18th Annual Conference
7–10 November 2017
at the Durban ICC

Hosted by RAPIDASA

WORLD-CLASS SPEAKERS | TOP EXHIBITORS
SA’S BIGGEST 3D PRINT DESIGN COMPETITION | BIG PRIZES

Game Changing Thinking:
3D Printing, Additive Manufacturing,
Internet of Things
GOLD SPONSORS

3dprintingsystems.co.za

SILVER SPONSORS

eos.info/en

Trade & Investment KwaZulu-Natal
Zulu Kingdom. Exceptional

tihzn.co.za

RAPDASA 2017 Conference proceedings
ISBN: 978-0-620-77329-4
November 2017
Full Papers Available on www.rapdasa.org
Sincere thanks to our distinguished supporters and sponsors who generosity made the success of this conference possible.
CONTENTS

RAPDASA Review Process ........................................................................................................6
Foreward by RAPDASA Chair .................................................................................................9
Technical Committee ............................................................................................................10
Organising Committee ..........................................................................................................11
Exhibitors .............................................................................................................................12
Pre-Conference Seminar on Additive Manufacturing of Titanium Parts .............................14
Pre-Conference Seminar Programme .......................................................................................15
Day 1 Programme ..................................................................................................................46
Day 2 Programme ..................................................................................................................120
Day 3 Programme ..................................................................................................................206
Design Competition ...............................................................................................................248
RAPDASA 2017 REVIEW PROCESS

A formal “Call for papers” for the 18th Annual International RAPDASA Conference was issued in April 2017 to submit an ‘Extended Abstract’ within the identified tracks/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 published as a conference proceeding. Both the Extended Abstracts and Full Papers were submitted online through the RAPDASA submission page www.rapdasa.org/conference where acknowledgement of receipt was sent to authors. Authors were informed that a double-blind review process is applied to Full Paper submissions.

The following dates were set by the technical committee:

- Call for papers ........................................................................................................ 24th April 2017
- Submission of extended abstracts (2 pages): ................................................................. 16th June 2017
- Notification of acceptance of abstracts: ........................................................................ 1st July 2017
- Submission of full papers: .......................................................................................... 11th August 2017
- Feedback on paper reviews: ...................................................................................... 8th September 2017
- Revised paper submissions: ....................................................................................... 22nd September 2017
- Selected papers to be submitted to SAJIE: ................................................................. 29th September 2017

Extended Abstracts were required to be a maximum length of 2 pages. Full Papers were required to be between 5000 and 6000 words and a maximum length of 15 pages. Both Extended Abstract and Full Paper submissions had the following formatting guidelines:

- Trebuchet font at 9-point size.
- Single spacing and a page margin of 20 mm along the sides, 20 mm at the top and 25 along the bottom.
- A gutter of 10 mm position left, with full justification.
- A4 paper size.
- A header and footer layout of 15 mm.

A double-blind reviewing process was used for the Full Paper submissions. As such, both the reviewer and author identities are concealed from the reviewers, and vice versa, 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 non-consensus between the first two reviewers. The reviews were completed by national and international academics, and experts in the respective field, listed on the Technical Committee page.

A total of 42 reviewers participated in the review process, each reviewing on average between two and three papers. 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 submission system, where acceptance emails together with review comments were sent to the authors, allowing them to revise the submission. The authors were given between 2 and 4 weeks to incorporate changes, after which the final document was submitted for approval and publication as a conference proceeding.

Full papers were accepted under the following themes:
• Additive Manufacturing business developments / New Additive Manufacturing applications.
• Impact of Additive Manufacturing on the intellectual property environment.
• Design for Additive Manufacturing.
• Reverse engineering.
• Internet of things.
• Simulation and modelling.
• Process monitoring and control.
• Material evaluation and selection.
• Post processing and qualification.
• Material / Process development.
• Product development.

Selected papers were submitted to the South African Journal of Industrial Engineering (SAJIE) to be published as a Journal Paper. These papers were removed from the conference proceedings and subject to SAJIE’s own review process.
Foreword by the RAPDASA Chair

The RAPDASA 2017 conference will be the first conference to be hosted in KZN, and we hope to engage with the AM community in South Africa and in KZN and meet new and interesting players. AM adoption is growing in South Africa and the typical South African innovative spirit comes to the fore in the application of the technology. We continue to see world class medical work using Ti implants from the SA team as well as greater application of models used for surgery planning, the first commercial company in Southern Africa specializing in the direct metal printing of tooling inserts, and more and more companies embracing AM for production purposes. It is encouraging to see South African businesses using the technology to solve challenges around logistics and machining capacity often in ways that are very different to other markets.

This year’s theme is “Game Changing Thinking” with 16 invited speakers both local and international, keynotes and topics ranging from the “State of Additive Manufacturing Worldwide” to “Tapping nature’s genius in 3D printing”

The RAPDASA Management Committee together with RAPID 3D would like to welcome you to Durban and sincerely hope that we can build on previous conferences to inspire and enable South African innovation through 3D Printing and Additive Manufacturing.

We are most grateful to our sponsors and participants from South Africa and around the world, thank you for your contribution to RAPDASA 2017.

David Bullock
TECHNICAL COMMITTEE

Dr Thorsten Becker
(technical chair, track director for Material evaluation and material development)

Mr Devon Hagedorn-Hansen
(technical co-chair, track director for AM business developments / applications, Design for AM and simulation and modelling)

Mr Heinrich van der Merwe
(track director for post processing and qualification)

Dr Malan van Tonder
(track director for internet of things, process monitoring)

Mr David Mauchline
(track director for Product development)

Mr Lucas Steven Anderson
Mr Nana Kwamina Arthur
Prof Uwe Berger
Mr Martin Bezuidenhout
Prof Deborah Blaine
Mr Martin Bolton
Ms Shyline Tafadzwa Chingowo
Prof Oliver Damm
Prof Olaf Diegel
Prof Dimitar Dimitrov
Prof Willie du Preez
Mr Philip Hugo
Ms Charmaine Johnston
Mr Jan Jooste
Mr Cornelius Petrus Kloppers
Mr Martin Lotz
Ms Tintswalo Mabuza
Ms Bathusile Masina
Mr David Mauchline

Prof Peter Mendonidis
Mr Lamech Mugwagwa
Ms Nneile Alexandrina Nhholise
Mr Godfrey Ositadinma Nwaneleh
Mr Bonjour Kasongo Didier Nyembwe
Dr Eyitayo Olatunde Olahanmi
Prof Tiaan Oosthuizen
Mr Ruaan Schoeman
Prof Surya Pratap Singh
Mr Gerrit Matthys Ter Haar
Ms Keheletso Thejane
Dr Monnnamme Tlotleng
Prof Michele Truscott
Prof Andre Francois van der Merwe
Dr Kobus van der Walt
Ms Liesl Van Reenen
Professor George Vicatos
Dr Bey Vranchen
Prof Igor Yadroitsev
ORGANISING COMMITTEE

Pauline Bullock
David Bullock
Jenny van Rensburg
Leanette Mtsweni

Special mention of:
Thorsten Becher, Technical Committee
Devon Hagedorn Hansen Design Competition
Willie du Preez, PreConference Workshop

With much assistance from past and present RAPDASA management committee members and the team at Rapid 3D.
## EXHIBITORS

<table>
<thead>
<tr>
<th>3D Systems South Africa</th>
<th>AMS</th>
<th>Altair</th>
</tr>
</thead>
<tbody>
<tr>
<td>3dprintingsystems.co.za</td>
<td>ams3d.co.za</td>
<td>solidthinking.com</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bohler-Uddeholm</th>
<th>Caldeaz</th>
<th>Central University of Technology, Free State</th>
</tr>
</thead>
<tbody>
<tr>
<td>bohler-uddeholm.co.za</td>
<td>caldeaz.co.za</td>
<td>cut.ac.za</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CRPM</th>
<th>CSIR</th>
<th>Demaplastech</th>
</tr>
</thead>
<tbody>
<tr>
<td>crpm.co.za</td>
<td>csir.co.za/csir-national-laser-centre</td>
<td>demaplastech.co.za</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EOS</th>
<th>Materialise</th>
<th>Modena</th>
</tr>
</thead>
<tbody>
<tr>
<td>eos.info/en</td>
<td>materialise.com</td>
<td>modena.co.za</td>
</tr>
</tbody>
</table>
PRE-CONFERENCE SEMINAR ON ADDITIVE MANUFACTURING OF TITANIUM PARTS

Tuesday, 7 November

Background
From its position as the world’s second largest producer of titanium raw material, South Africa has the potential to add significant value to this natural resource. In response to recommendations of the National Research and Technology Foresight Project, dating back to 1999, a national Titanium Metal Industry Strategy was developed by the Department of Science and Technology (DST). In 2009 the Titanium Centre of Competence was established as implementation vehicle of this strategy. Additive manufacturing of titanium alloys featured as one of the technology platforms of the Titanium Centre of Competence.

Following on the need for a national additive manufacturing plan expressed by the Rapid Product Development Association of South Africa (RAPDASA) in 2012, the DST commissioned the development of a South African Additive Manufacturing Strategy. This strategy, published in 2016 (see http://www.rapdasa.org), provides guidance to South African players in identifying economic opportunities, addressing technology gaps, focusing development programmes and informing investment decisions that would eventually enable local companies and industry sectors to become global leaders in selected areas of additive manufacturing.

In response to the recommendations of this national strategy, a national Collaborative Program in Additive Manufacturing (CPAM), funded by the DST, was initiated in 2015. This program is executed by a consortium consisting of the CSIR National Laser Centre, the Central University of Technology, Free State, Aerosud, Stellenbosch University, Northwest University, Vaal University of Technology, the University of Cape Town, University of Johannesburg, the University of the Witwatersrand, Rapid3D and Altair. An important sub-program of the CPAM focuses on Qualification of Additive Manufacturing of Ti6Al4V for Medical Implants and Aerospace Components.

Focus of the Seminar
This one-day seminar features research and development related to the CPAM sub-program on Qualification of Additive Manufacturing of Ti6Al4V for Medical Implants and Aerospace Components. The progress and achievements of this national program will be presented by researchers from the collaborating institutions. Postgraduate students from the participating universities will present their research executed under this CPAM sub-program.

For more information regarding the seminar, contact:
Prof Willie du Preez    Dr Kobus van der Walt
wdupreez@cut.ac.za     jgvdwalt@cut.ac.za
Tel: +27 51 507 3556    Tel: +27 51 507 3644
## PRE-CONFERENCE SEMINAR PROGRAMME

**Tuesday, 7 November**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:30 – 10:00</td>
<td>Registration. Tea &amp; Coffee,</td>
</tr>
<tr>
<td>10:00 – 10:05</td>
<td>Welcoming Address&lt;br&gt;Dr Kobus van der Walt</td>
</tr>
<tr>
<td>10:05 – 10:20</td>
<td>Opening Address&lt;br&gt;Mr Garth Williams</td>
</tr>
<tr>
<td>10:20 – 10:40</td>
<td>Progress towards Qualifying Additive Manufacturing of Ti6Al4V for Medical Implants and Aerospace Parts&lt;br&gt;Willie du Preez</td>
</tr>
<tr>
<td>10:40 – 11:00</td>
<td>The Effects of Selective Laser Melting Scan Strategies on Hybrid Parts&lt;br&gt;D Hagedorn-Hansen</td>
</tr>
<tr>
<td>11:00 – 11:20</td>
<td>Residual Stress Distributions within Components Manufactured using Selective Laser Melting&lt;br&gt;L Mugwagwa</td>
</tr>
<tr>
<td>11:20 – 11:45</td>
<td>TEA</td>
</tr>
<tr>
<td>11:45 – 12:05</td>
<td>High Cycle Fatigue Properties of As-built Ti6Al4V (ELI) Produced by Direct Metal Laser Sintering&lt;br&gt;LB Malefane</td>
</tr>
<tr>
<td>12:05 – 12:25</td>
<td>Dynamic Behaviour of Direct Metal Laser Sintered Ti-6AI-4V (ELI) Under High Strain Rates in Compression Loading&lt;br&gt;AM Muiruri</td>
</tr>
<tr>
<td>12:25 – 12:45</td>
<td>In-situ Alloying of Ti6Al4V-x%Cu Structures by Direct Metal Laser Sintering&lt;br&gt;EB Newby</td>
</tr>
<tr>
<td>12:45 – 13:05</td>
<td>Metal Additive Manufacturing of Blended Elemental Ti6AI4V Powder&lt;br&gt;A Zenani</td>
</tr>
<tr>
<td>13:05 – 14:00</td>
<td>LUNCH</td>
</tr>
<tr>
<td>14:00 – 14:30</td>
<td>The Face of Change: Impact of AM Titanium Implants&lt;br&gt;M Truscott, G Booysen</td>
</tr>
<tr>
<td>14:30 – 15:00</td>
<td>Commercial Readiness of Titanium Additive Manufacturing in South Africa&lt;br&gt;AF van der Merwe, L Bezuidenhout</td>
</tr>
<tr>
<td>15:00 – 15:20</td>
<td>Benefits of Innovation and Commercial Application of Ti6Al4V Additive Manufacturing for the South African Economy&lt;br&gt;I van Zyl</td>
</tr>
<tr>
<td>15:20 – 15:30</td>
<td>General Discussion&lt;br&gt;All</td>
</tr>
<tr>
<td>15:30</td>
<td>CLOSURE</td>
</tr>
<tr>
<td>15:35</td>
<td>TEA</td>
</tr>
</tbody>
</table>
Opening Address

BIOGRAPHY
Garth Williams has worked at the Department of Science and Technology as Director: Advanced Manufacturing Technologies since mid 2011 and is responsible for advanced manufacturing technology policy and strategy. Previously he worked at Mintek, a public research organisation specialising in minerals processing and extractive metallurgy, firstly as a precious metals researcher and then within an HR environment where he oversaw the company’s human capital development programmes amongst others. After graduating he worked as a metallurgist within a manufacturing environment at GKN Sinter Metals Cape Town, and then at Nampah Group R&D.

Garth Williams has an MSc (Eng) in Materials Engineering from the University of Cape Town and will graduate with an MSc in Science and Technology Policy from the University of Sussex, UK in January 2018. He is a trained ParticiPlan® group facilitator, has experience in strategy development using technology roadmapping, and enjoys doing the occasional MOOC in his spare time. Garth is married to Karyn and lives in Randburg.
Willie du Preez
Associate Professor
Central University of Technology, Free State
cut.ac.za

Progress towards Qualifying Additive Manufacturing of Ti6Al4V for Medical Implants and Aerospace Parts

BIOGRAPHY
A registered Professional Materials Scientist, directing and supervising research and development on additive manufacturing of titanium alloys and polymers for application in the fields of medical implants and devices, aerospace parts, advanced tooling and direct end-use in industry. He has broad experience of strategic planning and leading research and development on the production, processing and application of titanium and its alloys. In both industrial as well as research and developments environments Willie has gained solid understanding of product development utilising state-of-the-art product development technologies.
Michelle Truscott
Associate Professor in the Mathematical and Physical Science Department, Central University of Technology
cut.ac.za

Michelle has a BSc, BSc Hons, MSc and PhD degrees from the University of the Free State (CUT).

Michelle lectures Mathematics and is concerned with Medical Product Development research activities performed in the CRPM on the Bloemfontein Campus.

She has authored or co-authored 20 accredited papers, 10 non-accredited papers, 11 technical papers, nine chapters in books and has been an editor or co-editor of seven books. She has presented papers at a number of National and International conferences.

She has been an NFR Y- and L-rated researcher in the past.
Benefits of Innovation and Commercial Application of Ti6Al4V Additive Manufacturing for the South African Economy

BIOGRAPHY
Experienced Project Engineer with a demonstrated history of working in the mechanical or industrial engineering industry. Skilled in Computer-Aided Design (CAD), Materials Testing and Advanced Manufacturing. Strong engineering professional with a Master’s Degree focused in Mechanical Engineering.
Gerrie Booysen is the Director of the Centre for Rapid Prototyping and Manufacturing and also lectures for the School of Mechanical Engineering and Applied Mathematics at the Central University of Technology (CUT), Free State in Bloemfontein, South Africa. He obtained his master’s degree in 2007 from the CUT, which focused on bridge tooling using additive manufacturing technologies.

He is a grant holder in the Integrated Product Development Niche Area of the National Research Foundation since 2004 and his research focuses on rapid and hybrid tooling applications using additive manufacturing technologies.

His main achievements include best B Tech Mechanical engineering student in 1999 and best post graduate student for the Engineering faculty and received the S2A3 Bronze medal in 2007. He also received the Vice-Chancellors Award for best post graduate student at the University in 2007 and a merit award for best researcher in the Faculty of Engineering and Information Technology in 2011.
COMMERCIAL READINESS OF TITANIUM ADDITIVE MANUFACTURING IN SA
A.F. van der Merwe¹, L. Bezuidenhout¹, W.B. du Preez²

ABSTRACT
Additive manufacturing (AM) is considered a disruptive and emerging technology designated to replace conventional manufacturing processes. Technology Readiness Level (TRL) is widely used as a measure of technology maturity. However, TRL is not necessarily a good indicator of commercial readiness. In the renewable energy sector a Commercial Readiness Index (CRI) is used where only a technology with a high TRL qualifies for commercial readiness. Similarly TRL is used to measure the maturity of Additive Manufacturing (AM) technologies. This research proposes a Commercial Readiness Index (CRI) for Additive Manufacturing. The value of this research lies in the ability for investors to now assess the commercial viability of using AM in a specific product line. A case-study on maxillofacial Ti6Al4V implants manufactured with AM is referred to.

1. Commercial readiness follows technology readiness
Technological research is conducted towards an increased TRL. Commercial research aims to achieve an increased CRI. There exist a gap between these two parameters and the goal is to align TRL and CRI. Referring to Figure 1, TRL 2 is required for a CRI 1 concurrent engineering to commence. Furthermore, TRL 6 is required for CRI 2 engineering to commence. The CRI can be further described by compiling several commercial indicators: Regulatory Environment, Stakeholder Acceptance, Clinical Performance, Technical Performance, Financial Performance — Cost, Financial Proposition — Revenue, Funding, Industry Supply Chain and Skills, Market Opportunities and Company Maturity.

Figure 1: TRL and CRI

This presentation will investigate the desired “To-Be” levels of readiness for each indicator for a Metal Additive Manufacturing (MAM) case study. We will also attempt to consider the “As-Is” condition as an
example. Commercial research projects are then identified to move from As-Is to To-Be. Taking into account that any technology development destined for commercial exploitation firstly requires a certain TRL before starting to improve the CRI. Therefore, this provides a structure to align technology development research projects for commercialization.

2. Collaborative program in additive manufacturing in SA

Further towards the commercialization of AM in South Africa (SA) we wish to reference the document prepared by a CPAM working group; “CPAM COL AM Business Plan Jan 2017 ver 6.5” [1], with the necessary acknowledgement to the authors. In the document it is stated that titanium AM in SA is considered at TRL 6 or TRL 7 — ready for commercialization. The document mentions that the long-term strategy includes commercialization, and that uncertainty exists as to how commercialization should be handled in the medium term strategy. The document also refers to a requirement to develop the CRI for titanium AM products for aerospace. We use the work done by Bezuidenhout [2] to focus AM research in SA towards medium-term commercialization. We propose that researchers currently focusing on technology would continue as now, albeit with an alignment towards commercialization. This would mean an awareness of how to align emerging technology research towards an increased TRL of that technology; to integrate the supply chain (SC) predecessors feeding into the emerging technology (Integration Readiness Level — IRL, Systems Readiness Level - SRL); similarly the supply chain successors would typically require a full market integration strategy (IRL, SRL); consequently, this results in increased CRI for the SC enabling each technology.

The presentation then follows with a CRI indicators research projects map indicating current and proposed projects at various commercial and academic levels. Firstly, a statement is made on the proposed To-Be (and As-Is) TRL and CRI states of a typical AM SC in SA. Then a table is provided with projects towards CRI indicators distinguishing polymer from metal, and distinguishing medical from aerospace. Thirdly a gap analysis is done to position projects on the map and linked to the table with current projects allocated to researchers. Further projects are then proposed to address the medium-term strategy towards commercialization.

Specific projects aiming at standardisation have commenced. Standardisation falls within the regulatory indicator of CRI, but also addresses many aspects in the Stakeholder indicator. A comprehensive specification standardisation framework for AM medical and aerospace is required. The medium-term motivation is to have a structure through which to communicate the standards that have to be complied with. Also to assist the commercial AM bureaus to assess their own risk associated with non-compliance or partial compliance. The longer term motivation is progressive global competitiveness of the SA AM industry, especially in titanium products. South Africa can only be globally competitive if we focus, standardise and cluster our manufacturing activities to gain trust in the global supply chain. Standardisation refers to legal conformance to regulations that in turn refers to relevant and applicable standards. Standards called by regulatory law are set up by international committees representing stakeholders specific to the subject matter. ISO is the most widely accepted international set of standards, but often national regulations or industry require more specific detail in their supply chain specifications. We then attempt to identify the relevant standards that a product line has to meet, from those required by law through to technological best practice. The presentation provides further insight.
COMMERCIAL READINESS OF TITANIUM ADDITIVE MANUFACTURING IN SA continued

REFERENCES


1 Resource Efficiency Engineering Management, Department of Industrial Engineering, Stellenbosch University

2 Centre for Rapid Prototyping and Manufacturing, Department of Mechanical and Mechatronics Engineering, Central University of Technology, South Africa
RESIDUAL STRESS DISTRIBUTIONS WITHIN COMPONENTS MANUFACTURED USING SELECTIVE LASER MELTING

L. Mugwagwa1*, D. Dimitro1, S. Matope1

ABSTRACT
Major setbacks such as the occurrence of residual stresses still restrict the applicability of the Selective Laser Melting (SLM) process. The required product geometry plays an important role in determining the magnitudes of residual stresses and accompanying shape deviations. Presently, there is limited, non-conclusive research regarding the influence of part thickness on residual stresses in SLM-built components. This research seeks to fill this gap and build on existing findings by considering a wider range of part thicknesses, and studying the actual distribution of residual stresses in the components, using the neutron diffraction technique.

