by visiting a real site. A sighted person can get the three-
dimensional perception by mere movement of the head. This
perception is not available to the visually impaired. In such a
case, a physical model of a geographic region with legends in
Braille can provide a haptic experience to the visually
impaired and assist him in education.

This research presents a methodology to make physical
maps of geographic regions with legends in Braille. Additive
Manufacturing (AM), popularly known as 3D Printing, has
provided an opportunity to print such physical maps. AM
takes the CAD model of a part as an input and fabricates the
part layer-by-layer in a matter of hours without any human
intervention. In contrast to the machining processes such as
CNC, where the material is removed, this process is additive
in nature [4, 5]. The part is grown layer-by-layer without using
any tools. This is also called tool-less manufacturing. There
are several monikers of the process such as desktop
manufacturing, layered manufacturing technology, solid
freeform fabrication (SFF), automated fabrication and rapid
prototyping (RP). The research aim is to use the AM process
to fabricate physical maps of geographic regions using
Geographic Information Systems (GIS) data.

A. Literature Review

Jacobs and McGeeen [6] made a terrain model by
converting the USGS data into DEM format using an SDTS
to DEM converter. They used three other open or commercial
software packages to get STL file of a 3D model of the terrain.
The DEM data was loaded into Land Desktop for viewing and
ingenting. The data was then loaded in AutoCAD for scaling,
further editing and saving in DXF format. The DXF file is
opened in Magics RP for converting the data into 3D STL file.
The STL files thus obtained were used for additive fabrication
of terrain models in a Z403 3D printer and a LOM machine.
There were several intermediate steps in file conversion.
Agrawal et al. [7] translated the DEM ASCII XYZ file, a GIS
data format, directly into STL format using the Global Mapper
software for terrain modelling. The GIS data of the Modder
River sub-catchment and the Table Mountain was used for
terrain modelling. Furthermore, Magics RP was used to obtain
a 3D STL file of a terrain. An EOSINT P80 machine was
used for physical modeling of terrain.

Agrawal et al. [8] converted the DEM ASCII XYZ data
directly into a 3D STL file using their own in-house software.
They developed their own program in C language for
conversion. The DEM ASCII XYZ file format gives only the
data of the surface of the terrain. Walls and a base need to be
added by reading the input file for making a 3D STL file. They
also removed the singularities present in the input data and
performed interpolation for any gap in the data. Agrawal et al.
[9] converted the surfer grid and ARC/INFO ASCII grid data
into 3D STL file directly for making terrain models.

Pantazis and Priaivolou [10] have presented their work for
informal education using open-source 3D printing
technologies. They made artefacts of natural and cultural
heritage of the Zagori region, a hilly area of North-Western
Greece. One such artefact was the model of a local stone
bridge. Such artefacts improved the communication between
persons with and without visual impairment. The students
with visual impairments as well as their teachers found the
artefacts to be good educational tools. Shirsekar [11, 12] have
presented graphic symbols using raised dots for teaching
Braille alphabets to the primary school students with visual
impairments. For example, for teaching the alphabet ‘A’, they
have proposed to use a graphic symbol of an apple using raised
dots along with the word ‘Apple’.

Suciu et al. [13] have employed a tactile educational tool
fabricated by additive manufacturing for the visually
impaired. They have represented the counties of Romania
with raised boundaries. They used the Braille system for
embossing the names of the counties. Vozenilek and Vondrakova
[14] have presented a methodology for making
tactile maps for the visually impaired employing additive
manufacturing. They have presented symbols that can be
incorporated into GIS software packages. Their objective is to improve the spatial relationship, spatial orientation and mobility of the blind using such tactile maps.

Giraud et al. [15] showed that an affordable interactive small-scale model of a geographic region improves both space and text memorization in the visually impaired as compared to the raised-line maps (RLM). They obtained the models by additive fabrication. De Oliveira et al. [16] have developed tactile maps for mobility of the visually impaired in the local community. They have used tactile symbols for amenities in the community such as supermarket, restaurant, hotels, dentist, pharmacy, school, bakery and gymnasium. They have developed a tool for the mobility category under assistive technologies to support the Orientation and Mobility (OM) teacher for the visually impaired. Urbas et al. [17] developed a tactile floor plan for the visually impaired for use in a museum. They printed raised-lines and Braille letters for the floor plan. They had difficulty in printing both the English letters and Braille letters on the same map. They also concluded that it is essential to interact with the visually impaired and their teachers for developing a useful assistance tool such as this one.

Mikrou [18] designed and produced tactile maps of the Interactive Park and the Citadel of Leivithra in Greece for the visually impaired. They used the specifications for a tactile map in collaboration with an organization for the blind. They fabricated the map with its symbols using AM. Rener [19] produced tactile maps for persons with visual impairment using 3D printing technology. Such maps assist in mobility of the persons. He made maps of many regions and places of Slovenia. They also used standard symbols in the floor plans of museums and libraries. Slovenia has more than 30 standard symbols for tactile orientation and mobility maps. They have symbols for roads, streets, schools, banks, post offices, opera, green areas, etc. They also have symbols for orientation such as staircases, barriers, traffic lights and subways. Awad et al. [20] printed information in Braille alphabets and moon patterns on medicine tablets using 3D printing for assisting the visually impaired patients. They used the term printlets for such tablets. They printed patterns on the surface of the tablets to enable the patients in identifying the medicines and their doses.

Andrejka and Micetova [21] have created tactile maps interactively using GIS data. They used interactive web geo-processing. They created several types of typomaps such as General Overview or area Typomaps (GOT), Orientation and Mobility route Typomaps (OMT) and Thematic Typomaps (TT). Typomaps are maps created using typography. They created typomaps using the Braille system for haptic experience. Koehler et al. [22] performed a study on the use of AM for explaining geosciences concepts to the visually impaired students. They made models of earth layers, sedimentary rock layers, tactile map of earthquake distribution in the world, etc. for teaching of geosciences concept and found to be an effective assistive tool for education of the visually impaired.

Khoj and Agrawal [23] made physical maps with legends using the Braille system for geographical education of the visually impaired. They made a physical map of India with raised-lines for the boundary of the country and four metropolitan cities. They embossed the name of the cities and the country in Braille. They also made a physical map of Nanda Devi National Park, Uttarakhand, India using GIS data. The national park is natural World Heritage Site. They converted the GIS data into STL file format suitable for additive fabrication with 3D definition. They also placed legends in the physical map for geographical education of the visually impaired. Though they obtained the STL file that is suitable for additive fabrication, they have not reported additive fabrication in their work.