1. Introduction
Selective Laser Melting (SLM) has gained a lot of ground in the last two decades due to the vast advantages that the technology offers with regards to high geometric complexity capabilities, achievable final part density and minimum raw material wastage. The subject of residual stresses is a very active field of research in SLM due to the challenges that these stresses pose on the applicability of the process. The required final product size and shape determine the magnitudes of residual stresses and dimensional/form accuracy of manufactured components. Casanova et al. [1] as well as Mercelis and Kruth [2] studied residual stress distributions in parts of different thicknesses. Furumoto et al. [3] studied the effect of increasing number of layers on residual stresses. In all these previous related studies, no corresponding study on porosity was done, and the findings of [1] are not conclusive. The purpose of this paper, therefore, is to investigate how part thickness influences residual stress distributions and achievable density in SLM manufactured components.

2. Methodology and results
2.1 Methodology
Parts of thickness 9, 12, 15, 18 and 21 mm were considered for this paper. The parts were fabricated by selectively melting tool steel powder using the M2 laser cussing machine. The laser power was set to 165 W and scanning speed to 600 mm/s. After the parts were manufactured, the Archimedes’ density measurement method was used to investigate whether the number of laser beam passes had any effect on re-heating of the underlying layers and whether this significantly contributes to differences in achievable density. The Neutron Diffraction (ND) technique was used to measure residual stresses in this paper. Tri-axial stresses – longitudinal (σ_L), transverse (σ_T) and normal (σ_N) – were measured at various points across width (Y axis) and depth (Z axis) of specimens.

2.2 Results
The relative densities for the 9, 12, 15, 18 and 21 mm specimens were 98.18 (± 0.06), 98.97 (± 0.14), 98.75 (± 0.06), 99.02 (± 0.13) and 99.03 (± 0.08) respectively. The relative density slightly increases with increase in part thickness. This is because as the part gets thicker, the number of deposited and scanned layers also
increases. Exposure of the current powder layer to the laser beam has an effect of re-heating the underlying solidified layers, thus further melting them. All the specimens exhibited both compressive and tensile normal residual stress components at different measurement positions. The 9 mm specimen experienced a maximum normal tensile stress of 164 MPa whilst a maximum of 102 MPa was measured for the 21 mm thick specimen. The highest longitudinal component of residual stress was 146 MPa tensile, measured for the 21 mm thick specimen, whilst the maximum component for the 12 mm and 9 mm specimens stood at 106 MPa and 108 MPa (both tensile), respectively. Both longitudinal and transverse stresses are more uniform for the inner central regions of the thicker specimens (15 – 21 mm) compared to the 9 mm and 12 mm specimens. Overall, the highest residual stress magnitudes were measured along the transverse direction for all specimens. The 21 mm thick part suffered the highest tensile residual stress of 394 MPa. In comparison, the thinner specimens experienced lower stresses. The maximum residual stresses measured nearly vary directly with the measured relative densities. The porosity of the smaller parts relaxes stresses, hence the lower stresses for these parts compared to thicker parts.

3. Conclusion

- The in-plane stresses are much greater compared to the normal stresses. Normal stresses are greater for thinner parts whereas longitudinal and transverse stresses are greater for thicker specimens. The patterns of residual stress distributions are more consistent for the thicker parts compared to the thinner ones.
- Slight but important differences in final part densities can be observed for the different part thicknesses. The effect of re-heating of underlying layers is the reason for these differences. The differences in the relative density have a notable effect on residual stress magnitudes within the parts since porosity has an effect of relaxing residual stress. Residual stresses are greater in thicker specimens as compared to their thinner counterparts.

REFERENCES


Department of Industrial Engineering, Stellenbosch University (lamech@sun.ac.za)
METAL ADDITIVE MANUFACTURING OF BLENDED ELEMENTAL Ti6Al4V POWDER

A. Zenani*, W. Du Preez, I. Yadroitsev

ABSTRACT
South Africa is the second largest producer of titanium raw material in the world. Therefore, titanium metal powder development and application is a significant aspect of research with potential impact on growth of the titanium industry in South Africa. Commercially pure Ti has been successfully blended in conventional powder metallurgy processing, but the use of blended elemental Ti6Al4V powder in powder bed metal additive manufacturing (MAM), has not been demonstrated yet. This paper reports on a study to determine the feasibility of using blended elemental Ti6Al4V powder to produce alloy parts complying with international standards for wrought metal through powder bed MAM.

1. Introduction
Direct metal laser sintering (DMLS) is an additive manufacturing (AM) technology which is applied to build objects in a layer-by-layer fashion from a three dimensional (3D) CAD model, instead of removing material through machining in different steps in the conventional manufacturing way. The essential operation in DMLS is the laser beam scanning over the surface of a thin powder layer previously deposited on a substrate. DMLS has already had positive impact on manufacturing industries such as aerospace, medical implants and devices, automotive, sports equipment and marine applications. Complex parts, small and light components with complex geometric features such as hollows, thin walls and undercuts, are now possible to be made with DMLS [1, 2]. DMLS uses materials such as aluminium, stainless steel and titanium. DMLS allows for multiple components, such as fasteners and mountings, to be made at once and this reduces waste of time and resources.

Characteristics of the produced DMLS object such as porosity, microstructure and mechanical properties are influenced by the parameters used for the DMLS process. Parameters such as the layer thickness, as well as powder particle grain size and shape, are important for deposition of the powder layer. Laser power and temperature, spot size, scanning speed of the laser and the deposition time, determine the effectiveness and success of the process and the quality of the part produced [1]. To achieve high mechanical strength and adequate fatigue behaviour, it is important to produce high density parts with optimal surface quality and to minimize defects through the optimization of process parameters. In this way, a working window is obtained with a defined set of parameters where parts with high densities and low surface roughness are guaranteed [3].

In laser processes, the energy density is a key factor: sufficient energy density is needed to melt powder particles of the layer being processed and the previous layer to assure a correct joining between successive layers and to avoid lack of fusion and porosity, while excessive energy can cause evaporation of the material creating defects and reducing material density. To optimize parameters, it is common practice to manufacture simple geometries like cubes, maintaining constant power and varying the scanning speed in each cube, for a given layer thickness and hatch spacing [3]. Thus, each cube is manufactured with different energy density.
Afterwards, the cubes are characterized where interior density, sub-surface density and roughness are determined, to identify the right energy density window and corresponding parameters.

The thermodynamic enthalpy of mixing is expected to significantly influence the mixing process and the homogeneity of the alloy [4]. A negative mixing enthalpy results in an exothermic reaction with additional heat being supplied to the melt pool during the mixing of the elemental powders, aiding in homogenization of the resulting deposit. Similarly, a positive enthalpy of mixing results in an endothermic reaction, whereby heat is extracted from the melt pool making mixing and homogenization of the powder more difficult [4, 5]. The mixing enthalpy of Ti6Al4V is calculated to be – 11.35kJ/mol and therefore a homogeneous microstructure and rapid solidification is expected.

2. Methodology and results
The first step will be to run single tracks on a substrate, using the blended elemental powder. From the single tracks the continuity of the tracks, the penetration depth of the track into the substrate to relate it to the laser energy density and the microstructure of the tracks will be analysed. This analysis will support decision making on the optimum process parameters (scanning speed, laser power, powder layer thickness) based on the best track identified. Once the optimum process parameters have been selected, continuous single track layers at different hatch distances will be produced and surface analysis will be done to determine continuity and homogeneity of the tracks. This will allow selection of the best hatch distance.

3D specimens will then be built on the EOS M280 machine. The chemical composition, surfaces and microstructures of the specimens will be analysed, defects such as porosity will be determined and the uniformity of the alloy will be verified. Once that has been done successfully, the specimens will undergo tensile tests to determine the mechanical properties of the material.

The mechanical property results will be compared with the properties of the wrought alloy and pre-alloyed Ti6Al4V parts built through AM. Based on the outcome of the comparison, conclusions will be drawn on the feasibility of using blended elemental powders to produce Ti6Al4V parts by MAM.

3. Conclusion
Using the CSIR-Ti powder production process, it is anticipated that Ti powder will be produced economically in South Africa relative to Ti powder procured from international suppliers. Successful outcome of the current research should lead to Ti, Al and V powder blends being used in various MAM processes. This would open up market potential for commercialization.

REFERENCES
METAL ADDITIVE MANUFACTURING OF BLENDED ELEMENTAL Ti6Al4V POWDER conclusion


*1 Department of Mechanical and Mechatronics Engineering, Central University of Technology, South Africa (asazenani2@gmail.com)
IN-SITU ALLOYING OF Ti6Al4V-xCu STRUCTURES BY DIRECT METAL LASER SINTERING

E.B. Newby, D. Kouprianoff, I. Yadroitsava

ABSTRACT
The formation of in-situ Ti6Al4V-x%Cu (1%, 3% and 5% Cu) alloy structures by Direct Metal Laser Sintering (DMLS) for application in medical implants was investigated. Ti6Al4V (ELI) powder was mixed with pure Cu powder of similar particle size distribution. Optimal process parameters were established for in-situ alloying of Ti6Al4V-x%Cu to form dense parts with suitable microstructural and surface quality. Process parameters such as laser power, scanning speed, hatch distance and layer thickness directly affect the surface quality and part density. Firstly, single track formation was studied. Appropriate scanning speeds were determined for different laser powers (170 W and 340 W). The effect of laser power and scanning speed on the track width and penetration is described. The surface roughness, surface composition and homogeneity as well as micro hardness were considered. A rescanning strategy was investigated to improve alloy homogeneity, part density and surface quality.

1. Introduction
Ti6Al4V Extra Low Interstitial (ELI) alloy is commonly used for medical implants because of its suitable mechanical, corrosion resistant and biocompatibility properties. The most common reason for implant failure and complications after surgery, is infection. Coating the implant to produce a bone-implant interface with materials that have antibacterial properties (such as Cu) is a promising approach to infection prevention. Copper is a proven antibacterial agent and in small amounts not toxic to the human body [1]. DMLS can be applied to directly produce implants having a biocompatible Ti6Al4V structure with Cu additions at the bone–implant interface to reduce the risk of bacterial infection and implant failure.

Fundamentally, DMLS is a selective laser melting (SLM) process in which a laser beam is scanned over a thin powder layer. The laser beam melts a row of powder particles, forming a molten pool and finally a single track. Single tracks, or the continuous linear formation of the molten pool is the most basic building block in the DMLS process. SLM objects are formed by fusing multiple single tracks layer by layer upon one another. Thus the optimization of formation of the molten pool and single track plays a major role in the quality and mechanical properties of the manufactured 3D object. [2]

The geometric characteristics of the DMLS tracks are mainly determined by material properties, energy input (laser power, spot size and scanning speed) and the thickness of the deposited powder layer. The depth of penetration into the substrate is determined primarily by the power of the laser beam, and the layer thickness which determines the powder volume involved in the melting process [3]. At optimal process parameters, SLM single tracks are continuous and have stable geometrical characteristics.

2. Methodology
To produce the Ti6Al4V-x%Cu powder alloy, Cu powder was mechanically mixed with Ti6Al4V (ELI) powder for 30 minutes. To determine the effect of scanning speed on surface quality and homogeneity of the alloy, single tracks and surfaces with size 10mm x 10mm were manufactured by an EOSINT M280 machine. Two
sets of process parameters were used: laser power 170 W at six scanning speeds (0.4 m/s, 0.6 m/s, 0.8 m/s, 1 m/s, 1.2 m/s and 1.4 m/s) and laser power 340 W at increase in scanning speeds by two times accordingly. Laser spot size was approximately 80 µm and kept constant. This strategy was then carried out on all three Ti6Al4V-x%Cu alloys (1%, 3% and 5%).

3. Results and discussion
The surface roughness increased with an increase in scanning speed. Surfaces at higher scanning speeds produced more satellites on the surface and dramatically decreased the surface quality. Rescanning removed the satellites from the surfaces and therefore showed some improvement of the surface quality. Further rescanning strategies were investigated to further improve the surface quality of in-situ SLM alloying.

When the powder mixture is exposed to the laser beam, the powder mixture melts, but since Cu has higher thermal conductivity, lower heat capacity and viscosity than Ti6Al4V, copper transfers heat to the surrounding titanium alloy and fluid flow pushes the heavier copper to the peripheries of the molten pool. The molten pool rapidly solidifies before the copper can be completely mixed and alloyed with the Ti6Al4V. Better results of surface homogeneity and surface composition were noted at higher energy inputs because the Cu had more time to alloy with the Ti6Al4V before the molten pool solidified.

4. Conclusion
The surface quality of the produced layers were improved with a decrease in scanning speed. The applied rescanning strategy had minimal effect on surface roughness but did remove surface satellite particles, thereby improving the surface quality. Surface homogeneity and surface composition improved with an increase in input energy.

REFERENCES

1* Department of Department of Mechanical and Mechatronics Engineering, Central University of Technology, South Africa (ericnewby1@hotmail.com)
ABSTRACT
The utilisation of Additive Manufacturing (AM) for the production of intricate part geometries in the aerospace, medical, and tool-and-die industries is increasingly incorporated in manufacturing process chains. However, the high costs, long production times, and material integrity issues associated with AM technologies such as Selective Laser Melting (SLM) make the process suitable only for certain applications. In order to reduce SLM production costs for select parts, a combination of SLM and milling can be utilised. Metal parts produced with this method are referred to as hybrid parts. A challenge in producing hybrid parts is to reduce the geometrical deviation due to process induced warping. This paper discusses the effects of various laser scan strategies on the deviation of hybrid parts. A newly developed scan strategy is experimentally compared to its commercial counterpart with regards to as-built part warping and porosity. The novel strategy resulted in a significant reduction in warping and porosity.

1. Background
Mercelis and Kruth [1] found that the exposure strategy used to fuse the powder layers has a significant influence on residual stress levels within a part. Scanning strategies are often overlooked and focus is towards optimisation of process parameters [2]–[4]. However, it has been shown that varying the scanning strategy results in different defects, anisotropy of mechanical properties, and geometrical deviations in SLM parts [5], [6]. The objective of this study was to determine whether a newly developed scan strategy significantly reduces geometrical deviation (warping) compared to the machine’s patented default strategy.

2. Experimental setup and design
To determine whether changing the scan strategies would affect the geometrical deviation of hybrid parts (and subsequently SLM parts) manufactured with a commercial SLM machine, the following experiment was designed and the process steps can be observed in Figure 1.
3. Experimental results and discussions

Figure 2 presents a scatterplot of the Z-deformation against the position of measurement in the X-direction. Deformation in the Z-direction is represented by the difference between pre- and the post-SLM CMM measurements. The porosity of the new scan strategy was also found to be significantly lower than the default strategy.

![Figure 2](image)

Scatterplot of Deformation in Z against the X position, categorized by the scan strategy on the same graph

4. Conclusion

Certain aspects of the SLM process still inhibit it from mass integration into product process chains. This paper emphasises one of these aspects, namely geometrical deviation due to warping. It has been proposed that the scan strategy significantly affects this phenomenon. Several scan strategies from literature have been presented and the shortcomings associated with them discussed. From these, a new varying-helix island scanning strategy with the objective of reducing geometrical deviation has been developed and experimentally tested against the default island scan strategy on a commercial SLM machine. The results showed a significant reduction in geometrical deviation and porosity for the newly developed scan strategy.

REFERENCES


THE EFFECTS OF SELECTIVE LASER MELTING SCAN STRATEGIES ON HYBRID PARTS continued


*Stellenbosch Technology Centre, Department of Industrial Engineering, Stellenbosch University, South Africa (devonh@sun.ac.za)
HIGH CYCLE FATIGUE PROPERTIES OF AS-BUILT Ti6Al4V (ELI) PRODUCED BY DIRECT METAL LASER SINTERING

L.B. Malefane¹, W.B. Du Preez, M. Maringa

ABSTRACT
The high cycle fatigue (HCF) properties of Direct Metal Laser Sintering (DMLS) Ti6Al4V (ELI) in three mutually orthogonal build directions were investigated by cycling specimens under a load control, in a tension-tension fatigue testing machine. Semi-log graphs of maximum stress (S) against life (N) of the specimens produced along the respective three build directions were plotted and the displayed endurance limits compared. Optical and scanning electron microscopy were used to compare and analyse crack initiation and propagation characteristics of the specimens. The influence of the build direction on fatigue properties of the tested specimens is discussed here.

1. Introduction
Work done by the CRPM on skeletal reconstruction through the use of customized DMLS Ti6Al4V (ELI) skeletal implants has thus far been based on static mechanical properties of DMLS post additive manufacturing (AM) stress relieved Ti6Al4V (ELI). These static mechanical properties conform to standard wrought surgical Ti6Al4V (ELI) properties [1,2]. However, for DMLS Ti6Al4V (ELI) implants that are expected to experience cyclic loading, (e.g. femoral, mandibular and pelvic implants) there is uncertainty about whether they will last the life span of the host. This is due to limited fatigue life data for such implants. Fatigue is a 3-stage process consisting of crack initiation, crack propagation and final fracture. Crack initiation occurs as a result of localized plastic deformation on an atomic scale and is a critical stage in fatigue as it typically consumes more than 90% of the fatigue life, depending on the presence or absence of stress concentration sites [3]. Stress concentration sites in DMLS Ti6Al4V (ELI) parts could arise from process related surface irregularities, pores and inclusions [4]. The presence of tensile residual stresses in DMLS Ti6Al4V (ELI) test specimens during tension-tension fatigue testing increase the mean stress, which in turn decreases the stress ratio (R) during cyclic loading [5]. Decrease in the R-ratio decreases the fatigue endurance limit [6]. This is because at increased mean stresses, the flaw sizes from which a fatigue crack will initiate decrease and hence the fatigue cracks can initiate and propagate from micro flaws, in this case the micro pores present in DMLS Ti6Al4V (ELI) [5,1].

The study investigates the HCF properties of as-built DMLS Ti6Al4V (ELI) to establish the fatigue properties of such parts. This will be followed by the future determination of the improvement in fatigue properties as result of post-process heat treatment.

2. Methodology
A total of 30 rectangular bars of width = 11mm, height = 11mm and length = 60mm were built by an EOSINT M 280 DMLS machine; 10 in the X-, 10 in the Y-, and 10 in the Z-build direction. The bars were machined and polished down to dog bone fatigue test specimens in accordance with ASTM E466-15 and ISO 1099:2006E. The fatigue test specimens were tested at frequency of 10 Hz and a stress ratio R = 0.1, with varying maximum stresses, on a tension-tension fatigue testing machine at room temperature. From the tension-
tension test results, semi-log graphs of maximum stress against life of the specimens in each build direction were plotted. The fracture surfaces of the specimens were analysed using optical and scanning electron microscopy.

3. Results

Figure 1 below displays a semi-log \(_{10}\) S-N graph of the cycled X-, Y-, and Z-build direction, as built, Ti6Al4V (ELI) DMLS specimens. The stress levels at which the curves turn horizontal represent the endurance limits.

![Figure 1: S-N graphs of DMLS Ti6Al4V (ELI) specimens built in the X-, Y- and Z- directions](image)

Table 1 below shows the endurance limits of as-built DMLS Ti6Al4V (ELI) in the X-, Y-, and Z-build directions.

**Table 1: Run-out stresses for X-, Y- and Z-build direction specimens**

<table>
<thead>
<tr>
<th>Build Direction</th>
<th>X-build direction (run-out (\sigma_{max}) MPa)</th>
<th>Y-build direction (run-out (\sigma_{max}) MPa)</th>
<th>Z-build direction (run-out (\sigma_{max}) MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>450</td>
<td>486</td>
<td>486</td>
</tr>
</tbody>
</table>

The fatigue fracture surfaces of the as-built DMLS Ti6Al4V (ELI) specimens in their respective build directions were all characterised.

4. Conclusion

The endurance limits of the as-built DMLS Ti6Al4V (ELI) are similar for the X-, Y- and Z-build directions. The fatigue fractures displayed crack initiation from the surfaces.

REFERENCES


HIGH CYCLE FATIGUE PROPERTIES OF AS-BUILT Ti6Al4V (ELI) PRODUCED BY DIRECT METAL LASER SINTERING continued


*Department of Mechanical and Mechatronics Engineering, Central University of Technology, South Africa (leratamalefane@gmail.com)
ABSTRACT
Deformation behaviour under dynamic compression of Ti-6Al-4V (ELI) produced through additive manufacturing in two different forms; as-built (AB) and stress relieved (SR), was investigated. Both AB and SR specimens were printed using the DMLS EOSINT M280 system. Compression tests were performed on the specimens at strain rates lying between (300s⁻¹-400s⁻¹) and (600s⁻¹-700s⁻¹) using a Split Hopkinson Pressure Bar. This paper presents Scanning Electron Microscope (SEM) micrographs of the resulting fracture surfaces of the tested specimens, as well as scanned surfaces of through cuts, parallel and perpendicular to the load-direction of specimens that did not fracture, with a focus on the microstructural features peculiar to shear and adiabatic deformation.

1. Introduction
Ti-6Al-4V is an α+β titanium alloy. It has been used extensively for structural materials in air craft systems due to its high specific strength and excellent mechanical properties. This alloy has shown properties against armour piercing rounds superior to those of aluminium armour and is therefore employed as a material for combat vehicles (1). Generally, the mechanical properties of this alloy are closely related to the microstructural features governed by the relative fractions of the α and β phases (2). As-built AB, Direct Metal Laser Sintering (DMLS) Ti-6Al-4V has an α-martensitic structure resulting in a higher tensile strength but also a lower ductility in comparison with the stress relieved (SR) alloy DMLS Ti-6Al-4V, which has an α+β structure. Generally, Ti-6Al-4V contains interstitial impurity elements, which affect its mechanical properties. Moreover, the microstructure of the alloy, and therefore, its mechanical properties, are strongly influenced by its thermo–mechanical history. (3). According to Burhin and Love (4) the interstitial elements can be used to optimize the dynamic performance of the alloy.

Adiabatic shear bands (ASBs) are considered as a strain localization phenomenon of metals and alloys during high strain rate deformations. They are a result of plastic instability arising from thermal softening which can overcome the effect of work hardening/strain hardening. When a material is subjected to high shearing strain due to high rates of the applied load, the external work will initiate plastic deformation in the material. Most of this external work, especially for materials with considerable heat diffusion, will be dissipated as heat. This process increases the temperature of the material. But since materials are rarely pure without flaws, inhomogeneities in material form concentration areas for plastic deformation. For high rates of loading and therefore high rates of deformation, the heat generated at these areas is more than is dissipated. This gives rise to higher temperatures in materials at such areas. Ti-6Al-4V is a material that exhibits failure due to adiabatic shear banding because it possesses the properties of high strength and low thermal conductivity (5, 6). Further increase in strength due to strain hardening is accompanied by reduction in ductility. This paper seeks to examine the effect of high strain rates in compression and to study the resulting failure surfaces in order to identify any possible changes in microstructure of the Ti-6Al-4V (ELI).
2. Materials and experimental procedure

Ti6Al4V specimens were produced by the DMLS EOSINT M280 system. The specimens were cylindrical in shape with a nominal diameter of 6mm and a height of 12mm as per the specification of the SHPB apparatus in the Department of Mechanical Engineering, Blast Impact and Survivability Research Unit (BISRU) of the University of Cape Town that was used to conduct the test reported on here. 32 compression specimens were prepared, half of which were AB and the remainder SR. A standard Split Hopkinson Pressure Bar (SHPB) was used to realize the high test strain rates required. The schematic is as shown in Figure 1.

![Figure 1](schematic_representation_of_the_SHPB_for_compression_testing)

3. Experimental results and discussion

The test samples were examined using an optical microscope and a scanning electron microscope (SEM) in order to determine the deformation behaviour of the specimens upon imposition of dynamic compression on them. For compression loading in the strain rate range of (300–400) s⁻¹, the microstructure of the fractured specimens exhibited little noticeable change with reference to the microstructure of the unloaded material. However, adiabatic shear bands were noted using the SEM, with the width varying from the SR to the AB specimens. The locations of the shear bands for the AB and SR was found to differ along the longitudinal direction of the compressive specimens. It was evident that the number of fractured specimens were higher for the SR than the AB specimens at a strain rate range of (600–700) s⁻¹.

4. Conclusions

Compression tests of DMLS prepared Ti–6Al–4V (ELI) alloy in two different conditions AB and SR were performed to investigate the influence of the strain rates on the deformation behaviour of the material. The adiabatic shear band were the primary site of failure for the two form of specimens.

REFERENCES

DYNAMIC BEHAVIOUR OF DIRECT METAL LASER SINTERED Ti-6Al-4V (ELI) UNDER HIGH STRAIN RATES IN COMPRESSION LOADING continued


1* Department of Mechanical and Mechatronics Engineering, Central University of Technology, South Africa (amos.mwangi.muiruri@gmail.com)
2 Department of Mechanical Engineering, Vaal University of Technology, South Africa.
<table>
<thead>
<tr>
<th>Time</th>
<th>Session Details</th>
<th>Session Chair: David Bullock</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:30</td>
<td>Registration</td>
<td></td>
</tr>
<tr>
<td>09:15</td>
<td>Opening Address</td>
<td>Leon Kruger</td>
</tr>
<tr>
<td>09:45</td>
<td>Update on the State of Additive Manufacturing Worldwide</td>
<td>Terry Wohlers</td>
</tr>
<tr>
<td>10:30</td>
<td>From 3D to 4D Printing</td>
<td>Jan Van Humbeeck</td>
</tr>
<tr>
<td>11:15</td>
<td>TEA</td>
<td></td>
</tr>
</tbody>
</table>

**Session Details**

### SOUTH AFRICAN DEVELOPMENT

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Details</th>
<th>Session Chair: David Bullock</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:45</td>
<td>“De facto Futurist” = Knowledge economy + Shared Resourcefulness economy – Lesetja Mongoba</td>
<td></td>
</tr>
<tr>
<td>13:00</td>
<td>LUNCH</td>
<td></td>
</tr>
</tbody>
</table>

**Session Chairs**

### AM Business Development

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Details</th>
<th>Session Chair: David Bullock</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00</td>
<td>Transforming engineering applications and methodology in Additive Manufacturing to accommodate enterprise resource planning</td>
<td>Heinrich van der Merwe</td>
</tr>
<tr>
<td>14:20</td>
<td>A costing framework for Additive Manufacturing</td>
<td>Prof Andre Francois van der Merwe</td>
</tr>
<tr>
<td>14:40</td>
<td>Additive Manufacturing applications for the Maritime Industry</td>
<td>Devon Hagedorn-Hansen</td>
</tr>
<tr>
<td>15:00</td>
<td>Emerging technologies: Commercial Readiness Index (CRI) for medical Additive Manufacturing</td>
<td>Leri Bezuidenhout</td>
</tr>
<tr>
<td>15:20</td>
<td>TEA</td>
<td></td>
</tr>
</tbody>
</table>

**Session Chairs**

### Material Evaluation

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Details</th>
<th>Session Chair: David Bullock</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:40</td>
<td>Review of simulation techniques developed for the analysis of the selective laser melting process</td>
<td>Carlo Olivier</td>
</tr>
<tr>
<td>16:00</td>
<td>Improved cooling system of hot stamping tools though Additive Manufacturing</td>
<td>Rumbidzai Muvunzi</td>
</tr>
<tr>
<td>16:20</td>
<td>CFD modelling of laser Additive Manufacturing process of cylinders</td>
<td>Karim Kheloufi</td>
</tr>
<tr>
<td>17:30</td>
<td>Shuttle Departs from next to the Rhino (Durban ICC)</td>
<td></td>
</tr>
<tr>
<td>18:00</td>
<td>SOCIAL EVENT</td>
<td></td>
</tr>
</tbody>
</table>
08:30 Registration

09:15 Opening Address
Leon Kruger

09:45 Update on the State of Additive Manufacturing Worldwide
Terry Wohlers

10:30 From 3D to 4D Printing
Jan Van Humbeeck

11:15 TEA

11:45 “De facto Futurist” = Knowledge economy + Shared Resourcefulness
Lesetja Mongoba

12:10 Platforum — South African Development
Gerrie Booysen, Deon De Beer, Nelsa Martins, Amelia du Toit, Hannes Malan

13:00 LUNCH
ROOM A
ROOM B
ROOM C

14:00 Transforming engineering applications and methodology in Additive Manufacturing to accommodate enterprise resource planning
Heinrich van der Merwe
Design for metal Additive Manufacturing: printing the ahrlac flight grips
Duwan Bester
Characterisation and monitoring of Ti6Al4V (ELI) powder used in different Additive Manufacturing systems
Keheletso Thejane

14:20 A costing framework for Additive Manufacturing
Prof Andre Francois van der Merwe
Nano-additives for use in 3D printing polymers
Francois Seeliger
Performance evaluation and characterisation of EIGA produced Titanium alloy powder for Additive Manufacturing processes
Nana Arthur

14:40 Additive Manufacturing applications for the Maritime Industry
Devon Hagedorn-Hansen
Effectiveness of PrimeCast® and PMMA Additive manufacturing processes to produce patterns for investment casting
Nthateng Nkhasi
Thermal plasma spheroidisation of Titanium metal
Hertzog Bissett

15:00 Emerging technologies: Commercial Readiness Index (CRI) for medical Additive Manufacturing
Leri Bezuidenhout
Printed wireless devices for low-cost, connected sensors for point-of-care applications
Suzanne Smith
Evaluating recycled Tungsten Carbide powder as feedstock for Additive Manufacturing applications
De Wet Du Toit

15:20 TEA

15:40 Post Processing
Dean Kouprianoff, Michael Lucas
Destructive and non-destructive testing on small and intricate DMLS components
Dean Kouprianoff
Destructive and non-destructive testing on small and intricate DMLS components
Dean Kouprianoff
Non-destructive investigation of residual stresses in additively manufactured components using diffraction techniques
Andrew Venter
Residual stress: The application of diffraction techniques at different scales
Lucas Anderson
Stress relieving of maraging steel injection mould inserts built through Additive Manufacturing
Imdadullah Adam

16:00 Improved cooling system of hot stamping tools through Additive Manufacturing
Rumbidzai Muvunzi
Integration of cold spray and 3D printing for antimicrobial surface coatings
Michael Lucas
Residual stress: The application of diffraction techniques at different scales
Lucas Anderson
Stress relieving of maraging steel injection mould inserts built through Additive Manufacturing
Imdadullah Adam

16:20 CFD modelling of laser Additive Manufacturing process of cylinders
Karim Kheloufi
Stress relieving of maraging steel injection mould inserts built through Additive Manufacturing
Imdadullah Adam

17:30 Shuttle Departs from next to the Rhino (Durban ICC)

18:00 SOCIAL EVENT
Leon Kruger
Kemtek Imaging Systems
CEO
kemtek.co.za

BIOGRAPHY
BCom • CAIB • MBA • CFP

A high performing CEO/COO across multiple sectors. Leon had a proven track record of delivering sustainable profitable growth, providing strategic direction and engaging with key stakeholders to build brand reputation and create a commercial vision for the global marketplace. He is recognized for astute understanding of business development opportunities and consistently delivering strong fiscal and performance results.

As CEO at Kemtek Imaging Systems Leon is developing strategy including digital brand and strategy, developing and leading change management intervention to refresh the current business model and creating a performance orientated and empowered business culture.

Part of the Kemtek growth strategy is to invest and digital and Industry 4.0 technologies – investment in Additive Manufacturing through their relationship with Rapid 3D is one component of this strategy.
Terry Wohlers
Wohlers Associates
President
Fort Collins, Colorado, USA
wohlersassociates.com

Wednesday November 8 2017 | 09:45 - 10:30 | Meeting Room 12 Durban ICC

Update on the State of Additive Manufacturing Worldwide

BIOGRAPHY
Terry Wohlers is principal consultant and president of Wohlers Associates, Inc., an independent consulting firm he founded 30 years ago.

Wohlers has provided consulting assistance to more than 260 organizations in 26 countries, as well as to 180 companies in the investment community. He has authored 400 books, articles, and technical papers and has given 145 keynote presentations on five continents. Wohlers has twice served as a featured speaker at events held at the U.S. White House. In 2004, Wohlers received an Honorary Doctoral Degree from Central University of Technology in Bloemfontein, South Africa.

For 22 years, Wohlers has been a principal author of the Wohlers Report, an annual worldwide publication focused on additive manufacturing and 3D printing. Many refer to it as the “bible” of 3D printing. It has served as the undisputed industry-leading report on the subject for more than two decades.
Dr Jan Van Humbeeck

KU Leuven
Professor – Material Science
Leuven, Belgium
mtm.kuleuven.be

Wednesday November 8, 2017 | 10:30 - 11:15 | Meeting Room 12 Durban ICC

From 3D to 4D Printing

BIOGRAPHY

Dr van Humbeeck is a full professor in the Department of Materials Engineering (K.U.Leuven (MTM – Catholic University of Leuven). He studied engineering (specialising in metallurgy) and has a doctoral degree in Applied Science.

His main research interests include shape memory alloys and additive manufacturing.

He has written 14 chapters in books; been the editor of 4 conference proceedings, and has published 430 papers in peer reviewed international journals and 150 papers in conference proceedings. He holds six patents.
“De facto Futurist” = Knowledge economy + Shared Resourcefulness economy

BIOGRAPHY
Lesetja R.T. Mogoba is a:
- Senior Marketer (Diversification Portfolio) at Denel Aeronautics.
- Innovation Forum member at Denel Aeronautics.
- Co-Deputy Chair at BRICS Business Council Manufacturing Working Group.
- AeSSA Young Professional participant.
- Graduate of the AAA School of Advertising.
- IAA (International Advertising Association).
- Marketing practitioner designated by the MASA (Marketing Association of South Africa).
- Member of AMASA (Advertising Media Association of South Africa).
- Gold medalist: AMESA (Association for Mathematics Education of South Africa).
- Presidents Award bronze medal recipient.

Collaborative / Mentoring Concepts:
“Be set apart by virtue of pioneering thought, is you may: i.e. Chaos Theory & Murphy’s Law continuum.”

“Be a multipotentialite continuous improvement phrase, personified.”

Maneuvering Thought
“The decisively tactful shifting and perceptive shaping state, to affect the objectives of a set focus.”
Panel Discussion – Platform

Nelsa Martins
Head of Technical – Smelting and Refining
Lonmin
lonmin.com

Deon de Beer
Chief Director: Innovation and Technology Support
North West University
nwu.ac.za

Amelia du Toit
Process Specialist
Lonmin
lonmin.com

Hannes Malan
Commercialisation Specialist
North West University
nwu.ac.za

Gerrie Booysens
Director
CRPM
crpm.co.za
TRANSFORMING ENGINEERING APPLICATION AND METHODOLOGY IN ADDITIVE MANUFACTURING TO ACCOMMODATE ENTERPRISE RESOURCE PLANNING

H.L. van der Merwe

ABSTRACT
The purpose of this paper is to incorporate the key business functions of the Advanced Manufacturing Precinct and other business process management aspects that allow an additive manufacturing unit to use a system of integrated applications. The aim is to use this integrated application to manage the business and automate various back-office functions related to technology, services and human resources. This is done to develop the data capturing (the product data management), manipulations, calculation and validation for a unique enterprise resource-planning model for additive manufacturing units founded in a fail-safe quality management system.

1. Introduction
Future South African manufacturing companies need to implement advanced manufacturing engineering solutions and should give proper attention to the additive manufacturing (AM) processes and resources that are appropriate for the differences of each manufacturing AM platform. For an effective enterprise resource planning (ERP) system implementation in an AM environment, the digital integration of the product data management (PDM) is identified as one of the key aspects to ensure success. Product data integration dictates that the engineering bill of materials (EBOM) should be adapted into a manufacturing bill of materials (MBOM), however the transformation should be done in such a way that it will fit the uniqueness of each AM platform. In this process, a methodology suitable for incorporation and transformation is required.

2. Methodology and results

2.1 Digital engineering
This paper proposes that digital engineering should be used as the key data accumulation tool between PDM and ERP. Digital manufacturing, as a technology possessing methodology, encompasses physical and logical computer modelling and simulation techniques for actual manufacturing. This provides the methodology for transforming EBOM to MBOM that fits the uniqueness of each AM platform, based on the process and resource models which reflect the uniqueness of each AM platform.

2.2 Methodology for MBOM
The proposed study provides the methodology for MBOM verification as well as the process and resource model integration. Using this method, the MBOM and the process and resource data, verified and appropriate for each AM platform, can be sent to the ERP system.

2.3 AM’s capabilities
To take full advantage of AM’s capabilities, new management methods should be developed, taking the nature of these processes into consideration. In this setting, the methodology used to obtain an optimal
ERP methodology for additive manufacturing platforms was proposed taking both design requirements and manufacturing constraints into consideration.

3. Conclusion
Although this approach offers very interesting possibilities, very little existing work has been carried out in applying this new line of thought. A possible reason is that these processes are still relatively new, little-known within existing industries, and very different from conventional manufacturing processes. The resistance to change may deter industry role players from utilising AM effectively to enhance their capabilities and international competitiveness. [3]

The ultimate objective is to uplift and advantage local companies by making industrial AM technologies available to them. In this paper, the author aims to report on the benefits, disadvantages and potential of the different technologies under the umbrella of devising and implementing an all-encompassing management and operational tool (ERP for AM platforms).

REFERENCES

Department of Technology Transfer and Innovation, Vaal University of Technology, South Africa (hendrihv2@vut.ac.za)
THERMAL PLASMA SPHEROIDISATION OF TITANIUM METAL

H. Bissett*, I.J. Van der Walt

ABSTRACT

Additive manufacturing methods used to obtain high quality components, such as direct laser sintering, require spherical powders of a narrow particle size distribution as this affects the packing density and sintering mechanism. In-flight heating of titanium powders was examined experimentally in a radio-frequency thermal plasma. The plasma power, carrier gas flow rate and feed powder size distribution were investigated in order to optimise the spheroidisation (%) and reduce the fraction of evaporation (wt%). An increased spheroidisation (%) was observed at high plasma power and small powder sizes. However the optimum spheroidisation conditions are not necessarily at the highest spheroidisation %.

1. Introduction

Titanium and titanium alloys are widely used in industries such as aerospace, medical, sports and automotive due to their performance properties such as low density, relatively high strength, corrosion resistance and biocompatibility [1]. Relatively new technologies, such as additive manufacturing (AM), used to manufacture high quality titanium components have recently been employed particularly in the manufacture of specialised parts not produced in large quantities. In order to manufacture a high quality component, i.e. an implant, the titanium powder used as feed material should be dense and spherical. Powder particle size can affect the material spreading and the sintering rate due to the fact that the shape, density and size of the particles have an effect on their packing density, sintering mechanism and also the flowability of the powder during feeding. Chemical purity of the titanium or titanium alloy powder during processing is also important. Surface oxidation can increase surface tension, hindering the material from flowing during sintering. Oxidation also results in poor bonding between sintered lines affecting the manufactured structures, while nitrides reduce the material's corrosion resistance and hydrides cause brittleness. Typically metal powders for AM are made through processes such as gas atomisation and plasma rotating electrode processing (PREP). Recently, spheroidisation and densification of metal powders has been possible by the re-melting of irregularly shaped particles at high temperature by means of thermal plasma processes and solidifying the resulting droplets by rapid quenching. Thermal plasma processes also make it possible to spheroidise high melting point metals like Zr, with no contamination, which can occur when making use of other conventional methods [2].

Thermal plasmas are characterised by their extremely high temperatures (3 000 – 10 000 K) and rapid heating rates (~106 K/s) under oxidising, reducing or inert conditions. This makes them particularly suitable for spheroidisation of almost any metal powders [3]. In 2016 the South African Nuclear Energy Corporation (Necsa) purchased a 15 kW RF thermal plasma system from Tehna Plasma Systems Inc. by making use of the National Equipment Fund, managed by the National Research Foundation. Tehna is considered the world leader in induction plasma technology. In early 2017 the system especially designed for metal powder spheroidisation, was commissioned.

In this study, the spheroidisation of irregularly shaped pure titanium metal was investigated. The processing characteristics for the spherical particle formation were investigated at various processing conditions. The
particles obtained were characterised in terms of morphology and density. Spheroidisation of powders should result in an optimum spheroidisation (%), while minimising the fraction of material evaporated.

2. Methodology and results
Due to the fact that the 15 kW RF thermal plasma was obtained recently, the intended purpose of the study was to perform proof of concept experiments and to detect if similar trends than those observed in literature could be found. Pure titanium powder in the size range 150 – 180 µm was used in these experiments.

2.1 Experimental method
Various parameters influence the spheroidisation efficiency, spheroidisation (%) and the fraction of material evaporated. A simplified schematic of a RF inductively coupled plasma torch is shown in Figure 1. The powder was fed through the feeding probe with the assistance of a carrier gas. Inside the plasma “flame” the particles were rapidly melted, followed by rapid cooling to form spherical particles. A quartz tube separated the sheath (Ar/H2) and central gas (Ar), both of which could be adjusted to alter the parameters for spheroidisation. In a set of three experiments all parameters remained constant, while only adjusting the energy input of the plasma (Table 1). The powder was fed into the plasma at 0.22 kg/h.

![Figure 1](image)

*Sketch of a RF inductively coupled thermal plasma torch*

The collected powder was weighed in order to determine what fraction of powder evaporated (condensed as very fine particles (<<150 nm)). Optical microscopy images/pictures of the powders were taken to evaluate the spheroidisation (%).

2.2 Results
In Table 1 the results for the three experiments conducted at various plasma power inputs are shown. An increase in the energy input resulted in an increased fraction of evaporation, similar to what was observed in literature.
THERMAL PLASMA SPHEROIDISATION OF TITANIUM METAL continued

The feed powder is shown in Image 1. Comparing image 2 with image 3 and 4, it can be seen that the spheroidisation (%) increased with plasma power input due to the increase in the temperature of the plasma. The fraction evaporated however also increases with increasing power input. This corresponds with literature [2].

Table 1: Powder and varied plasma parameters. Experiments performed at 2 slpm argon carrier gas flow rate, plasma gas containing 5 vol % hydrogen with the feeding probe at the centre coil.

<table>
<thead>
<tr>
<th>Image #</th>
<th>Powder fed (g)</th>
<th>Plasma power (kW)</th>
<th>Fraction evaporated (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5.12</td>
<td>9</td>
<td>5.50</td>
</tr>
<tr>
<td>3</td>
<td>5.30</td>
<td>11</td>
<td>11.25</td>
</tr>
<tr>
<td>4</td>
<td>5.17</td>
<td>13</td>
<td>25.05</td>
</tr>
</tbody>
</table>

*slpm = standard litres per minute

The feed powder is shown in Image 1. Comparing image 2 with image 3 and 4, it can be seen that the spheroidisation (%) increased with plasma power input due to the increase in the temperature of the plasma. The fraction evaporated however also increases with increasing power input. This corresponds with literature [2].

Figure 2
Optical images of titanium feed powder (image 1) as well as the powder collected at 9 kW (image 2), 11 kW (image 3) and 13 kW (image 4) plasma power inputs.

3. Conclusion
Titanium powder was plasma treated by means of a 15 kW RF inductively coupled thermal plasma system from Tekna Plasma Systems Inc. Similarly to what was observed in literature, the spheroidisation (%) and fraction evaporated increased with an increase in plasma power due to the plasma temperature increase. This study indicated that titanium powder can be spheroidised by thermal plasma technology in order to increase the density and flow characteristics of the powder.
REFERENCES


Department of Applied Chemistry, The South African Nuclear Energy Corporation, South Africa (hertzog.bissett@necsa.co.)
CHARACTERISATION AND MONITORING OF Ti6Al4V (ELI) POWDER USED IN DIFFERENT ADDITIVE MANUFACTURING SYSTEMS

K. Thejane1*, W.B. Du Preez1, S. Chikosha2

ABSTRACT
The characterisation and monitoring of Ti6Al4V (ELI) feedstock powder is an essential requirement for full qualification of medical implants and aerospace components produced in additive manufacturing systems. Virgin and reused samples of this powder were characterised by determining their physical and chemical properties through techniques complying with international standards. This paper presents the results obtained for Ti6Al4V (ELI) powder of three different particle size distributions received from the same supplier. The characteristics of these powders after various numbers of reuse cycles in two different AM systems are also presented and discussed.

1. Introduction
The sub-program of the national Collaborative Program in Additive Manufacturing on Qualification of Additive Manufacturing for Medical Implants and Aerospace Parts requires characterisation of the feedstock powder used in the different additive manufacturing (AM) systems of this program [1]. The Ti6Al4V (ELI) powder of different particle size distribution ranges was obtained from TLS Technik GmbH and is used in Direct Metal Laser Sintering (DMLS) (<40 µm), concept laser (25–55 µm) and LENS systems (40–100 µm). The as-received powder was characterised and the powder properties were subsequently monitored after increasing numbers of reuse cycles.

2. Methodology and results

2.1 Methodology
Representative samples (50g each) of the virgin and reused powder, taken after 11, 20 and 25 build cycles, were analysed. The gas contents and composition were determined using ELTRA, LECO and ICP-OES analytical systems. The particle size distribution and morphology were determined by Microtrac (S3500) and Scanning Electron Microscope (JEOL JSM–651) instruments, respectively. For determining the flowability of the powder a FT4 Rheometer system was used.