Schwarzbach et al. [24] extracted Digital Elevation Model (DEM), Digital Surface Model (DSM) and other topographical features from the LIDAR data and digital orthophotos for physical modeling of landscape by additive fabrication. They used ZPrint software for data processing and visualization. They created a 3D model of an area around the Finnish Geodetic Institute located in the Nuuksio National Park in the city of Espoo, South Finland. It includes the Solvalla sports and recreation area, skiing hill and a small part of the lake Nuukso Pitkajarvi having a total area of 700 x 950 m². The model was printed in a Contex DESIGNmate CX printer that uses a binder printing process with plaster powder as the bulk part material. The build volume of the printer used was 250 x 350 x 200 mm³. They created the model to be used as a tactile map for the visually impaired and had features such as roads, houses and trees. They did not employ the Braille system for legends.

Survey of the literature reveals that there are only a few researchers who have attempted to make a 3D physical map of a large geographical region and used the Braille system in it for educational purposes. A physical map of such a geographical region such as a mountain, a landform or a natural World Heritage Site with legends in Braille will provide a tool for geographic education of the visually impaired. In this work the GIS data of some geographic regions in DEM ASCII XYZ file format is used for making 3D physical maps.

The following two regions of South Africa were considered – the Amphitheatre, KwaZulu-Natal and the Table Mountain, Western Cape. The Amphitheatre is a spectacular geographical feature in the Northern Drakensberg and lies in the Royal Natal National Park. It is a huge cliff. It has a spectacular cliff face measuring 5 km in length. The cliffs are rising approximately 1220 m along its entire length. They are formed of basalt rocks. A physical model of such a region will give a haptic experience to the visually impaired to understand the geographical features.

The Table Mountain located in Western Cape, S. Africa, a flat-topped mountain, is a prominent landmark overlooking the city of Cape Town. The main feature of the mountain, a level plateau with impressive cliffs, measures approximately 3 km in length. The Table Mountain is flanked by the Devil’s Peak on the East and the Lion’s head on the West. The uppermost layer of the Table Mountain consists of extremely hard sandstone commonly known as Table Mountain sandstone or peninsula formation sandstone. The Table Mountain is at the Northern end of a sandstone mountain range forming the spine of the Cape Peninsula. The Cape Peninsula extends up to 50 km to the South at the Cape of Good Hope and Cape Point. Robben Island and the Cape Town city are towards the South of the Mountain. Nelson Mandela was famously kept in prison in the Robben Island for twelve years before the introduction of a full, multi-racial democracy in South Africa.
Other regions of interest in South Africa are the Naval Hills, Bloemfontein, Free State Province; Swartberg pass and the Vredefort Mountain, a natural World Heritage Site in South Africa. Though these regions are not considered for making physical maps in this work. The Naval Hill in the Bloemfontein city of S. Africa is part of the Franklin Game Reserve. It derives its name from its use for British Naval guns during the Anglo-Boer war towards the end of the nineteenth century. Physical maps of the Table Mountain and the Amphitheatre provide a good educational tool for the people with vision impairment because of their geological and other characteristics.

B. An overview of the Braille system

Braille is a system of writing for the blind that uses characters made up of raised dots. A cell in the Braille system has different combination of dots arranged in three rows and two columns. The spaces among the dots are the same, irrespective of various combination of dots present in the cell. There are sixty-four (64) combinations that can be built from the six dots of a Braille cell. The Braille system for the alphabets, punctuation marks and symbols of English language are given by the National Braille Press [3] as shown in Fig. 1. Marburg [1, 2] and Shirsekar [11] have provided the standard dimensions to be used in the Braille system. The following are the dimensions in Marburg Medium Braille. The diameter of the dot is 0.6 mm and the minimum height of the dot should be 0.5 mm. The distance between the centers of the two dots in a character is 2.5 mm in both x and y-directions. The distance between two characters is 6 mm and the line spacing is 10 mm [1, 2].

II. OBTAINING 3D STL PART FROM THE GIS DATA AND FABRICATION OF THE PHYSICAL MAPS

The elevation data of terrain is available in several file formats such as USGS, surfer grid and DEM. The DEM ASCII XYZ file format, being an ASCII format, was found to be a suitable data format and is used for this work. The elevation data such as those in the DEM ASCII XYZ file format are the data on the surface of a terrain. It does not give 3D definition for making a physical model and does not provide a closed volume. It only consists of data on the surface of the terrain. For making a physical model of the terrain, the data needs to be converted into a 3D. In this work the DEM ASCII XYZ data is converted into STL file format with vertical walls and a horizontal base to make it a closed volume. The file format has a header containing the number of rows and columns of the elevation data, cell-size, the coordinates of the lower left corner of the elevation data and NODATA_value. The elevation data follows the header. A square of four elevation values in the data make a cell. A sample data format is given below:

```
ncols 5
nrows 4
xllcorner 823
yllcorner 372
cellsize 30
NODATA_value -9999
46 52 82 75 93
5 58 73 44 36
37 48 54 77 49
55 74 85 67 69
```

The parameter NODATA_value is kept at -9999 and signifies that there is no valid elevation value at this point.

STL is a file format suitable for AM. It is the de facto standard for interfacing with AM systems. The STL is a faceted file format and represents the part shape with connected three-dimensional triangles. The vertices of the triangles are ordered to indicate the side of the triangle that contains the part mass. An example STL file is as follows:

```
solid mystl_file
facet normal 0.0 0.0 1.0
vertex 20.0 90.0 15.0
vertex 21.0 40.0 17.0
vertex 19.0 70.0 26.0
endfacet
facet normal 0.0 1.0 0.0
vertex 18.0 50.0 25.0
vertex 23.0 60.0 24.0
vertex 22.0 70.0 31.0
endfacet
endsolid
```

In this example, two triangles in the faceted file format have been shown. The three vertices and the normal of the triangle are provided for each of them.

DEM ASCII XYZ data of the Amphitheatre has 422 columns x 922 rows. With a cell-size of 30 m, its area becomes 12.66 km x 27.87 km, i.e., 352.8 km². The DEM data of the Table Mountain has 396 columns x 472 rows. Its area becomes 186.2 km² with the same cell-size. As can be seen,
they represent very large areas. They have to be scaled down with large scale factors for making physical models. The Amphitheatre is a rectangular area whereas the Table Mountain is almost a square area. The DEM data is converted into 3D STL part following the methodology and pseudocode given by Agrawal, de Beer and Modi [8]. An overview of the methodology is given below.

A. Program structure

The user input for conversion of the data and the DEM ASCII XYZ data are read from two different input files. The software written in C language is used. The user provides an input on whether he/she wants to build an STL part or make an STL surface for the chosen DEM data. He/she also provides an input on whether the software should interpolate the data, if required, when there are gaps in the elevation data. The wall-height, the scales in the three directions and the names of input DEM file and output STL file are also provided by the user.