2.2 Results
The DMLS and concept laser powder samples showed properties complying with the specifications [1]. Even after 25 reuse cycles the DMLS powder still complied with the specification for medical implants. The concept laser powder was reused up to 10 cycles and these results will be presented in the full paper.

Figure 1 shows SEM images at x100 magnification of virgin and reused powder.
Morphology of virgin powder and powder reused up to the 25th cycle.

Some elongated irregular particles were observed but the majority of particles were still spherical. No clear deterioration was observed after the 25th cycle when compared to virgin powder.

The PSD curves for the Ti6Al4V (ELI) samples measured by laser diffraction analysis are presented in Figure 2.

The differential PSD curves of the virgin and reused powder samples.

Most of the curves are overlapping which implies identical particles sizes. A shift towards larger particle size distribution is observed for the Cycle 20 powder. This phenomenon is still being investigated and will be discussed in the full paper.

3. Conclusion
The CUT powder was reused up to 25 cycles without having measurable negative impact on the parts produced.

REFERENCES

1Department of Mechanical and Mechatronics Engineering, Central University of Technology, South Africa (kthejane@cut.ac.za)
2Materials Science and Manufacturing, Council of Scientific & Industrial Research, South Africa
EFFECTIVENESS OF PRIMECAST® AND PMMA ADDITIVE MANUFACTURING PROCESSES TO PRODUCE PATTERNS FOR INVESTMENT CASTING

N.P. Nhhasi1*, W.B. du Preez1, J.G. van der Walt1

ABSTRACT
Investment casting produces parts that need little or no secondary machining operations. Wax patterns used for investment casting are typically produced using an injection moulding process and the accompanying tooling. However, cost and lead-time to produce tooling can be high and complexity is limited by conventional machining ability. Additive manufacturing provides an alternative method for producing investment-casting patterns that can provide dramatic time and cost savings. This paper reports on a study to determine the advantages and limitations of using PrimeCast® and PMMA patterns produced for investment casting by two different additive manufacturing technologies.

1. Introduction
The use of investment casting to produce metal parts can be traced back thousands of years [1]. The process was refined when more complex designs were required by producing, through injection moulding, complex wax patterns that could be burned out before the metal was poured into the mould [2]. However, when used in short runs the production of the required wax patterns can be extremely expensive and time consuming. On the other hand additive manufacturing (AM) offers a faster, less expensive alternative to creating investment-casting patterns particularly at the production development stage [3]. In this study a comparison was done between patterns built by PrimeCast® and PolyMethyl Methyl Acrylate (PMMA), respectively. This comparison of the two types of AM patterns is expected to assist the foundry industry in achieving the most beneficial investment casting results when using either of these AM technologies.

2. Methodology and results

2.1 Methodology
A standard test part was selected to compare patterns produced by the two types of AM processes as shown in Figure 1 below [4].
At the same time, eight patterns of each were built in PrimeCast® and PMMA at Central University of Technology and Vaal University of Technology, respectively. Two patterns, one each of PrimeCast® and PMMA, were scanned at Stellenbosch University using a General Electric Phoenix V|Tome|X L240 / NF180 Micro-CT scanner [5]. X-ray settings used were 200 kV and 100 µA. Consequently reconstruction of the sample was done with system-supplied Datos reconstruction software. Then analysis was performed with volume graphics VGStudio Max 3 Voxel data analysis and visualization.

2.2 Results
The CT scan data was compared with the computer-aided design (CAD) data. The data set was colour-coded according to deviations between the AM patterns and the CAD design. Deviation values ranged between -0.30 mm and 0.30 mm. Green indicates the best fit, while yellow denotes areas where the pattern dimensions are larger than the original CAD dimensions. On the other hand, the blue indicates areas where the pattern dimensions are smaller than the CAD dimensions.

The nominal comparison of the voxel data of the PMMA pattern with the CAD showed more of the smaller measurements than the nominal comparison of the voxel data of the PrimeCast® pattern denoted by the blue colour in Figure 2 above.

3. Conclusion
The two AM patterns, PrimeCast® and PMMA, are both suitable to be used for investment casting. There were significant differences in dimensional accuracy between the two AM patterns. The advantages and limitations of each AM pattern will be outlined clearly in the full paper.

REFERENCES
EFFECTIVENESS OF PRIMECAST® AND PMMA ADDITIVE MANUFACTURING PROCESSES TO PRODUCE PATTERNS FOR INVESTMENT CASTING


Center for Rapid Prototyping and Manufacturing, Central University of Technology, South Africa (nthatengnp@gmail.com)
EMERGING TECHNOLOGIES: COMMERCIAL READINESS INDEX FOR MEDICAL ADDITIVE MANUFACTURING

L. Bezuidenhout1*, G. Booysen2, A.F. van der Merwe3

ABSTRACT
Technology readiness level has been widely used as a measure of technology maturity. However, technology readiness level is not necessarily a good indicator of commercial readiness. In the renewable energy sector a commercial readiness index is used where only a technology with a high technology readiness level qualifies for commercial readiness. Similarly technology readiness level is used to measure the maturity of additive manufacturing technologies. This research proposes a commercial readiness index for additive manufacturing. A case study on Maxilla-facial Ti6Al4V implants manufactured with additive manufacturing is referred to.

1. Introduction
It was identified from previous research [1] that the manufacturing of a maxillo-facial implant proved to be theoretically unfeasible due to the risks being too high. Although the physical process resulted in a successful implant, the theoretical calculations made it unfeasible. In order to move from theoretical feasibility to real feasibility a mechanism to analyse the high risks needs to be developed.

The following case study was used, a maxillo-facial implant manufacturing process. The Centre of Rapid Prototyping and Manufacturing (CRPM) [2] has been accredited to manufacture implants according to ISO13485. The commercialisation of this manufacturing process is currently in the ramp-up phase. The commercial sustainability of the manufacturing process still needs to be valued. This research uses as a base the commercial readiness index (CRI) assessment, created by the Australian Renewable Energy Agency (ARENA) [3,4]. The ARENA CRI is modified to apply to additive manufacturing (AM) by using an analysis and synthesis approach. The CRI is divided into several independent indicators assessing various commercial aspects and then combined into a single commercial index.

Therefore, the CRI is compiled from commercial indicators including: regulatory environment, stakeholder acceptance, clinical performance, technical performance, financial performance including cost and financial proposition (revenue, industry supply chain and skills, market opportunities and company maturity). A diverse group of 15 experts assisted in defining maturity in each of the commercial indicators. The compiled results are presented. The value of this research lies in the ability for investors to now assess the commercial viability of AM. AM is considered a disruptive and emerging technology designated to replace conventional manufacturing processes.

2. Methodology and results

2.1 Methodology
Interviewing several experts on their view and opinion on commercial readiness started the research. Their opinions contributed to defining the CRI indicators for AM. Using the technology readiness level (TRL),
introduced by NASA in 1970 [5], each of the technologies will be evaluated in terms of its maturity. The individual TRL's will be added in the value chain in order to calculate the CRI. Figure 1 demonstrates the tools used to discuss the risks of these emerging technologies.

2.2 Objectives
- Define CRI for AM based on CRI for renewable energy by process of expert opinion
- To define a framework against which the commercial maturity of processes using AM technology can be measured
- To use a case study to confirm the framework

2.3 Results
Expert opinions are compiled into different maturity levels of each indicator. Subsequently these indicators are reiterated with individual experts for their conformation. Results from expert opinions provided the different levels of maturity for each indicator. The case study on maxillo-facial implants was tested against this framework and the CRI reported accordingly.
3. Conclusion
A CRI for processing the using of AM technologies is proposed. The opinions of several experts were compiled into levels of maturity for several commercial indicators. Commercial indicators are used to assess the commercial maturity of an enterprise’s ability to unlock the potential of emerging technologies. Commercial indicators are independent parameters, averaged to a single CRI.

REFERENCES

1 Department of Industrial Engineering, Stellenbosch University, South Africa (17761379@sun.ac.za)
2 Centre for Rapid Prototyping and Manufacturing, Central University of Technology, South Africa
STRESS RELIEVING OF MARAGING STEEL INJECTION MOULD INSERTS BUILT THROUGH ADDITIVE MANUFACTURING

I. Adam¹*, W. B. du Preez², J. Combrinck²

ABSTRACT
Additive manufacturing (AM) has been identified as one of the key technologies in Industry 4.0 and has become quite appealing in the injection moulding industry. The development of metal powders for AM has created a possibility for AM to be used for the manufacture of high volume production injection moulding tooling inserts. While this is appealing, the resulting residual stresses present in AM produced parts could prove to be problematic. This paper describes the development of a suitable stress relieving heat treatment process for injection moulding tooling inserts built using maraging steel powder in the direct metal laser sintering process.

1. Introduction
Injection moulding (IM) is one of the most used plastic forming processes and is generally used to mass-produce dimensionally identical products. To continuously produce accurate moulded products, the IM tool has to be manufactured according to stringent dimensional tolerances. The use of AM to produce IM tool inserts, can be beneficial because AM offers freedom of design for parts having complex geometries and can also reduce toolmaking lead times.

With the continuous development of new metal powders for AM, a suitable material for the manufacture of tooling components comes to the fore in the form of maraging steel (MS1) powder, with material properties ideal for tooling applications. This study makes use of MS1 powder to produce IM tool inserts through the direct metal laser sintering (DMLS) process. Due to rapid temperature fluctuations during the DMLS process residual stresses are induced inside the component, resulting in geometrical deviation. Residual stress can be described as a stress present in an object without the influence of any external forces and are introduced into components during thermal processes such as heat treatments, forming or welding [1]. While these stresses have an impact on performance and longevity of an object, a major concern is the geometric deviation caused by these stresses [2]. Since no specific stress relieving process has been documented to date for AM maraging steel, this paper will describe the development of a suitable stress relieving heat treatment process.

2. Methodology and results

2.1 Methodology
A test was conducted as indicated in Figure 1, to determine a suitable stress relieving heat treatment for an IM tool insert manufactured through AM. Phase 1 of the test required that after the IM tool insert had been built, the hardness was determined and the tool insert scanned using a Kreon 3D scanner in an as built state. The scanned data was compared to the computer-aided design (CAD) model of the insert to determine whether any deviation had occurred during AM. The data was compared at 8 points on the tool insert geometry as shown in Figure 2.
During phase 2, the IM tool insert was heated to a temperature of 890°C for a time of 1 hour and 2 minutes and allowed to air cool to room temperature. Thereafter, the hardness was determined and the tool insert was scanned. This phase of the test was repeated to obtain a clear indication of the effect of the heat treatment process on the IM tool insert.

For Phase 3, based on the previous results, the temperature was kept constant at 890°C while extending the time of the heat treatment to 3 hours. The other experimental steps remained the same as Phase 1 and 2. The hardness of the tool insert, as well as any geometric deviation from the CAD design, was determined after this heat treatment.

2.2 Results
Table 1, shows a summary of the Phase 1 and 2 results obtained from the scan data and hardness tests. From these results, it is evident that the application of a heat treatment procedure had an effect on the IM tool insert of softening the metal, which is typical of an annealing process. Different heat treatment times had a clear effect on the deviation from the CAD model. The Phase 3 results will be presented in the full paper.

![Figure 1](Stress relieving test process)
STRESS RELIEVING OF MARAGING STEEL INJECTION MOULD INSERTS BUILT THROUGH ADDITIVE MANUFACTURING continued

3. Conclusion
A heat treatment that can be applied to AM parts built from MS1 powder to relieve residual stress induced during the build process was successfully developed.

REFERENCES

1 Department of Design & Studio Art, Central University of Technology, South Africa (iadam@cut.ac.za)
2 Department of Mechanical & Mechatronics Engineering, Central University of Technology, South Africa
EVALUATING RECYCLED TUNGSTEN CARBIDE POWDER AS FEEDSTOCK FOR ADDITIVE MANUFACTURING APPLICATIONS

D. du Toit1*, C.M. Olivier1,2, M.C. van Coller1,2, G.A. Oosthuizen1, N. Sachs2

ABSTRACT
Tungsten carbide has been used on a large scale in the mining, manufacturing and oil and gas industries due to its high hardness and outstanding wear–resistance material properties. An application field that is particularly sensitive to variations in powder properties is the additive manufacturing industry. Jagged, non–spherical powder particles may lead to parts with inhomogeneous material properties. Recycling of cemented tungsten carbide scrap to a powder form happens on an industrial scale; however, the concern exists that the recycled powders have different particle shapes and size distributions when compared to equivalent ‘virgin’ powders that are suitable for additive manufacturing purposes. Direct energy deposition technologies can typically accommodate larger size distributions. In direct energy deposition applications particle shapes have smaller effects on finished parts when compared to powder bed fusion technologies. The powders obtained from different recycling process are examined in this study to determine the suitability for use in both powder bed fusion and direct energy deposition applications.

1. Introduction
Tungsten carbide (WC) is a compound containing the same amount of tungsten and carbon atoms. Cemented tungsten carbide is traditionally used in the tooling industry, with applications in metal cutting and rock drilling [1].

Many industry experts view additive manufacturing (AM) as the future of manufacturing. Due to the rising popularity of AM, cemented WC powders used for AM applications will ever more frequently have to be sourced as recycled powders due to the expected increase in WC powders for AM purposes and the decrease in available tungsten to produce these powders.

Recycling of cemented WC can be classified into three broad categories, direct recycling, indirect recycling, and semi-direct recycling methods.

2. Machine input powder needs
In both direct energy deposition (DED) and powder bed fusion (PBF) applications the properties of the input powders are important [2]. The characterisation of a feedstock powder in general use is normally focussed on morphology, chemistry, and microstructure. In AM processes the characterisation is mainly focussed on morphological characterisation of the feedstock powders [3]. PBF technologies require powder with different characteristics than DED technologies as the two different manufacturing technologies have differing layer thickness capabilities.

PBF technologies in general need spherical powder particles due to flowability, melt uniformity, and packing reasons [4]. The more spherical the particles are with a size distribution the better the flow, packing and resulting melt uniformity will be. DED technologies are more robust and powder morphology is less important.
than PBF technologies, allowing for the use of near-spherical powders but spherical powders are still recommended [5].

3. Recycling process capabilities
There are numerous recycling processes for recycling cemented WC. These processes can be classified as either direct or indirect recycling methods. The most commonly used direct recycling method is the zinc reclaim method. Indirect conversion of WC–Co to precursors of WC through a hydrometallurgical route is possible. [6]

Indirect methods of recycling such as hydrometallurgical processes can be used to convert WC containing products to an intermediate. This intermediate, Ammonium paratungstate (ATP), is the general intermediate for most tungsten products. From ATP powders suitable for most applications, including AM grade WC can be obtained by the same processes as used when producing these powders from ores. It is, however, a high energy consuming and chemical waste producing process. [6]

4. Conclusion
This paper investigated the feasibility of utilising reclaimed cemented WC powders, obtained from different recycling methods, as feedstock for AM applications, with a focus on PBF and DED technologies. Published literature as well as machine information brochures were consulted. The study compared the available PBF and DED technologies’ powder feedstock needs with different reclamation process capabilities.

REFERENCES

1Department of Industrial Engineering, Stellenbosch University, South Africa (17511011@sun.ac.za)
2DST-NRF Centre of Excellence in Strong Materials, South Africa
DESIGN FOR METAL ADDITIVE MANUFACTURING: PRINTING THE AHRLAC FLIGHT GRIPS

D.C. Bester¹, M. Vermeulen², J. Prinsloo²

ABSTRACT
Powder bed fusion is the process of building a part, layer-by-layer, using a laser to melt the cross-sections of a part in a powder layer. Aeroswift is the first South African designed and manufactured powder bed fusion machine. As part of its commissioning, two advanced high-performance reconnaissance light aircraft (AHRLAC) throttle grips were built to show its functionality. The primary achievement being that the advanced high-performance reconnaissance light aircraft, a South African designed and manufactured multipurpose aircraft would be flying parts printed on a South African built machine. This paper discusses the steps that were followed to build the throttle grips; from design changes to better suit the build process, to the strategies used for the support structure design.

1. Introduction
Powder bed fusion (PBF) is an additive manufacturing (AM) technology, which builds a part by utilising a laser to melt the cross-section of the part onto a powder layer [1]. The part’s computer-aided design (CAD) model is sliced into thin layers in order to obtain cross-sections. After each cross-section is melted, in the powder layer, the build platform moves down by one layer thickness. A new powder layer is then deposited and the next cross-section is melted.

Aeroswift is the first South African developed metal PBF machine and, at full capacity, it is the largest and fastest in the world. The advanced high-performance reconnaissance light aircraft (AHRLAC), on the other hand, is a South African developed low-cost, multi-purpose aircraft. As part of the commissioning of the Aeroswift system, it was decided that two flight grips from the AHRLAC aircraft would be built in titanium (Ti6Al4V). The end goal being to show the functionality of Aeroswift and to show that the produced parts can be implemented on an aircraft.

The throttle grips were selected due to their complex geometries and that they are not high load bearing parts. The one is the throttle lever grip (Figure 2) and the other is the condition lever grip (Figure 1). The condition lever grip is a single part, whereas the throttle lever grip is composed of two shelled parts that fit together.

Figure 1
Condition lever grip
2. Methodology and results

2.1 Approach
The CAD files for the grips were obtained from the AHRLAC team and the first iteration test build layout and part orientation was done. The part orientation was chosen in order to minimise the required support structures and to minimise the support structures that would be in contact with the outside of the throttle grips. The reason being that these parts will be implemented as built and that post processing will be minimised. Contact of the supports on the outside surface of the grips will cause rough spots and make the grips wear the pilot’s gloves a lot quicker. A compromise was made between minimum supports and minimum outside surface contact because if one was reduced or eliminated, the other one would increase. The layout and support structures were done using Materialise’s Magics software with the SG+ module [2].

2.2 Test builds
The first test build was performed but stopped with 10 mm of the build remaining due to a large powder leak, which was starting to interfere with the build. Even though the build did not finish, the uncompleted parts could be investigated and much was learnt.

For the second test build, everything that was learnt from the first test build was taken into consideration, such as lowering the one part to decrease the build time, modifying the supports for easier removal and part design modifications to better suit the process. The design modifications were made to decrease the required supports, to prevent the supports from having contact with the parts in undesired areas and to account for the undersized holes from the first build.

2.3 Results and discussion
The second test build completed successfully.
A few times during processing it could be seen that a part moved, most likely due to residual stresses and after removal of the build platform it was observed that some support structures broke free. Some supports were too thick and some of them difficult to remove. The parts moving during the process caused dimensional inaccuracies, which resulted in more post processing requirements to get the two throttle grip shells to fit together. This can potentially be fixed with better support structures and different support structure parameters, together with optimisation of the build orientation.

4. Conclusion
From the test builds many issues were encountered, for instance support structures that were difficult to remove and parts moving during the process due to inadequate support. These issues will be addressed and a third build will be attempted in the future. Even though the second test build was successful, a lot still needs to be learned regarding the support structure design strategies. However, it has been proved that the Aeroswift system is capable of producing functional parts. Future work will be to optimise support structure design for Aeroswift and to have a set of design rules as a guideline to use when doing build preparation. Also, higher preheating temperatures will be investigated to reduce the residual stresses during a build. Build prediction software could also be considered and used to detect the possible build issues in a simulated environment.

REFERENCES


1 National Laser Centre, Council for Scientific and Industrial Research, South Africa (dbester@csir.co.za)
2 Aerosud Innovation Centre (Pty) Ltd, South Africa
Computer based simulation has become an invaluable tool in the modern manufacturing industry. It allows designers to access process information quickly and at low cost. Selective laser melting is an additive manufacturing process, which uses laser technology to produce fully functional 3D components by selectively melting and fusing feedstock powders. During the selective laser melting production process, melting of the powder occurs rapidly, to the extent that real-time observations and measurements are difficult or virtually impossible. However, computer based simulation provides a useful alternative for ‘visualising’ the melting process, as simulations can be time-controlled and visually enhanced in a controllable format. Various models have been developed for investigating the selective laser-melting phenomenon; however, due to the wide range of simulation software packages available, variations in results between models exist. Therefore, this paper reviews and evaluates current selective laser-melting simulation approaches in an attempt to determine the basis of these variations.

1. Introduction
The additive manufacturing (AM) industry consists of a collection of new and developing technologies. For this industry to compete with the current established near-net shaping technologies, it needs to improve on certain production capabilities such as the reduction in lead time, cost savings, quality enhancements and waste control [1]. Selective laser melting (SLM) is an AM process which utilises a high powered laser to selectively melt and consolidate powders of a variety of materials in order to form 3D objects. It is a highly valued technology due to the added advantage of being able to produce complex, high density and fully functional components from materials which are known for being difficult to process [2].

A current drawback of the SLM technology is that when a new powdered material is introduced to the SLM process, it first needs to undergo rigorous calibration tests, which are often costly and time consuming. Calibration is required in order to determine the SLM processing parameters (laser power, scanning speed, layer thickness, etc.) which will yield the optimal melting results for a specific material; each material has its own unique thermal properties [3]. Non-optimised process parameters will lead to build deficiencies such as poor surface quality (balling), high levels of porosity, and delamination in extreme cases [4,5].

Numerical methods, which simulate the SLM process, have been undertaken by several researchers since the introduction of powder bed fusion (PBF) technologies. Each simulation incorporates various established mathematical formulations used to develop accurate representations of physical phenomena such as thermal history, melt pool geometry, thermal stresses, etc. [6]. Although different numerical models may simulate the same process phenomena (i.e. melt pool geometry) for the same material, the models may differ in the results generated. These variations may be due to aspects such as simulation software, model construction, meshing, and other assumptions made during the modelling process. Depending on the
intended application, large variations in simulated results can be problematic. Therefore this paper will focus on reviewing the simulation software used by previous designers to construct successful SLM models.

2. Methodology

2.1 Background overview of SLM and computer simulation
Development of computer based numerical modelling has dramatically accelerated since the 90’s. Processing capacity has evolved rapidly such that current simulations are completed within a matter of minutes rather than a few days, as was the case during the introduction of early simulation software [7]. Similarly, AM processes including SLM, have improved considerably in production ability. Improvements in laser technology and feedstock powders have contributed towards better quality components, and faster adoption into industry applications [8]. One of the greatest advancements of the technology has been the combination of computer simulation and SLM production.