The wall-height is the height of the scaled model below the point on the surface of the terrain with minimum elevation. For example, the wall-height for the Table Mountain was kept at 7 mm. Therefore, there is a wall of 7 mm height uniformly above this height. The software makes an STL part of 7 mm along the periphery of the model. The relief of the terrain starts at this height. The input DEM file is converted into 3D STL part following the methodology and pseudocode given by Agrawal, de Beer and Modi [8]. An overview of the methodology is given below.

A pseudo code of the program is given below to illustrate the program structure:

```c
#include_files

main()
{ /* declaration of variables and the allocate memory to matrices*/
    /* initialize the matrices. */
    /* read the input whether to make a 3D STL file */
    /* read whether to interpolate the DEM data */
    /* read scales, wall height, and the name of the input DEM file */
    /* scale the elevation values and the parameters*/
    /* find the base of the 3D part */
    if (FlagStlPart = 'Y') {
        CheckNoGapXdir();
        if (SolidsContiguousOrSeparatedByRows = 1) {
            RemoveSingularity();
            BuildStlPartXdir();
        } else {
            CheckNoGapYdir();
            if (SolidsContiguousOrSeparatedByCols = 1) {
                RemoveSingularity();
                BuildStlPartYdirdir();
            } else {
                if (FlagInterpolate = 'Y') {
                    interpolate();
                    RemoveSingularity();
                    BuildStlPartXdir();
                } else {
                    MakeStlSurface();
                }
            }
        }
    } /*End of second level if-else statement. */
    } /*End of outer if-statement. */
    else {
        /* The case when FlagStlPart is equal to 'N'. The user wants to make an STL surface in this case. */
        if (FlagInterpolate = 'Y') interpolate();
        MakeStlSurface();
    } /* End of else statement */
    /* Free the memories of matrices */
} /* End of the main() function */

The program scales the parameters and the elevation values after reading the input. The user provides the input whether he/she desires to build a 3D STL part or an STL surface. The program proceeds as follows; in case the user wants to build a 3D STL part. The program attempts to make a 3D STL part depending upon the other input values and the given DEM data.

The program determines whether the DEM data is one or more sets of contiguous points separated by rows. If there are no gaps between two valid elevation values in each row of the data then the data is one or more sets of contiguous points separated by rows. There are complex search algorithms used for determining this. In this case, the singularities are removed and the 3D STL part is made by proceeding in the x-direction. A singularity is an elevation value which is not part of any of the four square-cells. It is a dangling data. The elevation values are tessellated with triangles. The vertical walls for the boundary of the data and a base are made. The base is a horizontal surface below the minimum elevation valued in the data at a distance equal to the wall height. The base and the walls are obtained by triangulation. Being planar surfaces, they are triangulated by the largest size of triangles possible. This saves the data storage space and the computation time for slicing.

If the data is not one or more sets of contiguous points separated by rows, the data is checked in the y-direction if it is one or more sets of contiguous points separate by columns. If it is so then the 3D STL part is built in the similar manner by proceeding in the y-direction. Otherwise, the data is linearly interpolated, if the user input allows so. The DEM data becomes a set of contiguous points and a 3D STL part can be built after removing the singularities. If the user has not allowed interpolation of the data, then in this case a 3D STL part cannot be built. A STL surface is made in this case. The STL surface can be made without removing the singularities.

If the user doesn’t want to build a 3D STL part, then he desires to make an STL surface. The user wants to make an STL surface for viewing purpose or for use in another software. The data is then interpolated provided the user has given this as input. The STL surface is made. The program writes the output in the STL file, the name of which was provided by the user. The program frees the memory allocated to pointer and other variables and the execution terminates.
There are several key features of the program. It uses several complex search algorithms to compute the gaps in the data. The conditions at the boundary of a row or column are to be set carefully in conditional statements. Unit-offset matrices are used while allocating matrices. Pointer to a row of pointers is used for memory allocation to matrices. Several functions were written for matrix manipulations.

III. RESULTS AND DISCUSSION

A. Physical map of the Amphitheatre with Braille legends

Using the C program, the DEM ASCII XYZ file of the Amphitheatre was converted into a 3D STL part with a scale factor of $5.53 \times 10^{-6}$ in the x and y-directions and $11.06 \times 10^{-6}$ in the z-direction. This gives 154 mm long model for the data of 929 rows with the cell-size of 30 m. A double scale was given in the z-direction to enhance the relief features in the physical map. The STL file was scaled down so that the 3D map can be printed in a Delta Wasp 2040 machine, an FDM based additive manufacturing machine, with a cylindrical build volume of $\phi 200$ mm diameter x 400 mm height. All the physical maps in this work are printed in the Delta Wasp 2040 machine. The STL file thus obtained cannot be further scaled after adding the Braille letters. This is because the Braille letters should be printed with the specifications given for readability and their dimensions cannot be changed.

The STL file is then hollowed with a shell thickness of 3 mm using the MeshMixer software. This was then cut by a horizontal plane near the base. This makes the base open. Making the map hollow saves the material used for printing. A shell thickness of 3-5 mm provides enough strength to the map as it is to be mainly used for viewing purpose by holding in the hands. Making the physical map hollow decreases the printing time and the amount of material used, thus decreasing the cost of the map. The STL file thus obtained is viewed in MeshLab, an image of which is shown in Fig. 2. MeshLab is an open source STL file viewing and manipulation software package.

Legends on the model of this geographical region were written with the Braille system using AutoCAD, a CAD modeler from AutoDesk Inc. They denote the name of the region (Amphitheatre) and some of the landmarks of this region such as Namahadi Peak, Tugela falls, Sentinel and Mont-Aux sources. The Braille legends were output in the STL file format from AutoCAD. They are added to the STL file of the geographic region. Figs. 3 and 4 show the STL file of the physical map of the region with legends in Braille from two different viewpoints. The length, breadth and wall height of the map printed is given by 154 mm L x 70 mm W x 15 mm Wall ht.
The physical map of the Amphitheatre was printed by the Delta Wasp 2040 machine in the Tinkering Lab, IIT Roorkee, India. It is a Fused Deposition Modeling (FDM) based machine. Figs. 5 and 6 show two views of the physical map. Fig. 7 shows a zoomed-in view of one of the Braille legends in the physical map of the Amphitheatre. The material used for the physical model was premium Polylactic Acid (PLA), red in color. PLA is a thermoplastic polymer and widely used for FDM based additive fabrication. The layer thickness used in the machine is 50 microns. It took 22 hours to print the map in this machine. The Braille legends have come out quite distinctively in the physical map as can be seen in the above two photographs. However, there are some issues of accuracy and surface finish. The raised dots are at some places connected by fibers of the part material. This reduces the readability of the legends for the visually impaired. An AM machine with better accuracy and surface finish will improve the features in the map.

B. Physical maps of the Table Mountain with Braille legends

Following the same steps as for the Amphitheatre, the 3D STL part of the Table Mountain was obtained from the C program. A scale factor of $9.82 \times 10^{-6}$ was used to obtain a 139 mm long model for the DEM data of 472 rows with a cell-size of 30 m. The STL file of the physical map was then hollowed with a shell thickness of 3 mm using the MeshMixer software. The legends in Braille were added in the STL file using AutoCAD. Figs. 8 and 9 show two different views of the 3D STL file with Braille legends. Fig. 10 shows the top view of the STL file with the legends explained in Latin script as well.

The physical map of the Table Mountain with Braille legends was printed in the same FDM based machine. The size of the printed physical map was 139 mm L x 116 mm W x 7 mm Wall ht. It took 19 hours to print the map in this machine. The photographs of the physical maps taken from two different viewpoints are shown in Figs. 11 and 12. Fig. 13 shows a zoomed-in view of a Braille legend in the physical map of the Table Mountain. The size of the raised dots came out on printing as per the specifications. However, there were accuracy and surface finishing issues. The raised dots are sometimes connected by fibers of the part material.
was directly obtained with walls and a base from the surface data. This prevents any data loss involved in translation involving several steps and different software packages. The legends in Braille were modeled in AutoCAD and added to the STL files. The STL file is then hollowed with base open to save on material, build time and part-building cost. The physical maps were printed by Delta Wasp 2040 machine, an FDM based machine. They were printed as per the specifications for the dimensions of the raised dots in the Braille system and without further scaling. Using the methodology developed, physical maps of other geographic regions can be printed using an AM machine. In this work physical maps of the Amphitheatre and the Table Mountain were made for geographical education of the people with low or no vision. These are spectacular landforms of the country. Many places of these two regions are connected by road and/or ropeways for tourism and trekking purposes. These are interesting regions for education. The length and the breadth of the physical map printed for the Amphitheatre are 154 mm L x 70 mm W and those for the Table Mountain are 139 mm L x 116 mm W.

Being an emerging area on developing aid for the visually impaired, there is a large scope for future work in this area. Much larger physical maps can be made with affordable material and fabrication process for classroom education of the people with low or no vision. A machine with better accuracy and surface finish can be chosen for improving the readability of the Braille legends. A different scale in the z-direction can be provided to enhance the relief features as done for the Amphitheatre in this research work. Pictorial symbols can be used in the physical maps of urban areas or cities for amenities in the community such as supermarket, dentist, pharmacy, hotel, restaurant and bakery. Pictorial or Braille symbols can be used for orientation such as traffic lights, staircases, barriers and subways. There are several standard symbols available in a country or region. Those symbols can be used or further symbols can be developed in collaboration with the stakeholders. Physical maps of urban and geographic regions will assist the visually impaired in education and mobility, make them independent and socially included, and improve their quality of lives.

ACKNOWLEDGMENT

The authors acknowledge the support provided by the following innovation lab and service bureau in this work. The physical maps were printed in the Tinkering Lab at IIT Roorkee, Uttarakhand, India. The authors thank Mr. Shahwez of the Tinkering Lab for the continuous support and providing service at short notice at times. The data for the two geographical regions of South Africa were obtained from GISCOE Pty. Ltd., Gauteng, South Africa earlier (www.giscoe.com).

REFERENCES


Improvement of space and text memorization in visually impaired students

Learning with a 3D printed interactive small-scale model: the International Scientific Conference technology


Improving space and text memorization in visually impaired students


An AM Solution to a Golfing Predicament - a Bespoke Golf Putter Head and Hosel with Multiple Configuration Options for Personalized Club Fitment

Wian van Aswegen
Department of Mechanical Engineering
Nelson Mandela University
Port Elizabeth, South Africa
s219164843@mandela.ac.za

Clive Hands
Department of Mechanical Engineering
Nelson Mandela University
Port Elizabeth, South Africa
Clive.Hands@mandela.ac.za

William Rall
Department of Mechanical Engineering
Nelson Mandela University
Port Elizabeth, South Africa
William.Rall@mandela.ac.za

Riaan Stopforth
Stopforth Mechatronics, Robotics and Research Lab
University of KwaZulu-Natal
Durban, South Africa
stopforth.research@gmail.com

Abstract — This study’s intent is to provide a unique and custom-designed putter head and hosel for both serious amateurs and professional golfers, which allows the golfer to hone the putter head and hosel configuration to their specific aesthetic and feel preferences. Considering the range of variables which dictate possible output configurations, this aesthetically pleasing stainless-steel 3D-Printed product has been designed to ensure elimination of support material while printing, reducing costly material wastage. The material used is similar to that of other contemporary putters, which allows the product to remain competitive in this specialized market, with the added attraction of being designed exactly to customer specification. The user is able to request any additional features or shapes they prefer, and this is quickly achievable by making small adaptations to the design before printing. Any adaptations in the hosel design will allow the user to specify their preferred lie angle and offset, but also improves fitment to a common or very specific shaft. With all the customizability available, it still adheres and conforms to the Royal and Ancient Rules of Golf, ensuring that it would be eligible for competition use. In the development of the final output, various simulation studies have been employed as well as physical testing to ensure compatibility with currently available putter’s frequency and impact behaviours of the Additively Manufactured putter.

Keywords—Additive Manufacturing, customization, weight distribution

I. INTRODUCTION

The rapid & continuing evolution of Additive Manufacturing has straddled multiple sectors from hobbyist, industrial, arts, homeware, wearables and sports equipment. The field has grown by billions of dollars and the adaptability of printed outputs allows for enhanced options in terms of customizability and personal preference, and this is particularly applicable in the higher-end user group found in sporting codes [1].

Golfers spend thousands of dollars on their golf clubs, having them perfectly fitted and tweaked, yet tend to ignore the very club that they use most frequently - their humble putter [2]. There are hundreds of golf putter designs that are available for the public to purchase, but they generally cater for the masses and the generic strokes of golfers. The customizability capability for Additively Manufactured putters allows the golfer to describe their ideal putter set up in terms of aesthetics, feel and performance. Things such as alignment aids, shape, inserts, colour and size all are categorized as aesthetics, whereas impact sound and weighting contributes to the feel and performance aspect. However, all these factors are vitally important to the success of the putter in the golfer’s eyes as they all contribute to what is considered a comfortable fit [3].