2.2 Identifying SLM models for evaluation
The most frequently employed simulation software programs used to simulate the SLM process, as described in literature, are reviewed. The selection of applicable simulation models is based on whether they satisfy the following criteria:

- Primarily focuses on the SLM production process
- Current simulation (2012 - 2017)
- Simulation has been validated experimentally

2.3 Defining a successful model
The task of defining success for a simulation model can be difficult, as each designer uses different methods, mathematical formulations, and software packages, to describe the specific SLM phenomenon under investigation. However, some design aspects that are consistently encountered by designers determine the quality of the results obtained through their simulations. The means by which these aspects are addressed can be used to measure success. These design aspects include [9]:

- Formulating the problem correctly
- Modelling system randomness in a reasonable manner
- Establishing model validity and credibility
- Use of the proper statistical procedures for interpreting simulation output

2.4 SWOT analysis
A SWOT (strengths, weaknesses, opportunities and threats) analysis, which aims to summarise all relevant information gathered on the current simulation software packages used to model SLM phenomenon, is provided.

2.5 Reasons for model variations
The review of the workings of the current SLM simulations and accompanying software programs provides insight into the phenomenon of model variation.
REVIEW OF SIMULATION TECHNIQUES DEVELOPED FOR THE ANALYSIS OF THE SELECTIVE LASER MELTING PROCESS continued

3. Conclusion
The objective of this paper is not to impose a specific framework; rather it aims at evaluating what has been accomplished by researchers over the past five years. Through the use of a SWOT analysis, the paper identifies some of the critical features that designers need to consider when using certain simulation software packages to construct SLM models. Clearly this is dependent on their specific simulation outcome requirements.

REFERENCES

1* Department of Industrial Engineering, Stellenbosch University, South Africa (carlooolivier2@gmail.com)
2 School of Chemical & Metallurgical Engineering, University of the Witwatersrand, South Africa
3 DST-NRF Centre of Excellence in Strong Materials, South Africa
This paper investigates the distribution of residual stress in selective laser melting produced Ti-6Al-4V samples by employing the complimentary neutron diffraction and X-ray diffraction techniques. These techniques extract stress information at different scales due to their vastly different penetration depths, with X-ray diffraction being useful for measuring near surface stresses, and within individual build layers, and neutron diffraction providing a depth resolved stress distribution throughout the sample volume. The stresses were low overall, with the major stress components lying in the plane of the build layers and varied from tensile at the surface to compressive in the central volume.

1. Introduction
The cyclic heating and cooling inherent to selective laser melting (SLM) causes thermal expansion and contraction leading to the development of non-homogeneous plastic strains in the material surrounding the melt pool. This is the primary method of residual stress build up in SLM components and is known as the temperature gradient mechanism (TGM) [1].

Diffraction refers to the phenomenon where constructive interference of scattered radiation results from the interaction of either a high-energy electron beam (X-ray diffraction (XRD)) or low energy thermal neutron beam (neutron diffraction (ND)) with the sample's crystalline structure. Due to the particular crystal structure, each material produces a characteristic set of diffraction peaks [2]. These peaks correlate directly to the interatomic spacing between the atomic planes as governed by the Bragg Law of constructive interference [3]. The peak positions shift in reaction to the extent of the atomic displacement caused by an applied or residual stress [4]. By comparing the peak position of the unstressed and stressed material, Hooke's Law can be used to calculate the stress in the material from the measured strain using the appropriate diffraction coefficients [3, p. 8]. As ND penetrates deeply into engineering materials it is able to give the distribution of residual stress throughout the volume of the sample [2]. Whereas XRD can typically penetrate up to 20 µm into Ti, delivering near surface stress information [3]. This paper deals with the application of both ND and XRD for mapping the residual stress distribution in Ti64 and forms part of a larger project investigating the influence of scanning parameters on the residual stress distribution in SLM Ti64. An outline of the methodology used will be given and the obtained results will be shown in more detail.

2. Methodology
All testing was performed on samples built at the University of Leuven, in Belgium, using their in-house developed SLM machine. The nine samples tested were built as shown in Table 1. Of these, four (130, 230, 290 and 330) were scanned using ND, five (130, 160, 190, 230 and 330) were profile scanned using XRD and all nine had surface XRD scans performed on them.

2.1 Neutron diffraction
Neutron diffraction testing was performed at NECSA using their MPISI neutron-scanning instrument along
a cross sectional plane through the centre of the sample, that was subdivided into a grid of points. Depth resolved measurements were taken by sequentially positioning the centre of the gauge volume at each grid point. Strain measurements were taken along the three orthogonal orientations of the sample (x, y, z). This allowed for the tri-axial state of stress at each grid point to be determined. The test parameters are given in Table 2.

### Table 1: Specimen build parameters

<table>
<thead>
<tr>
<th>Dimension (mm)</th>
<th>Laser power (W)</th>
<th>Laser speed (mm/s)</th>
<th>Hatch spacing (UM)</th>
<th>Layer thickness (um)</th>
<th>Layer orientation 1</th>
<th>Layer orientation 2</th>
<th>Layer orientation 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>20x20x10</td>
<td>250</td>
<td>1200</td>
<td>75</td>
<td>30, 60, 90</td>
<td>0°</td>
<td>[0°,90°]</td>
<td>[0°,30°,60°,90°]</td>
</tr>
</tbody>
</table>

2.2 X-ray diffraction
Near surface XRD scans were performed using NECSA’s Bruker D8 Discover instrument. Measurements were performed by employing the sin²ψ eqi-inclination technique. Each sample was investigated at one point at the centre of the top surface. Depth resolved measurements were conducted by StessTech using a G3R/XSTRESS device. These measurements were performed at the centre of the top surface in conjunction with electro-polishing in order to develop a stress-depth profile. The parameters used the XRD investigations are shown in Table 2.

### Table 2: Diffraction scanning parameters

<table>
<thead>
<tr>
<th>X-ray source</th>
<th>Spot size (mm) / volume (mm³)</th>
<th>Psi tilt (°)</th>
<th>Oscillation per tilt (°) / number of tilts</th>
<th>Bragg peak (°)</th>
<th>Miller Index (hkl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NECSA ND</td>
<td>---</td>
<td>2 x 2 x 2</td>
<td>---</td>
<td>77.6</td>
<td>(301)</td>
</tr>
<tr>
<td>NECSA XRD</td>
<td>Cu</td>
<td>0.8</td>
<td>0 – 50</td>
<td>110</td>
<td>(211)</td>
</tr>
<tr>
<td>StressTech XRD</td>
<td>Ti Kα</td>
<td>Ø3</td>
<td>(-45 – 0) &amp; (0 – 45)</td>
<td>137.5</td>
<td>(110)</td>
</tr>
</tbody>
</table>

3. Results
In all specimens investigated with ND, the results showed that the central volume experiences a higher compressive stress than the peripheries of the specimen. Although the surface stress was not tensile in all of the samples, it invariably tended towards being more tensile than the stress in the central volume. It should be noted that due to the large sample volume employed by ND, averaging of the stresses over the volume investigated does occur.

The near-surface results from the XRD investigations show that for all three of the sample series the stresses are largest in the sample built-up with 30 μm layer thicknesses with a general trend of decreasing
stress with layer thickness. Note that due to the limited penetration depth, up to 20 µm, only the top most section of the last deposited layer could be investigated. This finding is also partially supported by the results obtained from the stress profile scans, where it was found that the influence of an increase in build layer thickness is to reduce the magnitude of the stress in the specimen. The influence of the scanning pattern on the distribution of stress near the surface of the material is to make the stress a more uniform value.

4. Conclusion
This paper compares ND and XRD techniques. Through the use of ND, with its high penetration, it was possible to generate a stress profile through the volume. While XRD has a limited penetration depth, it is capable of performing near surface measurements and can thus resolve the stress state within a layer. The ND results showed that the surface stress was tensile in nature, becoming compressive towards the centre of the specimen. The results of the XRD showed a reduction in the overall stress as the build layer thickness is increased and that by increasing the misorientation of successive build layers a more constant stress profile can be achieved. It can be concluded that neither method provides a complete understanding of the stresses in a sample, but in combination it is possible to determine the stresses to different depths and subsequently contribute towards a better understanding of how residual stress manifests in SLM built components.

REFERENCES

1Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa (landerson@sun.ac.za)
2Research and Development Division, South African Nuclear Energy Corporation
3Department of Materials Engineering, University of Leuven, Belgium
NANO-ADDITIVES FOR USE IN 3D PRINTING POLYMERS

F. Seeliger¹, K.M. Bester¹*, J. Mentz², F.J.W.J. Labuschagné¹

ABSTRACT
Lubricant- and dye intercalated layered double hydroxides were synthesised and compounded into acrylonitrile butadiene styrene polymer for use as rapid prototyping filament. The filament material was tested in a desktop fused deposition modelling type printer using typical printing conditions, and a test-print was compared for the various additive blends and a commercially available filament. The dye intercalated additive showed the highest reduction in warping edges and in part shrinkage compared to the commercial test-print of 96% and 97% while the fatty acid (lubricant) intercalated additive showed a 66% and 70% reduction.

1. Introduction
Layered double hydroxides (LDHs) are a class of anionic clays, made up of a series of layered mixed metal hydroxides and interlayer of anions. LDH materials find use in industry as flame-retardants, catalyst packing, reaction catalysts, medicine delivery systems and absorbers of halogen free radicals, wastewater purifiers and many other useful products. The anions in the interlayer of the LDH can be replaced and new anions (e.g. organics) can be intercalated into the interstitial spacing to give the material new properties. The inorganic layers also offer the intercalated anions different physical properties due to the physical properties of the bulk material and due to the layering effect of the inorganic and anionic layers [1].

Small organic molecules do not find much use in polymer applications as they have high volatility and mobility in comparison to the long polymer chains, which allows the smaller molecules to easily diffuse through the polymer matrix. The compounding of small organic molecules, such as a passive organic dye (e.g. indigo carmine), usually results in plate-out and bleeding of the dye. The size of the small organic molecules also usually results in them degrading at typical polymer processing temperatures. Therefore, many of these molecules lose their intended effect in the polymer and can even catalyse thermo-oxidation of the polymer [2]. By intercalating the smaller organic molecules into the anionic layers of the LDHs, the organic molecules remain in the polar polymer matrix due to the polar and physical interactions between the polymer chains and the LDHs. The intercalated organic molecules are offered “protection” from thermal degradation during polymer processing due to the increased thermal stability granted by the LDH [3].

2. METHODOLOGY AND RESULTS

2.1 Additive synthesis and polymer compounding
The LDH materials were provided by Greenfield Innovations and synthesised using an in-house environmentally friendly method [4]. The intercalation of the organic molecules was accomplished using the reconstruction method, whereby calcined LDH is rehydrated in a solution containing the organic compounds [3].

An organic dye, indigo carmine, and a fatty acid were chosen as the additives of choice for the ABS filament
trials. The fatty acid acts as a plasticiser and increases the elongation to break of the ABS, which leads to an increased flexibility and lower rate of shrinkage. The indigo carmine was chosen as a proof of colouring ability, such that the additives used will not only be used to produce a filament material that is naturally coloured. Five additive combinations were chosen for filament trials: pure unmodified LDH, pure fatty acid intercalated LDH, pure indigo carmine intercalated LDH, a 70/30 blend of fatty acid and dye, and a 50/50 blend of fatty acid and dye.

All additive loadings were selected by weight of the polymer material based on industry standard loadings. The compounding of the additive and the polymer was performed in a lab-scale single-screw extruder with a barrel diameter of 1.78 cm and a length to diameter (L/D) ratio of 23 to 1. The filaments produced measured approximately 1.75 mm in diameter, a standard diameter for 3D printing on a desktop Fused Deposition Modelling (FDM) machine.

2.2 3D printing and test-piece comparison
The test filaments extruded were printed on a desktop FDM machine (Wanhao i3 Duplicator) with a bed temperature of 100°C and an extruder nozzle temperature of 245°C. The test-pieces were compared to a test-piece of a commercial filament, printed on the same day and device as the other pieces. The test piece shape, a parallelepiped of 5 mm total height, is shown below in Figure 1 where the commercial ABS (left) is compared to the indigo carmine intercalated LDH filament (right).

![Figure 1](image)

**Figure 1**
3D printed test-pieces. Commercially available filament is shown on the left and a nano-additive modified filament is shown on the right.

The warping of the corners on the longest diagonal of the parallelepiped was measured and averaged for each test-piece and plotted as a percentage of the highest warpage of the commercial material piece. The total height of each corner on the longest diagonal were also measured, averaged, and plotted as a percentage of the height of the shortest diagonal of each shape. These percentage functions of warpage and shrinkage are shown in Figure 2 below. The indigo carmine intercalated LDH filament (Figure 2) shows the best reduction in shrinkage and warpage (96 and 97%) while the 70–30 blend of fatty acid and indigo carmine LDH shows the lowest reduction (ca. 40% each). The fatty acid acts as a plasticiser and lubricating agent. It is therefore possible that the fatty acid LDHs decreases bed adhesion which results in unavoidable warping and shrinking of printed parts.
3. CONCLUSION
The nano-additives added into the raw ABS show a large improvement in warpage and shrinkage of printed parts.

REFERENCES

* Department of Chemical Engineering, University of Pretoria, South Africa (u12009271@tuhs.co.za)
2 Greenfield Innovation, South Africa
ADDITIVE MANUFACTURING APPLICATIONS FOR THE MARITIME INDUSTRY

L. van Reenen, D. Hagedorn-Hansen

ABSTRACT
Manufacturing industries are constantly in search of ways to reduce lead times, production costs and material wastage to remain competitive in the global economy. One technique that has developed in popularity due to its high level of customisation and overall efficiency in cost and manufacturing time, is additive manufacturing, which is present in the aerospace-, automotive-, medical- and consumer industry, but is yet to be implemented in the maritime industry. With vessels in constant need of spare parts or components at harbours, manufacturing efficiency is of utmost importance. The complete study proposes additive manufacturing as an alternative to sourcing maritime parts from traditional manufacturers, specifically in South African ports.

1. Introduction
Additive manufacturing (AM) is an expanding technology in many industries across the globe. Due to its nature of flexibility and cost efficiency, AM is an attractive manufacturing technique for production-on-demand business environments. AM, also referred to as 3D (three dimensional) printing, is the process by which materials are joined, by adding layer upon layer, to create objects. These objects are designed from computer-aided design software and therefore a high level of customisation can be provided in the final design [1]. Complex parts may be customised and manufactured at a rapid rate using AM methods. This opens doors for many industries at the forefront of manufacturing technology. According to Joshi & Sheikh, [1] AM allows for a significant reduction in manufacturing time, production costs and material waste, thus making it a largely beneficial technique for businesses.

AM has been adopted in a variety of industries such as the aerospace industry, the medical industry, the automotive industry and in consumer product manufacturing [2]. One industry that is yet to take full advantage of this technology is the maritime industry. Maintenance and mean response time is an ongoing issue for the crew of a vessel. With vessels demanding a variety of spare parts during breakdowns, AM is a possible solution to this costly, time-constrained supply chain. If spare parts can be manufactured when needed, the maritime industry may experience a reduction in waste and environmental impact, as well as an increase in cost savings. This study will address the applications of AM as a cost-effective solution to issues involving maintenance and spare parts, faced in the maritime industry. The focus will be on the economic and technical feasibility of using AM to manufacture spare parts for vessels specifically in South African ports.

2. Methodology and results
The data required about spare parts on vessels will be obtained from maritime companies in the Cape, as well as their suppliers. The data obtained will be analysed with reference to which parts will be possible to print using AM processes, for instance, the part size, materials and mechanical characteristics which need to be taken into account. Upon completing an analysis of the data, research will be conducted on the availability and capability (e.g. the maximum size that the machine is able to print) of AM machines in
South Africa. Technology institutes and university technology centres will be contacted in order to obtain quotations for manufacturing the identified marine vessel parts using AM processes. The basic structure of a developed decision framework can be observed in Figure 1. The framework can be used to determine which supply chain is the most resource efficient for supplying a certain vessel part. The framework will be validated using a case study.

3. Conclusion
As for supply chain advantages, the maritime industry will benefit from obtaining low volume parts, as they are required, which also decreases the risk of holding inventory. As AM requires fewer steps in the production process compared to traditional manufacturing, the lead time and manufacturing costs are reduced per part. Lastly, with an AM machine onboard, the risk of an unreliable supplier is eliminated and shipping companies would overcome import taxes for ordered parts. Currently, shipping companies are paying high tariffs for a single vessel to be docked at a port while awaiting maintenance – not to mention the loss in revenue of the freight not meeting its delivery date [3].

Figure 1 (right)
Decision making framework for maritime spare part supply chain

REFERENCES

* Department of Industrial Engineering, Stellenbosch University, South Africa (devonh@sun.ac.za)
ABSTRACT

Metallic powders are widely used as the feedstock material for many additive manufacturing processes. Titanium alloys in particular are used in aerospace construction as an attractive alternative construction material due to the superior properties they exhibit. This paper highlights the process used to produce titanium alloy powder for additive manufacturing, and the characterisation methods used to qualify the atomised powder against specifications contained in applicable test standards. The electrode composition was compared to commercially available wrought samples, and cylindrical rod structures 13 mm in diameter and 90 mm in length were laser printed.

1. Introduction

Metallic powders are widely used as the feedstock material for many additive manufacturing (AM) processes. Titanium alloys in particular are used in aerospace construction as an attractive alternative construction material due to the superior properties they exhibit, such as corrosion resistance, use at elevated temperatures and a high strength to weight ratio [1]. Due to the high costs of titanium powder, material recycling is recommended to reduce wastage and to achieve a more economical process [2]. However, it is necessary to analyse the powder after each use to track the powder chemistry and morphology to identify any changes that may affect powder quality, and hinder processing.

In an investigation by Goso and Kale [3], Ti-6Al-4V alloy powder was produced by the hydride-dehydride (HDH) process in order to make titanium components by blended elemental approach. Chemical analysis revealed that the composition of produced titanium matched specifications of commercially available titanium; however, high carbon content was identified, which reduces the ductility of titanium. Powder production methods such as oxide reduction and water atomisation are not preferred for reactive and refractive metals because the processes introduce chemical impurities, and do not produce the particle geometry and morphology required for additive manufacturing processes (ALD Vacuum Technologies [4]). Inert gas atomization is thus a preferred approach for refractive and reactive metals such as titanium, as the desired purity and specifications such as particle morphology required in achieving homogenous microstructures are achievable to a high grade [4].

For powder production by means of the electrode inert gas atomisation (EIGA) process, atomisation is achieved through inductive melting of a pre-alloyed bar. The bar is supplied in the form of an electrode, and atomised with an inert gas. This paper highlights the atomisation of Grade 5 wrought Ti-6Al-4V bar to produce feedstock material for AM. Rod structures 13 mm in diameter and 90 mm in length were fabricated using this powder by the directed energy deposition (DED) technique on the LENS™ system. The successful production of powder that compares well with commercially available powders, and can be used to produce...
AM components with comparable properties, could create the opportunity for local titanium alloy powder production. Considerable cost savings would be achieved through such an opportunity. The electrode was analysed to determine chemical composition, while the atomised powder was characterised to determine oxygen and nitrogen content, particle size, and morphology, and the manufactured samples analysed to determine defects. The samples were subsequently put through a hot isostatic pressing (HIP) post-process treatment to improve mechanical properties. Mechanical investigations were performed on as-built samples and HIP treated samples for comparative purposes. Only electrode and powder characterisation results are presented.

2. Methodology and results

2.1 Methodology
A Grade 5 wrought Ti-6Al-4V bar sourced from the Baoti titanium industry in China was used as source material to ensure a reliable electrode with accurate analysis for atomisation was obtained. The bar was prepared to specification for EiGA systems and shipped to TLS in Germany for atomisation. The atomised powder was classified using a standard fractional sieve system to achieve a 45 to 100 µm size range. The sieves were equipped with rubber seal rings, and the powder loaded and decanted in a glove box under argon atmosphere. Oxygen in the glove box was 0.2 ppm. Laser processing was performed on a LENS™ system mounted with a 1 kW IPG fiber laser in an argon atmosphere. A laser power of 330 W at a spot size of 1.3 mm was used to melt approximately 2.76 g/min material deposited at a scan speed of 8.47 mm/s.

2.2 Results
The chemical composition of Ti-6Al-4V bar used for the atomising process compares well with ASTM standard as analyses results obtained fall below the maximum acceptable ASTM standards. Table 1 indicates this. An inert gas (argon) environment is employed during LENS processing to ensure minimal oxidation due to the high oxygen content reported in Table 1. Only the oxygen and nitrogen content was determined for atomised powders, and was reported as 0.33% and 0.007% respectively for run one. Run two reported amounts of 0.36% and 0.012% respectively. Samples for gas analysis will be machined out of the LENS printed samples to determine the influence of LENS processing as this would give more accurate results.

<table>
<thead>
<tr>
<th>Material</th>
<th>N%</th>
<th>C%</th>
<th>H%</th>
<th>Fe%</th>
<th>O%</th>
<th>Al%</th>
<th>V%</th>
<th>Ti% (balance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V electrode</td>
<td>0.01</td>
<td>0.01</td>
<td>0.002</td>
<td>0.16</td>
<td>0.2</td>
<td>6.2</td>
<td>4.1</td>
<td>Balance</td>
</tr>
<tr>
<td>Wrought Ti-6Al-4V (ASTM F1472)</td>
<td>&lt;0.05</td>
<td>&lt;0.08</td>
<td>&lt;0.015</td>
<td>&lt;0.3</td>
<td>&lt;0.2</td>
<td>5.5–6.75</td>
<td>3.5–4.5</td>
<td>Balance</td>
</tr>
</tbody>
</table>

The process from sourcing of Ti-6Al-4V bar, used as electrode for atomising to the final laser printed rod samples, for evaluation is indicated in Figure 1.
PERFORMANCE EVALUATION AND CHARACTERISATION OF EIGA PRODUCED TITANIUM ALLOY POWDER FOR ADDITIVE MANUFACTURING PROCESSES continued

3. Conclusion
Analysis of the electrode compared well with ASTM requirements, indicating that a reliable source material was obtained. The laser printed rod samples were manufactured without challenges that could arise from particle distribution or flowability of the powder. Characterisation of the samples for defects, porosity and mechanical properties will inform the success of producing rod samples and powder performance.

REFERENCES


1 Laser Enabled Manufacturing Group, Council of Scientific & Industrial Research, South Africa (narthur@csir.co.za)
2 Materials Science and Manufacturing Group, Council of Scientific & Industrial Research, South Africa
IMPROVED COOLING SYSTEM OF HOT STAMPING TOOLS THROUGH ADDITIVE MANUFACTURING

R. Muvunzi1*, D. M. Dimitrov1; S. Matope1

ABSTRACT
Conventional methods of constructing cooling channels in hot stamping tools utilise straight channels which are costly, time consuming and do not allow uniform cooling for complex parts. On the other hand additive manufacturing technologies have created opportunities for the creation of channels, which conform to the geometry of hot working tools to improve cooling performance. Much of the study regarding conformal cooling systems was centred on moulding and die casting tools. There is a need to identify the range of parameters suitable for hot stamping tools. The paper presents a mathematical procedure for determining cooling channel parameters.

1. Introduction
The manufacture of hot stamping tools is costly and time consuming because of the complicated machining and tool segmentation involved [1]. This is mainly because of the amount of cutting tools and energy consumed to perform the machining operations. Furthermore, machining is limited to straight-drilled channels, which are unable to provide uniform cooling for complex geometric tools. Hence there is need to explore other methods of manufacturing the tools. According to previous studies, tools with conformal cooling systems have a higher cooling performance in terms of cooling time and uniformity when compared to other conventional tooling methods such as machining and casting [2]. This was found to be the case for the moulding, die casting and extrusion Industry [3-5]. Literature analysis reveals that a significant reduction in cooling time from 26 to 50 % was achieved through the application of conformal cooling systems in injection moulding [3,6].

Recent studies have shown that additive manufacturing (AM) processes have the potential to improve the performance of stamping tools [1]. Leal et al [8] compared the time involved in the manufacture of stamping tools using direct metal laser sintering (DMLS) and conventional tooling processes (machining and foam casting). According to the results obtained, the use of DMLS resulted in a reduction in lead time by 35% [8]. The challenge is to identify the parameters to utilize for hot forming tools. Hence the aims of the paper are to come up with a calculation procedure for identifying the parameters for maximising the cooling rate and uniformity without compromising the tool life. The developed procedure was validated using finite element analysis (FEA) simulation with PAMSTAMP. In its structure, the paper firstly presents the objectives of an improved cooling system design in hot stamping. This is followed by an account of the parameters affecting the cooling system. Thirdly, calculation procedure is given. Lastly a detailed case study and evaluation is presented.

2. Methodology and results

2.1 Method for determining cooling system structural parameters
The cooling system parameters considered include the distance from tool surface to cooling channels (Z), distance between channels (Y) and the diameter (d) of channels of channels. Equations are derived based on
heat transfer and structural analysis of the hot forming tool. To ensure an increased cooling rate, the distance between the tool surface and the cooling channels is minimised as much as possible while considering the deformation requirements of the tool. Also, to increase the cooling uniformity, the diameter and surface area covered by the channels are considered. Figure 1 shows the flowchart proposed for determining each of the structural parameters.

The proposed procedure is validated using FE analysis. PAMSTAMP software is used for the analysis because it allows evaluation of the cooling system design, assessment of quality through phase transformation ratio and estimation of the cooling time thus measuring the cooling system performance. A simple U-shaped part is used as a benchmark. The computer-aided design (CAD) model of the tool is developed and transferred to the hot stamping simulation software. The parameters used in the simulation are derived from the actual hot stamping process. The dimensions of the U-shaped part used for the analysis are shown in Figure 2.
IMPROVED COOLING SYSTEM OF HOT STAMPING TOOLS THROUGH ADDITIVE MANUFACTURING

Figure 2
Dimensions of simple part

REFERENCES


*Department of Industrial Engineering, Stellenbosch University, South Africa (rmuvunzi@sun.ac.za)
A COSTING FRAMEWORK FOR ADDITIVE MANUFACTURING

A.F van der Merwei¹

ABSTRACT
Are we really making a profit on our additive manufacturing product line? How should we factor in the learning curve and the teething problems? What percentage of capital cost should be allocated to each product? What should be the basis of quotation; product mass or machine runtime? This paper defines a thought process by which the actual cost of an additive manufactured product can be determined. It considers overheads, indirect costs and direct costs. Labour cost is based on standard time and skills development cost is considered on a learning curve. Schemes are suggested for fused deposition and powder based systems.

1. Introduction
The rapid prototyping industry using 3D printing is fast evolving towards an additive manufacturing (AM) industry. For this industry to be economically sustainable, the real cost of production should be known. Quotations should at least recover direct and indirect costs and the overheads be covered by gross profit. With high capital spent on equipment and regular teething problems in build quality, the required gross profit margin is still not known due to infrequent orders while the technology enters the market. Many man hours are spent by entrepreneurs and researchers, using family time, to satisfy their urge to understand AM. The ramp-up phase is still plagued by teething problems and is only now becoming commercially ready. Costing still contains some risk, which is either absorbed by the bureau or some research fund. Clients are unlikely to be willing to pay for technology development costs, or for reprinting of parts that “did not print right the first time”.

This costing framework considers required funding during the product lifecycle and suggests long and short term funding schemes. It also considers technology redundancy. Similar to the AM implementation framework suggested by Mellor et. al. [3], this costing framework is intended to support commercialisation of this disruptive technology.

The intent of this costing model is to serve as an open source platform for all additive manufacturing enterprises in South Africa, in order to strengthen our global competitiveness, as a cluster. The global market is still lucrative as quoted from Thomas & Gilbert: [2] The consensus among well–respected industry experts is that the penetration of the additive manufacturing market was 8 % in 2011; however, as seen in Table 1.1, goods produced using additive manufacturing methods represent between 0.01% and 0.05% of their relevant industry subsectors. Thus, additive manufacturing has sufficient room to grow.

2. Methodology and results
2.1 Defining the value chain
The process chain is analysed by dividing it into the smallest functional occurrences. These occurrences are sequenced as events, each with unique identifiers and characteristics. The sequential interaction is mapped out to depict the physical chain of events. Events that may occur simultaneously are mapped in parallel routes.
Path lengths of parallel routes are compared to determine delay times and holding costs accordingly. The progressive increase in value is calculated along the value chain.

2.2 Modelling the value chain
The defined value chain is modelled in Excel as a series of sequential events in single or parallel routes. Event characteristics and system interaction are added. A generic approach is used that allows changes in characteristics as well as sequence.

2.3 Simulating the value chain
A “walk through” batch processing approach is used. Each batch of similar products is progressed along the value chain. Cost is accumulated as value is added. The simulation reports cost incurred at each stage along the value chain. Risk of product non-conformance can be managed accordingly.

2.4 Validating the value chain
The simulated product costs are compared with accounted cost from historic case studies. All accounted costs are allocated as direct, indirect or overhead costs to the host enterprise. The cumulative value added to products generated in a fiscal period is compared to the accounted expenses in the same period. Baumers et.al. [1] reported a cost of £6.18 per cm³ of metallic material deposited using Direct Metal Laser Sintering (DMLS) in 2016.

2.5 Forecasting cost
The validated value chain model reports cost as the product batch is produced progressively along the chain. The full cost of the product is an output of this model. The full cost can be used for quotation by adding overheads such as marketing, admin, management and accounting.

3. Conclusion
The costing framework for AM attempts to provide a comprehensive guideline to the engineer responsible for product job costing with quotation generation in mind. As many AM platforms exist, no one costing system will work for all. Therefore, this guideline should be used as a way of thinking for the costing engineer to develop their own model. It remains imperative that the model must be constantly validated with current information and pricing. The costing engineer should understand the fundamental mechanisms in the model, to enable customisation for special cases. The fundamental framework however remains standard to serve all cases, with certain selectable options.

REFERENCES

1 Department of Industrial Engineering, Stellenbosch University, South Africa (andrevdm@sun.ac.za)
NON-DESTRUCTIVE INVESTIGATION OF RESIDUAL STRESSES IN ADDITIVELY MANUFACTURED COMPONENTS USING DIFFRACTION TECHNIQUES

A.M. Venter

ABSTRACT

Complex near-net-shape three-dimensional metallic geometries are nowadays routinely formed by layer-by-layer melting of wire or powder feedstock. The high thermal gradients and repetitious local heat transfer can though lead to detrimental residual stress build-up owing to inherent changes in local heterogeneous microstructures and crystallographic textures that directly impact the mechanical properties and dimensional stability – distortion. X-ray and neutron diffraction techniques are well suited for the non-destructive characterization of macro residual stresses and textures by direct probing of properties at the atomic level. We introduce the diffraction facilities existing at Necsa, illustrated with studies of additively manufactured samples.

1. Introduction

In conventional manufacture excess material is removed by machining cast or wrought stock material to achieve the desired component. For complex structures this becomes time intensive, requires specialised setup and machining with generally large volumes of material loss. With the significant advances in additive manufacturing (AM), complex near-net-shape three-dimensional geometries are formed by micro layer-by-micro layer melting of metal wire or powder feedstock. A major difference between the two production routes is the microstructure of the material in the final component that impacts its ultimate performance. Production of wrought stock material by casting and thermo-mechanical processing is well tailored to attain specific bulk microstructures from thermal and deformation processing. In contrast, with AM small melt volumes undergo melting, rapid solidification and fusion to the preceding layer, as well as repeated thermal cycles as additional layers are added. Since components are built to near-net shape limited opportunities exist to optimize microstructures after manufacture being limited to surface deformation treatments such as shot or laser peening, rolling and bulk or surface thermal/chemical treatments.

AM processing parameters strongly influence the component microstructure. The difference in microstructures between AM and wrought components can be significant, similar to the changes observed within welded microstructures. Welding can lead to the introduction of additional phases (appearance of ferrite in austenitic stainless steels) and substantial residual stress build-up in and around the welded region due to large thermal gradients and rapid cooling. These features are often present in AM materials as well [1]. The high thermal gradients and repetitious local heat transfer cause residual stress build-up in the part and local heterogeneous microstructures and textures, which can have negative effects on structural integrity, geometry tolerances and dimensional stability. Moreover, residual stresses can cause significant distortion of the component after build plate removal. Subsequently parameters such as microstructure and residual stresses need to be well understood to control their impact on the mechanical response of the material.

2. Residual stress analysis with diffraction techniques
Neutrons and X-rays, inherent to their interaction mechanisms with matter, offer complementary probes of crystalline materials [2 - 4]. This leads to penetration depths of different extents into materials: X-rays tens of microns, high-energy synchrotron X-rays up to tens of millimetres and neutrons some centimetres, dependent on the material absorption and scattering strength. These diffraction probes enable non-destructive investigation of phenomena such as chemical phase composition, residual stress and texture (preferred crystallite orientation). Materials include metals, alloys, composites, ceramics and coated systems. Especially, depth-resolved analyses are possible when using high-energy X-rays and neutrons. The elastic strain $\varepsilon_{hkl}$ in the gauge volume can be calculated from variations in the lattice spacing $d_{hkl}$ from the stress-free lattice spacing, $d_{hkl}^0$, using:

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{hkl}^0}{d_{hkl}^0}$$

The principal stresses (e.g. $\sigma_{xx}$, $\sigma_{yy}$ and $\sigma_{zz}$) can be calculated from measured lattice strains (e.g. $\varepsilon_{xx}$, $\varepsilon_{yy}$ and $\varepsilon_{zz}$) using Hooke's law:

$$\sigma_{ij} = \frac{1}{1/2S_2} \left[ \varepsilon_{ij} - \delta_{ij} \frac{S_1}{1/2S_2 + 3S_1} \varepsilon_{ii} \right]$$

where $S_1$ and $1/2S_2$ are the diffraction elastic constants. Strain/stress components are specifically measured along the diffraction scattering vector, i.e. perpendicular to the diffracting planes.

2.1 Diffraction facilities at Necsa [5]
Dedicated instruments exist at Necsa for residual stress investigations using X-rays and neutrons. In addition, various NRF programs support access to synchrotron facilities internationally.

Figure 1
Photos of the Necsa instruments: (a) XRD: Bruker D8 Discover; (b) ND: MPISI neutron strain scanner
NON-DESTRUCTIVE INVESTIGATION OF RESIDUAL STRESSES IN ADDITIVELY MANUFACTURED COMPONENTS USING DIFFRACTION TECHNIQUES

2.2 Residual stresses in SLM produced Ti6AI4V

Residuals stress results from a SLM produced TiAl6V4 sample of size 30 x 30 x 13 mm³ studied using a neutron gauge volume of 2 x 6 x 2 mm³ and the 103 reflection are shown in Figure 2.

![Figure 2](image)

Measured residual stress profiles in a SLM produced Ti6AI4V sample: (a) Line scans along the sample directions at mid-plane; (b) Across a cross-sectional slice as indicated.

3. Discussion

Many diffraction studies of AM materials are reported in the recent literature. Due to their non-destructive nature, samples can be analysed during different production steps, i.e. as-built, after removal from base-plate, before and after thermal and surface treatments, etc. The diffraction based approaches are well suited to provide valuable research inputs towards establish both empirical connections between input parameters and the achieved microstructure and properties, and physics-based models to guide AM process optimization.

REFERENCES


*Research and Development Division, Necsa SOC Limited, South Africa (andrew.venter@necsa.co.za)*
PRINTED WIRELESS DEVICES FOR LOW-COST, CONNECTED SENSORS FOR POINT-OF-CARE APPLICATIONS

S. Smith*, K. Land*, J.G. Korvink & D. Mager*

ABSTRACT
We present wireless devices towards the realization of connected, automated and low-cost sensing solutions, with focus on point-of-care (POC) diagnostics for South African clinics as an initial example. Specifically, ultra-high frequency (UHF) radio frequency identification (RFID) and near-field communication (NFC) device implementations are presented, utilizing the printability of antennas on to low-cost, flexible substrates as a foundation on which to develop low-cost, connected sensors.

1. Introduction
The evolution of the internet of things (IoT) has resulted in a drive to include intelligence in and connectivity between devices and systems [1]. In parallel, healthcare has seen a shift towards low-cost and automated point-of-care disease diagnostic solutions, particularly in resource-limited countries [2]. Data connectivity of such devices has become increasingly important to enable patient and result tracking and record-keeping [3,4]. RFID techniques provide a potential solution for POC data connectivity, by providing a wireless – and thus contamination-free – connectivity solution, where both ultra-high frequency UHF RFID and NFC techniques can be implemented and have been investigated.

RFID has a number of advantages over existing identification techniques such as barcodes, including longer reading ranges, faster data transfer, and multiple, simultaneous tag reading. Passive RFID tags draw energy from the electromagnetic field radiating from the reader when the tags are within the reader range, a favourable implementation that does not require a battery or external power source, thus lowering the cost of the device. The field of printed electronics, and specifically printed antennas, has seen rapid growth in recent years, enabling wireless communication systems to be implemented on flexible substrates [5]. This can be achieved using established, accessible, low-cost printing techniques such as screen printing, which lends itself to scale-up and mass manufacturability of printed devices.

Different RFID categories are suited to different POC diagnostic applications. NFC can make use of a mobile phone as a reader and thus is well suited to home-based use or personal healthcare applications. UHF RFID typically uses external reader devices and can achieve longer read-ranges using simple antenna designs, making it well suited to testing in clinics or hospitals, where the reader can be a permanent fixture. The printability of both NFC and UHF RFID tag antennas on to flexible, paper-based substrates has been investigated using inkjet printing techniques, with assembly of the tag integrated circuit (IC) to the printed antenna implemented in each case. Functional tags were illustrated by wireless communication of information stored on the ICs to a mobile phone or a personal computer (PC). This information could include the type of test, serial number, manufacture and expiry date for POC applications.

Integration of sensing capabilities with RFID solutions can also be explored for POC applications. The SL900A UHF RFID IC (ams, Austria) allows for a number of different sensors – including resistive, capacitive and
optical - to be connected and the measured values to be wirelessly communicated. This provides a compact platform on which to develop sensors with automated, wireless communication of the results to an external device or cloud. Previous work using a similar approach illustrated temperature readout and fluidic detection [6]. Colour detection for lateral flow test read-out is currently being explored and could make use of the RF field to power a small light-emitting diode (LED) to realize a passive, low cost device.

2. Methodology and results
NFC and UHF RFID tags were designed and inkjet printed on to photo paper (NB-RC-3GR120, Harima Chemicals, Japan) using a Dimatix DMP 2831 materials printer (Fujifilm, Japan) and conductive silver ink (NPS-JL silver nanopaste, Harima Chemicals). The devices were assembled by mounting the NFC and UHF RFID ICs and other surface mount device (SMD) components using silver epoxy and tested to illustrate the functionality of the tags for wireless communication of information from the tags. Figure 1 shows the design, manufacture and testing of the tags. The antenna designs were based on the AS3955 NFC IC development kit (AS3955-WL_DK_ST, ams, Austria) and SL900A UHF RFID IC development kit (SL900A-DK-STQFN16, ams, Austria). Initial results show the feasibility of printing RFID tags on to different, low-cost substrates, which could be compatible with paper-based diagnostic tests — a field that has also seen rapid development in recent years [7].

Figure 1: (a)
NFC tag: multilayer design, and resulting functionality of manufactured and assembled tag with AS3955 NFC IC (ams, Austria) tested using a Samsung Galaxy S6 smart phone as a reader (NFC-enabled mode). Scale bar = 3 mm.

Figure 1: (b)
UHF RFID tag: design and functionality of manufactured tag with SL900A UHF RFID IC using an AS3993 reader and antenna (AS3993-QF_DK_R FERMI, ams, Austria) to illuminate an LED using the RF field and to read out temperature. Scale bar = 5 mm.
PRINTED WIRELESS DEVICES FOR LOW-COST, CONNECTED SENSORS FOR POINT-OF-CARE APPLICATIONS continued

3. CONCLUSION
The solutions presented can be used for tracking and identification of diagnostic tests, and for sensing capabilities to provide automated, integrated, and connected sensing solutions using few components in a low-cost form factor. Additional work will explore the printability of additional components such as inductors, and the feasibility of using die format ICs to provide more flexible, thin device solutions. The devices presented have great potential for the development of low-cost, smart and connected POC diagnostics for resource-limited settings, and could greatly benefit rural clinics in South Africa.

REFERENCES

1 Materials Science and Manufacturing, Council for Scientific and Industrial Research, South Africa (ssmith@csir.co.za)
2 Institute of Microstructure Technology, Karlsruhe Institute of Technology, Germany
DESTRUCTIVE AND NON-DESTRUCTIVE TESTING ON SMALL AND INTRICATE DMLS COMPONENTS

D. Kouprianoff*, A. du Plessis², I. Yadroitsava¹, I. Yadroitsev¹

ABSTRACT
Direct metal laser sintering is one of additive manufacturing technologies that utilise metal powders. The main advantages being geometrical freedom that allows designing parts with complex shape, which are difficult or impossible to produce by conventional technology; shortened design to product time; customisation and possibility to use several materials in one process. But due to the powders layer–by–layer nature, direct metal laser sintering has drawbacks such as, low accuracy and high surface roughness, and size and design limitations for parts containing overhangs. High thermal gradients cause residual stress. This can result in the formation of internal cracks and eventually to a substantial deterioration of the mechanical properties of the products and their application properties. In this study, some non-destructive testing techniques, in terms of their applicability for quality control for small and intricate direct laser sintering components, are considered. A comparison is based on the data obtained from computed tomography, visual testing, acoustic emission, ultrasonic testing and destructive cross sectioning with microscopic analysis.

1. Introduction
Direct metal laser sintering (DMLS) is a technology that allows producing 3D parts directly from computer-aided design (CAD) data by fusing of powder material by a laser beam. Microstructure and mechanical properties of DMLS materials are different from traditional cast or wrought material. For the introduction and wide application of DMLS components produced with this undoubtedly promising and powerful technology, it is required to study DMLS material and its mechanical properties, degree of dimensional accuracy and roughness. The design of the DMLS object is subjected to some limitations due to the fact that the powder materials have certain specifications; the diameter of the laser beam spot, laser energy and speed of the movement, features of the chosen scanning strategy of various parts of the object, etc. – all influence the result. Therefore detailed quality control and certification of the DMLS process is necessary for understanding the capabilities of this technology. It is very important to identify defective parts before they are brought into service. Non-destructive testing (NDT) is effective for detection of internal defects without causing damage and widely used for various industrial applications [1-2]. Computed tomography (CT) is a very useful tool for accuracy measurements, especially for control of the inner walls and complex inner structures, their sizes and locations. CT combined with the additive manufacturing (AM) industry is also often used in reverse engineering with applications in the medical, industrial, archaeological and historical fields [3].

2. Methodology and results
Different samples were manufactured using from Ti6Al4V (ELI) powder that was pre-alloyed gas atomised powder. The equivalent diameters (by volume) of the powder particles were d10 = 12.03 µm, d50= 21.38 µm and d90= 31.15 µm. Ti6Al4V (ELI) samples were produced by the EOSINT M280 DMLS system with volume rate 5 mm³/s for 30 µm powder layer thickness. Three sets of samples were manufactured: i) Pins with small rectangular gaps (vertical built cavities) to estimate accuracy of fine inner structure. Prescribed gap thickness was: 7.5–200 µm. ii) Rectangular lockes with horizontal semi–cylinder channels of diameter 60–360 mm. ii) A massive rectangular block with artificial defects that mimicked a crack or big inter-layer
porosity in the centre of the block. The design of the defect thickness was 90 µm. These samples have previously been analysed by microCT [2]. Detailed description of applied scanning strategy was done. Samples were subjected microCT scans and acoustic emission. Surface roughness was measured and accuracy of manufacturing was estimated. To compare prescribed CAD sizes with the actual size of the voids in the samples, cross-section of the DMLS Ti6Al4V pins and blocks were made and images were studied using an optical microscope and SEM.

At chosen scanning strategy, continuous gap in the pins was achieved only for the prescribed size of more than 80 nm. For the smaller gap sizes, the attached powders closed voids and formed closed porosity.

It should be noted that the straight shape of the gap, which was developed in the CAD model during the DMLS manufacturing was transformed into the circle. In DMLS blocks with semi-cylindrical shape showed some peculiarities. Semi-spherical CAD shape of the pore in actual DMLS part changed to irregular shape.

It was found that CT scanning provides accurate information non-destructively, but a more clear analysis of small pores is obtained by physical microscopy. The combination of the two techniques is powerful for investigating unknown/unexpected defect formation. The possibility of detecting defects in-house with use of acoustic emission was investigated due to its low cost and simplicity; AE is based on the natural vibrating frequency of a component. Any defect will change the stiffness and/or mass causing a change in frequency to be measured. Samples free of artificial defects are compared to that of blocks containing defects.