The golfer has various options for alignment aids to choose from and they include, but are not limited to, all types of lines, grooves and dots that are currently utilized by other competitors [4]. For this design, known as the WvA Design, the shape and size of the putter can both be altered with a quick adjustment within the Computer Aided Design (CAD) software, as the software allows for accurate and relatively fast adjustments to be made according to individual preference. 3D Printing ultimately reduces production time as many iterations can be produced simultaneously for comparison [5]. Furthermore, incorporation of custom logos and various colouring options allow the golfer to receive a putter that is completely unique to him/herself which also adds to the exclusivity of the various designs [6].

When considering the feel of a putter one looks at the total weight, weight distribution, impact recoil and impact sound (also known as the frequency or ‘pitch’ of the sound) [7]. As all golfers have their own subjective personal preferences, these play a substantial role in the selection, perceived performance and attraction of a putter [6]. The golfer has the ability to choose from many different weighting combination options to suit all stroke paths and rhythms. There are a wide variety of materials and weighting setups that the golfer can choose from which adds to the complete customizability of the putter introduced in this study. As people are also constantly undergoing physical changes and attempting new techniques as their individual game evolves, the golfer will possibly choose to alter some of their weight distribution with the
incorporation of interchangeable weights that are normally attached by means of a simple screw to the base of various putters [8]. In the design suggested in this study, this is achieved using attachable custom-designed weights which are almost endlessly adjustable to personal preference.

Also, in this study, the frequency (and hence the 'pitch' of the sound) of this Additively Manufactured putter is compared with other commonly manufactured putters. Golfers are notoriously fickle about the tools of their trade and have become accustomed to the specific sound of their current putters. With the use of simulation studies in CAD software and frequency recorded data, this study attempts to compare the real-world sounds with computationally derived expected sounds & ‘feel’ [9]. The material used and geometrical configuration of any putter determines the frequency produced and all this was accommodated in the design process for this putter [10].

To be labelled as a success, this putter will not only have to satisfy all the aesthetic, feel and performance requirements of the individual golfer, but would also have to strictly adhere to the Royal and Ancient Rules of Golf. The putter in this study was designed following these sets of rules and that will allow the putter to become certified for competition use, which is the ultimate goal as this putter is aimed at serious amateur and professional golfers [11]. Emphasis in this study is placed on how Additively Manufactured products can become a well-suited substitute for traditionally manufactured products with beneficial customizability and performance aspects, together with comparable costing comparisons.

The research contributions are:

- A customisable, balanced golf putter, that can be adjusted across many settings for personal configuration settings.
- A golf putter that was developed by means of Design for Additive Manufacturing (DfAM) techniques.
- A competitively priced bespoke golf putter that is unique to the customer’s aesthetic preferences.
- A golf putter that has multiple options with respect to material selection for the discerning golfer.
- Manufacturing a physical product for further testing and analysis.

II. DESIGN AND DEVELOPMENT

The design and development of the putter is dependent on the performance of the putter. The performance is primarily dependent on the weighting, putter face and hosel. The bespoke putter created in this study is shown in Fig 1 together with its component parts. Although there are very limited design that have been constructed purely of AM methods and there are very limited references on AM golf clubs, the performance and aesthetic requirements remain the same.

A. Weighting

Weight distribution is one of the most important aspects to consider as it is vital to the performance on the putter. The weighting looks at the center of gravity position and moment of inertia of the club.

1) Balancing

As the targeted demographic are players with a fairly high skill level, their recognition of imbalances and misalignments are far more honed than the casual golfer. People often get fitted for the correct putter setup in Golfing Shops with their in-house fitment specialists, and the main priority of the fitting is to determine what length, lie angle and balance would be most beneficial for the individual.

The balance of a putter is a term used to describe where the center of gravity (CoG) of the putter head is in relation to the shaft. The three different types of balances are namely: face balanced, quarter hang and toe hang [12].

1. Face Balance – the axis of the shaft extends through the CoG of the putter head which is generally found in the middle of the club face. Therefore, when the putter head is allowed to hang off the edge of a table the face will point straight upward.

2. Quarter hang – the CoG is slightly offset (to the right for right-handed putter) to the shaft axis, this causes the toe of the putter to hang slightly lower which allows the putter face to point at roughly a 45° angle.

3. Toe hang – the CoG is greatly offset from the axis of the shaft which allows the face to point at roughly 80°.

Fig 2 illustrates the naming convention of the toe and heel end of the putter head. The heel is the side of the putter where the hosel is located and the toe is the opposite side.
The weight distribution of the WvA design putter is designed so that by only changing the hosel length and angle and therefore shifting the shaft axis in relation to the CoG, a preferred balance of the putter can be attained. If any adjustments are required later, it can be done by means of the interchangeable weights which can vary in mass, mass distribution and symmetry. The changing of the weights will accordingly shift the CoG slightly to achieve a more refined or preferred balance.

In conjunction with a club fitting session, the golfer can specify the amount of hang that they would require to correlate with their respective stroke arc and face rotation. The correct hang will result in the golfer squaring up the putter more consistently, which in return will cause more putts to start on their intended line. This is entirely adaptable in this putter design.

Fig 3 shows the balancing of the WvA design with respect to other traditionally manufactured putters. The Wva design and the Odyssey white hot are face balanced putters, where the Scotty Cameron and PING Karsten are quarter hang balanced.

Figure 3: Balancing of the (from left to right) WvA Design, Scotty Cameron, Odyssey White Hot and PING Karsten. (photo: author’s own)

2) Moment of Inertia

The distribution of weight away from the center towards the heel and toe of the putter will result in the increase of the Moment of Inertia (MoI) along the vertical axis. The higher the MoI value, the more consistency that will be present on off-center hits. By definition, inertia is a body’s resistance to rotation and inconsistencies in the roll of the ball occurs when there is rotation of the putter face at impact [13], as seen in Fig 4.

With an increase in MoI, there is a decrease in speed which can prove to be beneficial as it brings more stability [14]. Stability is the term used to describe the ability to have the putter repeatedly follow the intended stroke path, whilst maintaining a square putter face.

With Additively Manufactured putter designs, the golfer has the choice to request more stability and forgiveness. This will be done by slight adaptations to the design to increase the MoI by shifting some mass away from the center of the putter. However, this would not be advisable for golfers who have a lot of putter rotation in their stroke as the increased MoI will hinder their ability to return the putter face to square at impact.

B. Putter Face and Hosel

Apart from weight distribution, the putter face and hosel allow for numerous adjustments that can be made to the design to alter both performance and aesthetics of the putter.