3. Conclusion

High roughness of surfaces and size resolution for fine structures remain a limitation in DMLS, even after applying special scanning strategies. CT in combination with physical sectioning is shown to be a powerful analysis combination. AE showed the possibility of determining the defects in DMLS samples. Establishing the limitations of AE (minimum size and the typical defects) will allow showing whether it can be applied in-house as a quality control method for DMLS components.

REFERENCES


1 Department of Mechanical and Mechatronic Engineering, Central University of Technology, South Africa. (dhouprianoff@cut.ac.za)
2 CT Scanner Facility, Stellenbosch University, South Africa.
CFD MODEL OF LASER ADDITIVE MANUFACTURING PROCESS OF CYLINDERS

T. Tamsaout1, K. Kheloufi1, E.H. Amara1, N. Arthur2, S. Pityana2

ABSTRACT
A theoretical approach, based on a numerical simulation using experimental data, is proposed as a contribution for the study of laser based additive manufacturing by metallic powder injection. The aim is to simulate the stages of the clad formation by considering the induced generated liquid metal in a cylindrical geometry. For normal atmospheric conditions, a 3D model is developed using the finite volumes method to solve the governing equations of the occurring fluid flows and heat transfers. The model is based on the experimental work performed at the CSIR-NLC on the LENS system, where Ti-6Al-4V cylindrical coupons are laser printed and characterised.

1. Introduction
Laser additive manufacturing (LAM) has become an established processing technique for repair and manufacture of products in a variety of industrial applications. LAM with powder feeding can be configured with the powder directed by a single side nozzle (off-axis powder feed method), but most modern systems use either a co-axial nozzle with an annular outlet passage or a radially symmetrical nozzle with multiple outlet passages arranged around the laser beam. Particular advantages of this method are Omni-directional cladding, better protection from the ambient atmosphere. Other advantages of the co-axial powder supply are the controlled heating of the powder before it enters melt pool and the higher powder efficiency [1-4].

There are many variables which strongly influence the characteristics of the built part. These variables include laser power, beam diameter defocus distance, spatial distribution mode of the laser beam, shielding gas flow, powder delivery gas flow, scan speed, powder feed rate, material properties (absorptivity, melting point, thermal conductivity), powder characteristics (particle size distribution and particle shape), powder delivery method (side injection or co-axial injection) and percentage overlap between tracks. Some of these processing parameters are strongly coupled to each other [5,6]. Optimization of these processing parameters is necessary to obtain the desired dimensional accuracy and material integrity and to produce a built part with good strength and minimum amount of defects (porosity, cracks, high residual stress and dilution). Computational modelling is one such approach used to optimise these parameters, as well as to gain a better understanding and improve upon the process.

In this work, a 3D numerical model using a dynamic mesh approach based on the resolution of fluid flow and heat transfer equations is developed, and results are presented. The numerical study was performed in a co-ordinate system fixed to the base material and a moving laser beam with a constant scanning speed. The model is based on the experimental work performed at the CSIR–NLC on the LENS system, where Ti-6Al-4V cylindrical coupons are laser printed and characterised.

2. Methodology and results
In the present study, only the powder particles entering into the molten pool contribute to form each layer.
The other particles bouncing from the solid surface are lost. The deposited energy on the top surface can be expressed by the following equation:

\[ Q = \frac{P_l \eta}{\pi r_l^2} e^{-\frac{r^2}{r_l^2}} \left( -h_c(T - T_\infty) - \varepsilon \sigma (T^4 - T_0^4) \right) \]

Where \( P_l \) and \( r_l \) are the laser beam power and radius, \( \eta \) is the absorption coefficient. The Gaussian energy distribution is assumed and heat loss from convection and radiation are included. The thickness of the built layer is calculated only for cells where temperature is equal or higher than the melting point of the substrate material and for each increment in time, \( \Delta t \), its height \( \Delta h \) is given by Toyershani et al. [7]:

\[ \Delta h = \frac{m \Delta t}{\pi \rho r_{jet}^2} \]

The numerical study was performed, on Ansys Fluent code, in a co-ordinate system fixed to the base material and a moving laser beam with a constant scanning speed. The dynamic mesh technique is used in our modelling to follow the clad formation. Figure (1) represents the evolution of the built part and the temperature field, for parameters used on the experimental work performed on the LENS system (in this model, the thickness used for the substrate is 1 mm and the cylinder shape is 15 mm diameter, with a laser power of 360W.).

Figure 1

Temperature field and the evolution of built part and the temperature field
CFD MODEL OF LASER ADDITIVE MANUFACTURING PROCESS OF CYLINDERS continued

Figure 1 shows the evolution of the built part and the temperature field of the workpiece for different views. The figure corresponds to a powder feed rate of 1.2 g/min and a scan speed of 10.58 mm/s. The deposition process illustrates the isothermal lines in the whole domain where the maximal temperature is about $T=3000\text{K}$ for the first pass, and about $4000\text{K}$ for the second one.

3. Conclusion
A 3D numerical model using dynamic mesh approach based on the resolution of fluid flow and heat transfer equations was developed. The computational modelling enables the prediction of the temperature field, shape, and the geometry of the built part, which plays an important role in predicting the build geometry of the printed parts.

REFERENCES


* Laser Material Processing Team, Centre de Développement des Technologies Avancées, Algeria (ttamsaout@CDTA.DZ)
2 National Laser Centre, Council for Scientific and Industrial Research, South Africa
INTEGRATION OF COLD SPRAY AND 3D PRINTING FOR ANTIMICROBIAL SURFACE COATINGS

M.D.I. Lucas¹*, I. Botef², S. Van Vuuren³

ABSTRACT
Studies show that metallic coating of polymers could improve their surface properties and extend their application. The additive manufacturing techniques of cold spray and 3D printing were used to develop a novel antimicrobial surface coating, for the mitigation of Hospital Acquired Infections (HAIs). Theoretical cold spray modelling aided in parameter value selection. Surface topography was investigated for its potential in improving coating formation and enhancing antimicrobial ability. The developed coatings, irrespective of surface design, performed as effective antimicrobial agents.

1. Introduction
“Approximately one in seven patients entering South African hospitals are at risk of acquiring an HAI”, according to Dr Brinh, et al. [1]. Targeting contact sites through the development of antimicrobial surface coatings, using additive manufacturing techniques, aims to mitigate this risk. Cold spray uniquely allows coating of thermally sensitive and chemically dissimilar materials, and direct fabrication and thick coatings are possible [2], making this an attractive additive manufacturing technique. 3D printing offers design-for-function opportunities; affording increased part complexity, tailored to a design’s functional requirements. Artifacts of surface roughness and surface area are purported to achieve higher cold spray deposition efficiencies [3] and improve antimicrobial ability [4], respectively. The study aimed to investigate this.

2. Methodology and results
A solid interior fill style, a high strength printed-part orientation and various surface geometries were considered for the 3D printed Acrylonitrile, Butadiene and Styrene (ABS) substrates, with the intention of improving cold spray deposition efficiency, coating adhesion, operational durability and antimicrobial efficacy.

High purity copper powder was cold sprayed onto these substrates. Copper has innate antimicrobial properties, which act as the antimicrobial agent in such a coating. A one-dimensional, isentropic flow model [5] and a particle impact model [6] were programmed to calculate the cold spray system velocities and predict particle depth of penetration, respectively. Parameter selection aimed to achieve sufficient particle embedment and mechanical entanglement, thus strengthening the substrate, onto which subsequent layers could build.

A mixed, copper dominant surface coating was observed via Scanning Electron Microscopy and Energy Dispersive X-Ray (SEM-EDX) analysis. EDX analysis, Figure 1(A), revealed an 82.12% copper content (by weight) in spectrum 2, with only 4.71% in spectrum 1. A threshold segmentation analysis, using image processing software ImageJ, indicated an overall copper coverage of approximately 73%. The results are suggestive of material jetting, inducing effective mechanical entanglement. The copper coating, although thin as seen in Figure 1(B), proved sufficient in the antimicrobial testing.
Antimicrobial analysis was carried out; subjecting the surfaces to Staphylococcus aureus, Pseudomonas aeruginosa and Candida albicans. The results suggested that the copper coatings were inhibitors to microbial growth and therefore effective antimicrobial agents. It was further postulated that surface area enhancement attributed to an improved efficacy. There was, however, no discernible difference between samples with designed surface geometries and those without.

3. Conclusion
The research aimed to investigate the combined use of cold spray and 3D printing in the development of novel antimicrobial surface coatings. Cold spray theoretical modelling and subsequent spray trials were successful in isolating a parameter set for suitable copper coating of 3D printed substrates. Surface geometry effects were investigated; suggesting that for antimicrobial touch-contact applications, as-printed surface finish is ideal for both coating creation and bacterial growth inhibition. It is claimed that copper cold spray coatings out-perform pure copper samples, with respect to antimicrobial activity, due to an increased surface area and coating qualities unique to the cold spray process. Further research is being conducted to validate this claim.

REFERENCES

1* Department of Mechanical Engineering, University of the Witwatersrand, South Africa (michaeldilucas@gmail.com)
2 Department of Industrial Engineering, University of the Witwatersrand, South Africa
3 Department of Pharmacy and Pharmacology, University of the Witwatersrand, South Africa
## CONFERENCE PROGRAMME

### Thursday, 9 November

### Session Details

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:00</td>
<td>Opening</td>
</tr>
<tr>
<td>08:15</td>
<td>Delivering Design Complexity in AM – Sarat Babu</td>
</tr>
<tr>
<td>09:00</td>
<td>Digitally Driven Engineering: an holistic approach to industrial and research problem solving – Dr Ian Gibson</td>
</tr>
<tr>
<td>09:45</td>
<td>Tapping nature's genius in 3D printing – Claire Janisch</td>
</tr>
<tr>
<td>10:30</td>
<td>TEA</td>
</tr>
</tbody>
</table>

### Session Details

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:00</td>
<td>Createneering – Michaella Janse van Vuuren</td>
</tr>
<tr>
<td>11:55</td>
<td>Redefining Reality – Clive de Lange</td>
</tr>
<tr>
<td>12:20</td>
<td>EOS – Sponsor Presentation – Yusuf Üzümçü</td>
</tr>
<tr>
<td>12:45</td>
<td>Qualification of Additive Manufacturing Processes using In-Process Monitoring and Computed Tomography – Dr. Sven Cornelissen</td>
</tr>
<tr>
<td>13:10</td>
<td>LUNCH</td>
</tr>
</tbody>
</table>

### Session Chairs

**Material / Process**

Monnamme Tlotleng, Duwan Bester

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00</td>
<td>Evaluation of Ti15Mo alloy manufactured by DMLS from elemental powders – Thywill Dzogbewu</td>
</tr>
<tr>
<td>14:20</td>
<td>LENS produced binary TiAl structure: Effect of heat treatment – Monnamme Tlotleng</td>
</tr>
<tr>
<td>14:40</td>
<td>Determination of the optimal process parameters for INVAR 36 component repair, using a layer metal deposition technique – Razia Adam</td>
</tr>
<tr>
<td>15:00</td>
<td>Evaluation of carbon fibre powder scraper used in metal Additive Manufacturing – Duwan Bester</td>
</tr>
<tr>
<td>15:20</td>
<td>TEA</td>
</tr>
<tr>
<td>15:30</td>
<td>Poster Session (Exhibition Centre) – TZbigniew Kesy, Andrzej Kesy</td>
</tr>
</tbody>
</table>

### Session Chairs

**Product Development** – Martin Bolton

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:40</td>
<td></td>
</tr>
<tr>
<td>16:00</td>
<td>Low cost tooling and machinery: Additive Manufacturing and open source machines for the South African seating – Martin Bolton</td>
</tr>
<tr>
<td>16:20</td>
<td></td>
</tr>
<tr>
<td>16:40</td>
<td>RAPDASA AGM</td>
</tr>
<tr>
<td>18:30</td>
<td>GALA Dinner</td>
</tr>
</tbody>
</table>
### Session Details
**SESSION CHAIR:** Deon de Beer

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:00</td>
<td>Opening</td>
</tr>
<tr>
<td>08:15</td>
<td>Delivering Design Complexity in AM – Sarat Babu</td>
</tr>
<tr>
<td>09:00</td>
<td>Digitally Driven Engineering: an holistic approach to industrial and research problem solving – Dr Ian Gibson</td>
</tr>
<tr>
<td>09:45</td>
<td>Tapping nature’s genius in 3D printing – Claire Janisch</td>
</tr>
<tr>
<td>10:30</td>
<td>TEA</td>
</tr>
<tr>
<td>11:00</td>
<td>Createneering – Michaella Janse van Vuuren</td>
</tr>
<tr>
<td>11:55</td>
<td>Redefining Reality – Clive de Lange</td>
</tr>
<tr>
<td>12:20</td>
<td>EOS – Sponsor Presentation – Yusuf Üzümcü</td>
</tr>
<tr>
<td>12:45</td>
<td>Qualification of Additive Manufacturing Processes using in-process Monitoring and Computed Tomography – Dr. Sven Cornelissen</td>
</tr>
<tr>
<td>13:10</td>
<td>LUNCH</td>
</tr>
<tr>
<td>14:00</td>
<td>Material / Process – Sand Casting – Didier Nyembwe</td>
</tr>
<tr>
<td></td>
<td>Material Evaluation – Dr Ntombizodwa Ruth Mathe, Shyline Chingowo</td>
</tr>
<tr>
<td></td>
<td>Rapid sand casting trials using local ceramic sand – Dady Oyombo</td>
</tr>
<tr>
<td></td>
<td>Characterization of Aluminium alloy structures produced by high speed Selective Laser Melting technology – Dr Ntombizodwa Ruth Mathe</td>
</tr>
<tr>
<td></td>
<td>Density of sand parts produced on a Voxeljet VX 1000 three-dimensional printer – Didier Nyembwe</td>
</tr>
<tr>
<td></td>
<td>Evaluation of Tungsten-Titanium composite Carbides and their viability for production using Selective Laser Melting applications – Marius van Coller</td>
</tr>
<tr>
<td></td>
<td>Assessment of residual strength of Additive Manufactured sand parts – Didier Nyembwe</td>
</tr>
<tr>
<td></td>
<td>Effect of alpha casing on the mechanical properties of Ti6Al4V components manufactured by Selective Laser Melting – Shyline Chingowo</td>
</tr>
<tr>
<td></td>
<td>A case study of rapid sand casting defects – Didier Nyembwe</td>
</tr>
<tr>
<td></td>
<td>Density of sand parts produced on a Voxeljet VX 1000 three-dimensional printer – Didier Nyembwe</td>
</tr>
<tr>
<td></td>
<td>Evaluation of Tungsten-Titanium composite Carbides and their viability for production using Selective Laser Melting applications – Marius van Coller</td>
</tr>
<tr>
<td>14:20</td>
<td>LEAN produced binary TiAl structure: Effect of heat treatment – Monnamme Tlotleng</td>
</tr>
<tr>
<td></td>
<td>Characterization for qualification of Ti–6Al–4V ELI parts build by Selective Laser Melting – Nhele Baloyi</td>
</tr>
<tr>
<td></td>
<td>Design for AM – Thorsten Becker, Daniel Glaser</td>
</tr>
<tr>
<td></td>
<td>Characterisation for qualification of Ti-6Al-4V ELI parts build by Selective Laser Melting – Nhele Baloyi</td>
</tr>
<tr>
<td></td>
<td>Stepping out on a limb: the design and manufacture of a 3D Printed titanium prosthesis – Lionel Dean</td>
</tr>
<tr>
<td></td>
<td>SLM-produced Ti6Al4V: Novel annealing strategies to improve ductility – Gerrit Ter Haar</td>
</tr>
<tr>
<td></td>
<td>The potential enhancement of components produced by metal Additive Manufacturing using laser shock processing – Daniel Glaser</td>
</tr>
</tbody>
</table>
Claire Janisch
Biommicry SA
Director
Dargle, KZN, South Africa
biomimicrysa.co.za

Thursday November 9, 2017 | 09:45 - 10:30 | Meeting Room 12 Durban ICC

Tapping nature’s genius in 3D printing

BIOGRAPHY
As a Certified Biomimicry Professional, Claire spends her time exploring nature’s genius in diverse ecosystems and shares this new way of viewing and valuing nature through biomimicry expeditions and coaching—teaching & training professionals, students and scholars.

She also dives deeper into research for companies and organisations - translating nature’s innovation and sustainability principles for the design of new products, processes and systems.

Claire has a MSc Chemical Engineering in Clean Tech. She is both a graduate of and has been a lead trainer for the Biomimicry Professional Program offered by Biomimicry3.8. She is the Founder and Director of BiomimicrySA.
Michaella Janse van Vuuren
Nomili
Owner Engineer/Artist
South Africa
createneering.com | nomili.co.za

Thursday November 9, 2017 | 11:00 - 11:45 | Meeting Room 12 Durban ICC

Createneering

BIOGRAPHY
Dr. Michaella Janse van Vuuren’s work spans multiple disciplines from her PhD in Electrical Engineering from the University of Cape Town and post doctorate in medical implant design to being an internationally recognized 3D print designer, artist and consultant in education. In 2017 she was named as one of the 40 Most Influential Women in 3D Printing by All3DP.com. In 2012 she was the VISI emerging designer of the year and in 2014 she was named one of the City Press 100 world class South Africans.


Createneering is her most recent project. She is bringing her wealth of knowledge in the arts, design and engineering to education, developing courses that introduce technology learning playfully through the arts. Encouraging students to become createneers, individuals that use technology as tools to create and innovate instead of just being digital consumers.
BIOGRAPHY
Sarat Babu is founder of Betatype a company the specialises in enabling additive manufacturing for end users through expertise multi-scale design and scanning technologies for laser powder bed fusion.

Sarat has a background in Materials Engineering, Industrial Design and Adaptive Computation. He has extensive academic and commercial expertise in Additive Manufacturing and product development spanning over eight years.
Digitally Driven Engineering: an holistic approach to industrial and research problem solving

BIOGRAPHY
University educator for over 25 years, specialising in design technology, additive manufacturing and product development.

- Co-editor of the Rapid Prototyping Journal.
- Compiled two research texts in Rapid Prototyping by John Wiley.
- Co-author of Additive Manufacturing Technologies by Springer.
- Co-founder of the Global Alliance of Rapid Prototyping Associations.
- Published over 200 papers.
- Editorial advisory board member for three international journals.
- Member of organising committee for more than 25 international conferences, at least eight of them as chairman or similar.
- Regular keynote speaker on 3D Printing and Design Technology in Education.
- Specialities: Well-known researcher in additive manufacturing, more commonly known as 3D Printing.
- Experience in developing new applications like multi-material systems, micro-RP, and tissue engineering.
- Significant interest in virtual prototyping, focusing on medical systems using haptic interfaces. Developing a secondary reputation in the field of rehabilitative engineering and assistive technology.
EOS – Sponsor Presentation

BIOGRAPHY
Yusuf has a Diploma in Electrical Engineering and a Master in Industrial Engineering from the Technical University Munich.

He is currently the area sales manager at EOS where he is responsible for the Middle East and Africa (excluding Maghreb).
New process: High speed sintering (HSS) – Voxeljet

BIOGRAPHY
Mustafa Yagci (born in 1987) started at voxeljet in July 2016. After graduating at the Technical University of Munich with a degree in Mechanical Engineering & Management, he started to work as project and design engineer in the automotive industry. In this job, he got in touch with Additive Manufacturing. Meanwhile he also graduated as Sales Engineer.

As Sales Manager for 3D printing systems at voxeljet, he is responsible for Turkey, Africa, Middle East, Gulf States, Pakistan and South America.
Qualification of Additive Manufacturing Processes using In-Process Monitoring and Computed Tomography

Dr. Sven Cornelissen is a Senior Research Engineer at Materialise, Belgium. In the core R&D team of Materialise, he runs activities investigating Metal Additive Manufacturing. Applying his process optimization expertise, he develops state-of-the-art process characterization tools and algorithms, and provides leading edge process knowledge as well as process validation methodologies. The consolidation of this work translates into new software features for Metal AM.

Before joining Materialise, Sven held different positions at imec (Leuven, BE) in the field of nano and micro-electronics processing and characterization. He graduated in Engineering at the Technical University of Eindhoven in 2006, and received his PhD degree in Engineering from the Catholic University of Leuven in 2011.
Redefining Reality

BIOGRAPHY
Clive is one of few examples in the marketplace, of a sales consultant with an intricate knowledge of the value-selling process, coupled with engineering practice and the integration of design software. He currently heads up Business Development for the Durban branch of the Modena Group of Companies.

Being in the business of design for over 12 years, Clive started his career as a sales consultant for Sharp Electronics and worked his way up to a directorship in Modena Design Centre, Durban.

Clive is a visionary, who stands by the notion that design software, and the way it is currently evolving, will not only revolutionize the way we do business, but also how we build sustainably and make the world a better place, using technology as the conduit.

As the only Autodesk Partner in Africa that holds Platinum status, Modena Design Centre provides software solutions, training implementation & customization to Architectural and Engineering professionals.
Dr. Lionel Dean
Future Factories
futurefactories.com

Thursday November 9, 2017 | 15:40 - 16:10 | Meeting Room 12 Parallel B Durban ICC
Conference Track: Design for AM

Stepping out on a limb: The design and manufacture of a 3D Printed titanium prostheses

BIOGRAPHY
Dr. Lionel T. Dean’s specialism in Additive Manufacture (AM, aka 3D printing) began in 2002 with a one-year residency at the University of Huddersfield UK. The project, considered at the time to be blue-skies research, set out to explore the application of what were then termed Rapid Prototyping technologies in end-use manufacture and though that, mass customisation.

The project proved timely and quickly developed into a PhD thesis and from there to Dean’s formation of FutureFactories Studio in 2003. This presentation will consider 15 years of creative professional practice focused exclusively on Additive Manufacture. The projects presented range from gallery pieces to retail products for well-known manufacturers. They include works acquired by MoMA, The Museum for Modern Art in New York and DHUB, Design Museum Barcelona for their respective permanent collections.

In 2008 the MoMA piece was included in a ‘Highlights Collection’ of the Museum’s 250 most significant acquisitions since 1980. Dean’s work sits at the intersection of art, craft and design challenging traditional boundaries and definitions of practice. He employs the virtual realm as a creative playground where time plays a part and artefacts exist with past and future states. This is a space in which ephemeral designs exist beyond the physical constraints of material or process. The resulting artefacts are at once familiar and yet strange, exhibiting formal structure while defying the patterns and logic associated with industrialisation: the flora and forna of an alien landscape.
Journey to change the cycling industry with the help of additive manufacturing

BIOGRAPHY
At Calculus Bikes we believe there is no reason every rider should only have a choice of three frame sizes when choosing a bicycle.