1) Loft

With the large number of high-quality golf courses currently in operation, the WvA design has a 2° loft which is relatively low compared to most current putters. However, this lower angle will be better suited on good quality fast greens as it induces a more immediate roll which adds to consistency. Golfers tend to hit slightly up on the golf ball during the putting stroke so the ball will launch at a slightly higher angle, known as the dynamic loft [15]. More loft can easily be added to the design if requested. Loft exceeding roughly 4° would be beneficial for golfers who mainly play on slower and rougher greens, as the loft helps to lift the ball up and out of any small depression the ball may be lying in, to limit the amount of bouncing that occurs.

The more loft added to the putter will result in more backspin being applied to the ball which is unwanted in putting. The generally accepted middle ground for lofts are between 4.5° and 3° because this would be compatible with most greens and conditions that golfers may be faced with [16]. However, the golfers putting style and technique would all affect the loft that they would require. This is again emphasising the importance of going for a club fitting before specifying all details. Face loft is illustrated in Fig 5.
2) Grooves

The groove pattern on the face can be an added aesthetic feature as well but its main purpose is to provide some increased grip on the ball at impact. This small addition of grip allows the roll to be more controlled and improves the impact feel of the putter [16]. The depth and width of the grooves affect the frequency of the putter at impact, so this is one feature that is considered to create the desired feel. However, there are limits on the dimensions of the grooves set in place by the Royal and Ancient (R&A) rules of golf. The grooves may not exceed 1.016 mm in depth and 1.524 mm in width, where a spacing ratio equation is used to determine the distance between grooves [11]. The WvA design makes use of a horizontal groove pattern as shown in Fig 6. However, there are also other options available to the golfer besides grooving - there are also milled and cross-hatching options. These are all easily achievable in this putter design as part of post-processing according to individual requirements.

3) Hosel

The lie angle of the WvA design is at 71° to the horizontal, this value is an average of the majority of currently produced putters. This angle is entirely dependent on the height and posture of the golfer as it is determined by considering the comfortability and preferences of the golfer. This angle is fully controlled by the angle of the hosel and it can be completely modified in the design to suit the specifications set by the golfer.

III. METHODOLOGY

Preparation and research that is done before creating a design helps to reduce the risk of mistakes which could prove to be very costly and time consuming to fix. The following sections will look at the planning and production of the WvA design.

A. Planning and conceptualization

To determine the targeted type of golfer, things such as the performance requirements, feel requirements, aesthetics and pricing will all have to be estimated and included in the decision process. As the design will be unique to each golfer’s personal preferences, and due to the relative expense of the 3D metal printing process, it is important that all these aspects are just right prior to committing to the final print.

As the putter has a wide variety of customization setting options, it would be advisable to target golfers that would appreciate and benefit the most from having a highly specific putter to suit their technique. High level golfers, such as professionals and serious amateurs would be able to detect the changes in performance as they have a good understanding of what is expected from a putter. As part of the research, several competitive golfers were asked if they would be interested and all of them were excited for the opportunity to have a direct input into the design of their own putter.

The 3D metal printing process is performed by a machine that deposits the selected metal that is in powder form on the printing platform, thereafter a laser is used to melt the powder together to form the cross-sectional area. The excess powder is removed leaving the cross-sectional layer of melted metal, new powder is deposited and the process is repeated multiple times to build the part layer by layer [17]. The printers are able to create parts with close precision, the precision allows the design to include small details without the need for post processing. The metal printing is limited to printing overhang angles of 45° as any overhang exceeding this will cause the melted metal to creep or sag. To prevent any unwanted deformation, support structures can be added but this adds to the amount of material used which in result further adds to the cost due to post-processing. Therefore, prior planning for the best possible printing layout and orientation for the design will generate the most efficient and cost-effective product which is all part of the DfAM process. The WvA Design makes uses of printing with the putter face as the base. This means that the putter face will be used to locate the horizontal plane and any angle relative to this plane that exceeds 45° will have trouble printing. The holes for the screws were the main concern while designing and to counteract the threat of deformation while printing the circular holes were removed and a diamond shaped cut out was used. The diamond cut outs will require post processing to create the circular holes, but the rest of the design does not contain any other overhangs.

The ease of adaptation to the design will aid in the longevity of the design. Each putter that is produced will have to undergo a process of changing certain key points to account for the required specification, the faster this can be done, the more efficiently putters can be produced. This can easily be achieved via modern CAD methods, especially via implicit methods where workflows can be pre-set-up to accommodate quick and easy insertion/adaptation of setting variables to produce almost instantaneous design changes and ‘unbreakable’ geometric outputs.
Although additive manufacturing has become popular in many other disciplines, it has only started being used in the golfing industry. Cobra is the most recent manufacturers to construct an AM putter, but it is only partially 3D printed. Callaway have also touched on the thought of creating AM putters but there is very minimal research present in this field.

B. Production

With the capabilities of modern CAD software, there are seemingly no limitations to the design. Although this is somewhat true, there are always some shortfalls in both the software and the production process. However, the customizability of the design and the precision of the printer allows a putter to be produced that can accurately portray the specification made by the golfer. The production process can be described as shown in Fig 7.

The following steps were followed:

- A golfer is given various putters that have different setups and visual aids to see what the golfer’s preference is. Things such as different lofts, lie angles, weights and lengths will be tested to determine what the most optimal combination would be to improve the general performance of the golfer [18]. The person performing the fitting will make a list of all the specifications that the putter will need and this will be given to the golfer.

- The golfer can then contact the designer and define the specifications from the club fitting and would notify the designer of any additions they would like the design to incorporate, such as logos or colouring...this could be easily achieved electronically as well

- The designer would use the details specified by the golfer to adjust the design to cater for the requirements needed by adjusting implicit inputs and producing a virtually instantaneous output.

- The final design would be uploaded to the Print Bureau with all specifications, printed and the correct weights would be made.

- After printing the putter head base would enter post-processing if needed. Post-processing would typically involve the colouring of the logos and alignment aids and refining of the face finishing if the pattern walls gradients were too severe for the printing process. This is also where assembly would take place, for example the hosel, shaft, grip and all relevant parts would be attached.

The final assembled WvA design is shown in Fig 8(a) and 8(b).

IV. ANALYSIS AND RESULTS

To determine the effectiveness and addition to golf putter manufacturing research, comparisons between the WvA design and other traditionally manufactured putters would need to be made. Weight, frequency (or sound) and moment of inertia will be compared as these will be the deciding factors to assess the effectiveness of the WvA Design. Aesthetics, balancing, loft and groove patterns are all subject to the golfer’s preferences or playing conditions. Therefore, they will not be included in the comparisons.

Fig 9-12 show the natural frequencies of the WvA design, PING Karsten, Odyssey and Scotty Cameron. The dark blue colour represents a lowest frequency and the colours change according to frequency change with red illustrating the highest frequency. These natural frequencies are shown in Table 1, along with the mass, balancing, face loft, groove patterns and recorded frequencies of each putter.

Figure 8(a): Assembled WvA Design (photo: author’s own)
Figure 8(b): Alignment of WvA Design (photo: author’s own)

Figure 9: Natural frequency and mass of AISI 304 club base and onyx weights
The WvA design is lighter than all the putter models, except for the PING Karsten Anser. The Odyssey White Hot Tour #5 is as light as the WvA putter a face balanced while the others are quarter hang.

A. Mass

As seen in table 1, the PING is the lightest with a mass of 323 g, where the Odyssey is the heaviest weighing at 412 g. The WvA design is in a good middle ground as it weighs 379.33 g, but this weight can be easily altered depending on any changes to the design or the materials used.

The Scotty Cameron was chosen as the generic benchmark for the testing and the WvA Design is 15.67 g lighter. This difference is a relatively small change and each adaptation to the design will yield a change in mass. The use of different materials alone can create a mass range of 185-656 g.

B. Frequency

Fig 13-17 display the masses of various material combinations for the WvA design and its respective natural frequencies.

Table 1 shows the comparison of mass, balancing, face loft, groove pattern, natural frequency and recorded frequency for the various putters. The comparisons will be explained further in the following sections.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass (g)</th>
<th>Balancing</th>
<th>Face Loft</th>
<th>Groove Pattern</th>
<th>Natural Frequency [Hz]</th>
<th>Recorded Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WvA design</td>
<td>379.33</td>
<td>Face Balanced</td>
<td></td>
<td>2°</td>
<td>491          *</td>
<td>1344          *</td>
</tr>
<tr>
<td>PING Karsten Anser</td>
<td>323</td>
<td>Quarter Hang</td>
<td>6°</td>
<td>None</td>
<td>1307.3</td>
<td>1839</td>
</tr>
<tr>
<td>Odyssey White Hot Tour #5</td>
<td>412</td>
<td>Face Balanced</td>
<td>3°</td>
<td>Cross-hatching</td>
<td>7895.1</td>
<td>1387</td>
</tr>
<tr>
<td>Scotty Cameron Newport 2</td>
<td>395</td>
<td>Quarter Hang</td>
<td>4°</td>
<td>Milled</td>
<td>2007.1</td>
<td>1409</td>
</tr>
</tbody>
</table>
In Table 1, the natural frequencies for the WvA, PING, Odyssey and Scotty Cameron are 401 Hz, 1307.3 Hz, 7895.1 Hz and 2007.1 Hz respectively. The WvA design has the lowest natural frequency as the geometry of the base and hosel, which are made of AISI 304 stainless steel, are relatively thin. The weights of the WvA design are made from Onyx® which is 3D printed short carbon fibre reinforced Nylon that has elastic modulus of 3.6 GPa and density of 1.2 g/cm³, which is far less than that of steel and this lowers the natural frequency even more [19]. The PING and Scotty Cameron are relatively similar in geometry, causing the natural frequencies to be similar as well. The natural frequency of the Odyssey is far greater than the other putters as it is heavier and has a sturdier geometry.

With the use of a frequency recorder, the frequency at impact was recorded to determine how the sound of the WvA design compares to the other putters. The recorded frequencies of the WvA, PING, Odyssey and Scotty Cameron are 1344 Hz, 1839 Hz, 1387 Hz and 1409 Hz respectively. One can see that the frequencies are very similar apart from the PING which has a much higher value. However, the PING is known for its high-pitched sound at impact. As the frequencies of the other putters are very similar, this shows that the sound of the WvA design would be well suited to many golfers and this can be adjusted to satisfy any preferences that the golfer may have.

The frequency of the putter refers to the ‘pitch’ of the sound that the putter makes as it comes in contact with the golf ball. Natural frequency refers to the stiffness or the natural vibration of an object or material [20]. In Fig 14-18, one can see that the natural frequencies remain relatively similar irrespective of the mass or material, thus indicating that, although the mass and material do affect the natural frequency, the main driving factor for the natural frequency of the putter is its geometry.

C. Moment of Inertia and Center of Gravity

Fig 18(a) illustrates the CoG of the PING Karsten Anser putter that is known as one of the most popular putters to ever be created. Karsten Solheim was the founder of PING golf and he created the most iconic putter design in 1966 which is still regarded as one of the most popular putter shapes in modern times [22]. One can see that the CoG is not centered as the weight distribution was not as refined as it is in modern putters. Thus, this reduces the consistency and quality of feel of the putter. Originally these putters were made of brass, but soon replaced that with Manganese Bronze for durability purposes and ultimately replaced with Stainless Steel to create the putters of today [23].
Scotty Cameron have been one of the top putter manufacturers for many years and the Newport, which was originally launched in 2008, has been one of their most popular models. In Fig 20(a), one can see that the CoG is centrally positioned indicating once again good weight distribution, which is similar to that of the WvA design. This putter was designed for a quarter hang balance, so if a line is drawn through the shaft that extends through the putter head, as seen in Fig 20(b), then one will be able to see that the CoG was left (would be right if it was a right-handed putter) of the drawn line. This putter could be regarded as a good benchmark for comparisons as it was, and still is, one of the most widely used putters globally.

This Odyssey is an older version (launched in 2009) than the before mentioned Scotty Cameron (launched in 2014), but the CoG is still laterally positioned well in the center (as can be seen in Fig 21). However, the CoG is slightly lower than what can be seen in the Scotty Cameron and WvA Design, this creates unwanted backspin on the ball which hinders the ball’s ability to roll consistently.

Table 2: Comparison of moment of inertia for each putter.

<table>
<thead>
<tr>
<th>Model</th>
<th>MoI ($10^{-3}$) kgm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>WvA design</td>
<td>0.52909</td>
</tr>
<tr>
<td>PING Karsten Anser</td>
<td>0.45290678</td>
</tr>
<tr>
<td>Odyssey White Hot Tour #5</td>
<td>0.33507109</td>
</tr>
<tr>
<td>Scotty Cameron Newport 2</td>
<td>0.45348045</td>
</tr>
</tbody>
</table>

In Table 2, the MoI is indicated that is measured from the CoG. The MoI across the yy-plane is the most important value to consider as this is the plane that will rotate around the y-axis on off-center strikes—here this value is $0.52909 (10^{-3})$ kgm².

For comparison purposes all designs were given the same material, 304 AISI Stainless Steel. In Table 2, one can see that the MoI of both putters across the yy-plane are relatively similar, but the WvA design has a higher MoI value than the PING, which has a value of $0.45290678 (10^{-3})$ kgm².

The MoI of the Scotty Cameron Newport 2 across the yy-plane is $0.45348045 (10^{-3})$ kgm², as seen in Table 2. This value is higher than the MoI of the PING which shows how designers have started considering the effects that MoI has on performance in more recent times as club design becomes more sophisticated. The MoI of the WvA design has a higher MoI value while remaining at a similar weight to that of the Scotty Cameron, illustrating the effectiveness of the WvA design weight distribution.

As seen in Table 2, the MoI across the yy-plane is $0.33507109 (10^{-3})$ kgm² and this is far less than the other designs. This is because of the smaller dimensions of the putter head and not much of the weight is distributed away from the center, thus causing more inconsistency for off-center strikes.

The following figures (Fig 23-25) compare the moment of inertia, mass and loft of the various putters and display the range that the Additively Manufactured design offers.

Fig 22 shows the higher MoI of the WvA design compared to that of the other putters, which is beneficial to the performance of the putter. However, Fig 22 indicates that upon request the WvA design can be altered to satisfy a wide range of preferred MoI values.
Figure 22: Moment of inertia comparison for the various putters

Table 3 shows how various materials can be used to change the mass of the WvA design to suit the preferences of the golfer.

Table 3: Comparison of mass and natural frequency for WvA design with different material combinations.

<table>
<thead>
<tr>
<th>Base Material</th>
<th>Weights Material</th>
<th>Mass (g)</th>
<th>Natural Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>Onyx</td>
<td>370.33</td>
<td>401</td>
</tr>
<tr>
<td>Steel</td>
<td>Aluminium</td>
<td>440.37</td>
<td>390.71</td>
</tr>
<tr>
<td>Steel</td>
<td>Steel</td>
<td>656.06</td>
<td>369.71</td>
</tr>
<tr>
<td>Titanium</td>
<td>Onyx</td>
<td>239.8</td>
<td>392.97</td>
</tr>
</tbody>
</table>

Fig 23 shows that only by changing the material used, there is a large range of masses that can be selected from, while the traditionally manufactured putters have a relatively limited range.

The loft of traditionally manufactured putters is normally predetermined by the manufacturer and therefore creating a very limited range. However, Fig 24 shows the WvA design allows the user to select their preferred loft between the range of 0° and 10°, as this range is regulated by the R&A Rules of Golf [11].

The moment of inertia of the WvA design is higher than that of the other compared putters, suggesting that it should prove to be more consistent than the others. As the golfers with a high skill level are the targeted group, they often have putters in competitive environments where there is a lot at stake, be that prize money, media exposure or pride. Thus, more consistency will result in more important putts finding the bottom of the cup. This putter displays the opportunity that golfers have to be directly involved with the development of their putter to tune the club to their own personal preferences. They have a vast array of materials, weightings and aesthetics to choose from to ensure a putter is produced that they trust and feel comfortable with.

V. CONCLUSION

Additive manufactured (AM) products have become a fast-growing attraction for both manufacturers and customers. The interest in incorporating it in golfing equipment has become apparent as large companies, such as Cobra and Callaway, have recently started producing partial AM putters. The customizability of AM putters is near limitless and with the variety of different weighting, materials and balances choices that the WvA design offers the golfer can build their ideal personalized putter with high precision.

During physical testing, the golfers were pleased with the feel and sound of the WvA Design putter. As such, the setup of the current WvA design is a good generic starting point to use as a template for further design iterations. The recorded frequency (or pitch) of the putter is in close range with that of other current traditionally manufactured putters and the fact that golfers can request a different sound will ensure that it would be appealing for all golfers. The weighting of the current setup is also quite neutral as the golfer would be able to specify the addition or removal of weight. The current design has a weight distribution that favours a face balanced setup, as this is the favoured balance for many high-level golfers.

The natural frequency of the WvA design is very low and this will have to be looked at for future designs. The putter head may need to be made more compact to increase the natural frequency value if experienced as problematic. It would be beneficial to thicken some areas, such as the hosel, to increase frequency and reduce risk of damage due to bending or fatigue. A more compact design would also allow the movement of more weight away from the center to increase the moment of inertia.

The moment of inertia of the WvA design is higher than that of the other compared putters, suggesting that it should prove to be more consistent than the others. As the golfers with a high skill level are the targeted group, they often have putters in competitive environments where there is a lot at stake, be that prize money, media exposure or pride. Thus, more consistency will result in more important putts finding the bottom of the cup. This putter displays the opportunity that golfers have to be directly involved with the development of their putter to tune the club to their own personal preferences. They have a vast array of materials, weightings and aesthetics to choose from to ensure a putter is produced that they trust and feel comfortable with. For the WvA design, some of the weight was removed from the center to increase inertia, but with the incorporation of interchangeable weights the golfer
has the option to adjust the inertia and balancing of the putter at any time.

Contemporary Computer Aided Design (CAD) platforms allow for fast adjustments to be made to the design and simulations are readily available and far more accessible than previously. Thus, each new design can be viewed and simulated to ensure that the outcome would be exact within the specifications requested for by the golfer. As the process of 3D metal printing is quite costly, it is obviously beneficial to address any issues before the final printing is committed to.

The research contributions were achieved in the following ways:

- A customizable, balanced golf putter, that can be multiply adjusted for personal requirements, was achieved, which showed to have better overall achievable specs compared to the standard off-the-shelf products.
- A golf putter that was developed by means of Additive Manufacturing techniques, which showed the weight of the WvA putter to be lighter compared to the other compared putters, except for the PING Karsten Anser putter. The Additive Manufacturing techniques also allowed for a customisable putter to be developed.
- Modern implicit techniques allow for virtually instantaneous variable adaptability to produce very quick model outputs for uploading to Print Bureaus, resulting in a very short-term result of final physical output.

In conclusion, AM putters would prove to be a good substitution for traditionally manufactured putters as the same sound, aesthetics and feel can be created with the added benefits of near limitless customizability. The WvA design will prove to be very competitive with other currently manufactured putters, due to the efficient weight distribution while still satisfying the feel and sound preferred by many golfers.

ACKNOWLEDGEMENTS

The team would like to acknowledge Altair, Customworks, eNTSA and Rapid 3D for their contributions.

REFERENCES


2021 CONFERENCE
PLATINUM SPONSOR

Department of Science and Innovation
www.dst.gov.za
2021 CONFERENCE SILVER SPONSORS

Central University of Technology, Free State, Bloemfontein
www.cut.ac.za

Vaal University of Technology, Vanderbijlpark, Gauteng
www.vut.ac.za

EOS
www.eos.info

CSIR National Laser Centre
www.csir.co.za

3D Printing Systems South Africa
www.3dprintingsystems.co.za

Simteq
https://simteq.co.za/