We engineer each bike exactly according to our clients’ needs to build them their best riding dream bike using a range of techniques including additive manufacturing.
DENSITY OF SAND PARTS PRODUCED ON A VOXELJET VX 1000 THREE DIMENSIONAL PRINTER

N.P. Nhhasi1*, W.B. du Preez1, J.G. van der Walt1

ABSTRACT
Density of sand moulds and cores is an important foundry property to ensure production of quality castings. This property has not been assessed for sand parts manufactured by three-dimensional printing. This paper assessed the density of sand specimens printed on a Voxeljet VX 1000 using three types of refractory sands.

1. Introduction
Three-dimensional printing (3DP) has become a mainstream process for the production of sand moulds and cores for metal casting applications [1]. This additive manufacturing (AM) technology provided several advantages compared to conventional sand moulding and core making processes including the elimination of pattern and core boxes, the adaptability for complex geometry and the reduction of lead design time [2].

The density of sand parts achieved by AM has not been previously investigated. It is well established that this property is important as it fundamentally affects the final strength and dimensional accuracy of sand moulds and cores [3]. In addition, casting defects due to sand expansion (e.g. scabbings) and to alloy solidification (e.g. shrinkage and hot tears) are directly related to the final density of the sand mould.

The present paper assessed the density of sand parts produced by three-dimensional printing using Voxeljet VX 1000 equipment. Three different refractory sands are considered in the study in order to understand the interactions between the sand properties and the effects of the printer.

2. Methodology and results

2.1 Experimental procedure
The experimental work consisted of three steps including:

- Characterization of silica sands in terms of grain size distribution grain shape and specific gravity.
- Additive manufacturing of 15 AFS sand specimens for each type of silica sands.
- Sand specimens were weighted and the part density determined as the mass divided by volume.

Density test results were interpreted using descriptive statistics (mean and standard deviation) and two tails Fischer-Snedecor (F) statistical test to compare the standard deviations.

Figure 1 below shows the grain shape of the three different types of sands. It can be seen that the synthetic sand (c) is spherical and smooth. The imported silica sand (a) is elongated and angular. The local silica sand (b) lies between the two other type of sand in terms of roundness and angularity.
Table I below presents the means and standard deviations of the specimen density distribution obtained for the three types of sand. In all cases, the density achieved by 3DP is a poor fraction of the specific gravity of the based sands. The standard deviations of density distribution appear to vary for the three types of sand. The standard deviation for sand B ($\sigma_B$) is higher than the standard deviation for sand C ($\sigma_B$) which in turn is higher than the deviation for sand A ($\sigma_A$). This could at first glance suggest a variability of part densities induced by the 3DP process depending on the type of sand.

Table 1: Statistical results of various sands

<table>
<thead>
<tr>
<th>Sand Type</th>
<th>Mean of specimen densities $- \mu$ [g/cm³]</th>
<th>Achieved packing densities as percentage of specific gravity [%]</th>
<th>Standard deviation of specimen densities $- \sigma_x$ [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand A – imported silica sand</td>
<td>1.354</td>
<td>51</td>
<td>0.029</td>
</tr>
<tr>
<td>Sand B – local silica sand</td>
<td>1.477</td>
<td>55</td>
<td>0.040</td>
</tr>
<tr>
<td>Sand C – synthetic ceramic material</td>
<td>1.954</td>
<td>60</td>
<td>0.031</td>
</tr>
</tbody>
</table>

3. Conclusion
The study revealed that the density achieved during 3DP is only a poor fraction of the specific gravity of the based sand. The study appears to suggest that the density of sand parts produced by 3DP is mainly influenced by sand characteristics. Further research could investigate the variation of this density bias between the different types of printers for rapid casting applications.

REFERENCES
DENSITY OF SAND PARTS PRODUCED ON A VOXELJET VX 1000 THREE DIMENSIONAL PRINTER continued


1 Department of Metallurgy, University of Johannesburg, South Africa (dnyembwe@uj.ac.za)
2 Technology Transfer and Innovation, Vaal University of Technology, South Africa
3 Technology Transfer and Innovation Support, North-West University, South Africa
A CASE STUDY OF RAPID SAND CASTING DEFECTS

K.D. Nyembwe1*, K van der Walt2, D.J. de Beer3, E. Gonya1

ABSTRACT
The issue investigated in this study is the practical implementation of the rapid casting for tooling concept using locally available technologies. Rapid casting for tooling is a tool making process chain essentially consisting of metal casting in sand moulds obtained by rapid prototyping. The production of a sand casting pattern is the case study used to uncover and discuss possible sand casting defects occurring during additive manufacturing.

1. Introduction
Rapid casting for tooling (RCT) is one of the rapid tooling process chains proposed for manufacturing metallic tools [1,2]. It consists of five steps that include computer-aided design (CAD), casting simulation, additive manufacturing, metal casting and finishing operations. Basically in RCT, the tool or die is made by casting a suitable metallic alloy in a sand mould produced by additive manufacturing processes such as laser sintering or three-dimensional printing. Potential advantages of RCT over computer numerically control (CNC) machining comprise easy learning curve, suitability for producing foundry tooling and low overall processing cost. A study [3] conducted on the selection of the best additive manufacturing system available using the analytic hierarchy process (AHP) shows that the laser sintering process is the overall more suitable process for RCT when considering four criteria: manufacturing cost, manufacturing time, dimensional accuracy and surface finish.

This paper investigates a practical implementation of the RCT concept using a real case study obtained from the local foundry industry. No experimental trial of RCT has been published so far therefore tool and die makers do not know the technical challenges involved and how to resolve them. For example, what types of defects are prone to appear in the tool due to casting in sand moulds produced by additive manufacturing? Therefore the study contributes to the initial development of how to make and the building of knowledge management around RCT.

2. Methodology and results

2.1 Case study
The case study was provided by a local foundry and consisted of manufacturing a sand casting pattern for moulding with a Disamatic machine. This tool will be used as one of the two Disamatic machine plates for making greensand moulds for a steel engineering bonnet shown in Figure 1a.

2.2. Experimental procedure
The experimental procedure followed in the casting trial of the sand casting pattern is summarised in Table 1. The entire mould is made of four sand parts that were grown using an EOSINT S700 laser-sintering machine at the Centre for Rapid Prototyping Manufacturing (CRPM) at the Central University of Technology in Bloemfontein.
Figure 1

(a) Two-dimensional drawing of the steel bonnet to be produced using the pattern manufactured by RCT. (b) Final casting exhibiting some defects.

Table 1: Software, Equipment and Casting parameters used in trials of the sand casting pattern

<table>
<thead>
<tr>
<th>RCT steps</th>
<th>Experimental parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD modelling (Pro Engineering software: wildfire II)</td>
<td>• Filleting of designs (default setting of the casting toolbox software)</td>
</tr>
<tr>
<td></td>
<td>• Shrinkage allowance factor: 1.10</td>
</tr>
<tr>
<td></td>
<td>• 10 mm machining allowance added</td>
</tr>
<tr>
<td>Casting simulation (Magmasoft software)</td>
<td>• Objectives: complete filling of the mould and escape of air during pouring</td>
</tr>
<tr>
<td></td>
<td>• Iterations: 3</td>
</tr>
<tr>
<td>Rapid prototyping (SLS EOSINT S 700 machine)</td>
<td>• Standard operating parameters</td>
</tr>
<tr>
<td></td>
<td>• Curing of mould parts at 750° C</td>
</tr>
<tr>
<td></td>
<td>• Shell sand (silica)</td>
</tr>
<tr>
<td>Metal casting (gravity casting)</td>
<td>• Charge: Pig iron + steel scrap (Appendix 3)</td>
</tr>
<tr>
<td></td>
<td>• Induction melting</td>
</tr>
<tr>
<td></td>
<td>• George Fisher inoculation (Magnesium treatment)</td>
</tr>
<tr>
<td></td>
<td>• Pouring temperature: 1400° C</td>
</tr>
<tr>
<td>Finishing operation</td>
<td>• Sand blasting followed by fettling for the plate</td>
</tr>
</tbody>
</table>

Figure 1b shows a front picture of the final sand casting plate. The finishing operations included sand blasting and fettling to remove the casting runners. No machining of the cast pattern was performed. The picture shows the features of the component to be produced as well as the gating and feeding system. The casting picture also shows evidence of defects including:

• Cold lap mainly visible in the top half of the casting
• Shrinkage porosity in top right region
• Vertical alignment fault in the middle of the casting

3. Conclusions and recommendations
The case study illustrates the practical implementation of RCT using locally available technologies including
A CASE STUDY OF RAPID SAND CASTING DEFECTS
continued

CAD, casting simulation, additive manufacturing and casting. These are combined to constitute an alternative manufacturing of metallic tooling.

Although casting simulation predicts that the casting will be free of defects, this case study has shown that the RCT success also depends on exogenous factors such good workmanship during mould assembly and casting. These stages were found to be the most challenging.

REFERENCES


1* Department of Metallurgy, University of Johannesburg, South Africa (dnyembwe@uj.ac.za)
2 School of Mechanical Engineering and Applied Mathematics, Central University of Technology
3 Technology Transfer and Innovation Support, North-West University, South Africa
DETERMINATION OF THE OPTIMAL PROCESS PARAMETERS FOR INVAR 36 COMPONENT REPAIR, USING A LASER METAL DEPOSITION TECHNIQUE

R. Adam1*, A. Botes1, G. Le Roux2

ABSTRACT
Invar 36 is a low carbon ferrous alloy containing 36% nickel, with properties such as low thermal expansion coefficient, good formability and toughness. The main challenge of Invar welding is its susceptibility to reheat cracking. Laser based refurbishment is a suitable technology to repair cracks and dimensional defects on Invar components. A 3kW, IPG fibre laser was used to generate test coupons, to investigate the optimal process parameters for Invar welding. Results show that optimal fusion to the substrate is achieved at low heat inputs. Thermal expansion coefficient, Vickers micro-hardness and hot-spot evaluation results are all viable for the desired application.

1. Introduction
Invar 36 is an austenitic steel containing 36% nickel, the addition of nickel provides Invar with a very low thermal expansion coefficient, which remains almost constant up to temperatures of approximately 400°C. Thus, Invar is generally used for applications that require dimensional stability across a wide range of temperatures, such as manufacturing methods used in the aerospace industry. These applications are fairly bulky, and welding is generally used as the primary method of joining [1]).

Previous welding investigation studies on Invar, showed its acute sensitivity to solidification cracking. This is expected since Invar is an austenitic steel. The selection of the filler material used for the welding procedure is crucial in limiting the solidification, currently filler materials contain elements such as Ti, Mn and a greater percentage of carbon is used to reduce the effect of solidification cracking and porosity. The introduction of oxygen into the weld pool should also be limited in order to avoid cracking during the welding procedure [2].

Laser based refurbishment has been identified as a suitable technology to repair cracks and dimensional defects on Invar surfaces, since it is a high energy, low heat input process, with extremely fast cooling rates in excess of 2000°C/s. Due to the fast cooling rates, the deposited alloy forms unique microstructures i.e. extremely fine, which results in high hardness accompanied with high toughness [3].

2. Methodology and results

2.1 Methodology
The laser power was supplied by a 3 kW IPG multi-mode Ytterbium fibre laser with a feeding fibre of 200 um. A Precitec cladding head with a standoff of 193 mm between the nozzle interface plate and the work piece was used to give a resultant beam diameter of 2 mm on the workpiece. The clad layers were deposited on Invar 36 substrate coupons that were milled clean and wiped with acetone. Carrier gas flow rate was kept constant at 1.5 l/min and a shielding gas flow rate of 8 l/min.

A total of five layers were deposited on the Invar base metals, and cleaned of oxides by wire brush between
consecutive layers. Metallurgical evaluation was conducted by taking cross-sections through the clad layers and observing the samples using an optical microscope. Samples were also analysed using Vickers microhardness (traverse), thermal expansion coefficient measurements, and hot spot testing (infrared thermal camera).

The experimental parameters of the cladded layers are shown in Table 1.

### 2.2 Results
The resulting microstructure, defects and clad layer appearance are discussed and grouped in terms of heat input values i.e. line energy.

![Figure 1](image)

*Figure 1
Typical clad layer appearance for line energies a) 50-59 kJ/m, b) 60-69 kJ/m, c) 70-85 kJ/m and d) 90-99 kJ/m.*

<table>
<thead>
<tr>
<th>Sample nr</th>
<th>Laser Power (W)</th>
<th>Cladding Velocity (m/s)</th>
<th>Heat Input (kJ/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>1000</td>
<td>0.017</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>0.018</td>
<td>55</td>
</tr>
<tr>
<td>1A</td>
<td>1000</td>
<td>0.013</td>
<td>75</td>
</tr>
<tr>
<td>3A</td>
<td>1200</td>
<td>0.013</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>1200</td>
<td>0.02</td>
<td>60</td>
</tr>
<tr>
<td>3B</td>
<td>1200</td>
<td>0.023</td>
<td>51</td>
</tr>
<tr>
<td>5</td>
<td>1200</td>
<td>0.013</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>0.015</td>
<td>67</td>
</tr>
<tr>
<td>7</td>
<td>1000</td>
<td>0.013</td>
<td>75</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>0.011</td>
<td>92</td>
</tr>
<tr>
<td>9</td>
<td>1100</td>
<td>0.017</td>
<td>66</td>
</tr>
<tr>
<td>10</td>
<td>1100</td>
<td>0.013</td>
<td>83</td>
</tr>
<tr>
<td>11</td>
<td>1100</td>
<td>0.012</td>
<td>94</td>
</tr>
<tr>
<td>12</td>
<td>1100</td>
<td>0.02</td>
<td>50</td>
</tr>
<tr>
<td>13</td>
<td>1100</td>
<td>0.015</td>
<td>67</td>
</tr>
<tr>
<td>14</td>
<td>900</td>
<td>0.015</td>
<td>60</td>
</tr>
</tbody>
</table>
DETERMINATION OF THE OPTIMAL PROCESS PARAMETERS FOR INVAR 36 COMPONENT REPAIR, USING A LASER METAL DEPOSITION TECHNIQUE continued

Metallographic evaluation of the cladded layers revealed that good fusion was obtained between the base metal and clad layers for all samples produced. Process parameters that resulted in thicker layers showed a greater tendency to form cracks within the clad layers. The cracks primarily occur at the grain boundaries of large columnar grains. All samples produced showed some degree of porosity, with limited porosity for the cladded layers with line energies between 60–69 hJ/m.

Vickers micro-hardness results of the cladded layers did not show any metallurgical notch, or hard phases present in the cladded layer, HAZ, or the base material.

The coefficient of thermal expansion (CTE) values of two build-up samples (cladded layers) and base materials were determined to be 1.32 x 10^-6/°C, 1.51 x 10^-6/°C and 2.45 x 10^-6/°C, respectively within a temperature range of 25°C to 180°C, under annealed conditions. Results from the cladded samples are lower than that of the base material, and the variation is relatively low (0.94 x 10^-6/°C).

A FLIR infrared camera was used to determine whether the samples had hot spots, no hot spots were observed over a cycle period of 24 hours at 180°C.

3. Conclusion
In conclusion, heat inputs in the range of 60–69 hJ/m are suitable for repairing Invar moulds. The heat input is sufficient to prevent reheat cracking and obtain good fusion with the base, and limits the porosity produced in the samples. Since no metallurgical notch is introduced from the cladded layer down to the base metal, it is evident that the process does not alter the hardness of the properties. Similarly, a lower CTE than the base material shows that the process improves results and should therefore not adversely affect the Invar components.

REFERENCES

1 Council of Scientific & Industrial Research, South Africa (radam@csir.co.za)
2 Tool Room & Maintenance, Denel Aerostructures, South Africa
LOW-COST TOOLING AND MACHINERY: ADDITIVE MANUFACTURING AND OPEN-SOURCE MACHINES FOR THE SOUTH AFRICAN SETTING

M. Bolton

ABSTRACT
The tooling and machinery costs associated with plastic component manufacture are generally considered extremely high and inaccessible to small-scale and batch product manufactures. This paper serves as a technical overview of the fabrication of low-cost open-source machinery which were used for the experimentation with plastic recycling, and 3D printed press-form tooling for sheet metal forming. This was undertaken as experimental research in the department of Industrial Design at the University of Johannesburg with the aim of developing appropriate low-cost tooling and machinery for use within the South African setting.

1. Introduction
The availability of waste plastic from food and beverage packaging may be considered an available source of stock plastic for manufacturing elements of some products, if lower cost machinery and tooling were to be available. Similarly the availability of standard metal sections and basic metalworking machinery are universal. A range of open-source plastic recycling machines have been developed by Netherlands based Dave Hakkens as part of his graduate project at the Design Academy Eindhoven in 2013 titled Precious Plastics [1]. Machines that were developed include a plastic shredder, an extruder, injection moulder and a press-form moulder which can all be fabricated from low-cost and available materials using minimal tools (Figure 1).

2. Method

2.1 Machine fabrication
Several of these machines have been fabricated at the Department of Industrial Design, University of
Johannesburg to assess the effectiveness thereof for the South African context. These machines included the plastic shredder, injection moulder, and an adaptation of the press-form moulder.

These machines allow for a basis for the testing and experimenting with low-cost press-form tooling made through additive manufacture (AM), resin casting and mild-steel fabrication. Thus far the machines have proved effective for recycling polyethylene (PE) plastic from household plastic into small bowls, plates and plastic sheet stock. The press-form moulder operates with clamping force applied from a small automotive hydraulic, which operates at a much lower pressure than industrial machines, coupled with a bed area of approximately 400 x 300 mm that allows for a multi-functional platform.

To form a product using this machine using PE plastic, shredded plastic particles are placed within a mould half (plastic forming will work only with mild-steel mould halves) and this in turn is inserted into a standard household oven which softens the plastic. Once the plastic has softened sufficiently, the mould can be removed from the oven and placed in the press-form moulder and clamping pressure applied. The same machine with two mild-steel plates allows for sheets to be manufactured from the waste plastic. With the 3D printed moulds the machine serves as a sheet-metal forming machine for subtle forms at this stage, as the strength of the mould is the area of weakness.

2.2 Tooling fabrication
Various types of tooling were manufactured: some 3D printed using FDM in ABS plastic, and some were fabricated from mild-steel. The 3D printed tooling has proved effective for press-forming thin-gauge aluminium, and the fabricated mild-steel tools were used for press-forming components from recycled shredded PE plastic. An example is shown below (Figure 2).

Figure 2
Press-formed PE condom carrier prototypes and low-cost tooling. Photo by author.

Types of machines fabricated:
• Plastic shredder (adapted Precious Plastics design)
LOW-COST TOOLING AND MACHINERY: ADDITIVE MANUFACTURING AND OPEN-SOURCE MACHINES FOR THE SOUTH AFRICAN SETTING continued

- Press-form machine (adapted Precious Plastics design)
- Injection moulding machine (adapted Precious Plastics design, final stages awaiting heating components)

Types of tooling fabricated and tested:
- 3D printed ABS tooling for press-forming thin-gauge aluminium
- Resin cast tooling (from 3D printed patterns) for press-forming aluminium and plastic

3. Conclusion
Although the samples, which have been moulded, formed and shaped in these machines are relatively basic in complexity, it serves as a step in the right direction for low-cost tooling and manufacturing systems that may prove beneficial for the South African setting. Further developments in the machinery and tooling composition will allow for more complex components to be manufactured, using more appropriate and accessible machines and in turn empowering small-scale manufactures to utilise waste material to manufacture products in-house as opposed to outsourcing to larger-scale manufacturers.

REFERENCES

1* Department of Industrial Design, University of Johannesburg, South Africa (mbolton@uj.ac.za)
CHARACTERISATION OF ALUMINIUM ALLOY STRUCTURES PRODUCED BY HIGH SPEED SELECTIVE LASER MELTING TECHNOLOGY

N.R. Mathe, L.C. Tshabalala

ABSTRACT
The purpose of this paper is to demonstrate the process window for additive manufacturing of aluminium alloy metal powder using high-speed selective laser melting technology. In this study, the higher levels of laser power and laser scan speed were used to evaluate the effects of processing parameters on the part building using the aluminium master alloy, AlSi10Mg. The manufactured specimens produced were structurally dense cubes with the desired microstructure and porosity of an AlSi10Mg metal.

1. Introduction
Selective laser melting (SLM) is a technique that allows for the building of components using a laser to melt powder layers [1]. This is a process that involves rapid heating and cooling of the metal powder, and therefore it is important to understand the consolidation properties of the metal powders. SLM is used because it results in strong, homogeneous, high tolerance and complex near-net-shape components. Research in SLM has revealed that the process parameters or scanning strategies have an influence of the porosity, part density, microstructure and mechanical properties of the built part [2].

For the purpose of this work, aluminium alloys will be studied to determine their consolidation properties as a result of the processing parameters. Aluminium silicon alloys are characterised by high strength-to-weight ratio, good weldability, alloying magnesium to the Al–Si alloy enables the precipitation of Mg2Si strengthen the matrix to a significant extent without compromising the other mechanical properties [3]. The AlSi10Mg alloy used in this study is therefore relatively easy to process by laser applications due to the near-eutectic composition of Al and Si which is known to lead to a small solidification range, compared to high strength aluminium alloys. Therefore the successful printing of Al parts will contribute to the decrease of weight in aircrafts without the loss of the engineering/mechanical properties required in such high-end applications.

The aim of the research is to design experiments to evaluate process parameters and determine the relationship between the parameters and the part properties focusing on microstructure, density and porosity. Although some research group use lower laser power due to preheating, [4, 5], the focus of this work will be on high power.

2. Methodology and results

2.1 Methodology
The SLM experiments were planned according to the factorial design of experiments using Design Expert 8 software. The laser power and scan speed were varied at the first phase of the experiment to determine the ideal processing parameters for the high speed and high power consolidation of Al alloys. The parameters for building cubes are presented in Table 1; in this case, the processing parameters were narrowed to build the cubes. The laser power was varied from 600 W to 1000 W and the scanning speed was varied from...
750 mm/s to 1500 mm/s. This resulted in the building of 12 cube samples. As-built samples were mounted, polished and viewed under the optical microscope before and after. The specimens were characterised using the optical microscope to evaluate microstructure, density and porosity of the laser scan path patterns.

2.2 Results
The elemental composition was compared with the TLS powder specifications. As observed from the SEM-EDS results in Table 2, the composition obtained is within the manufacturer’s specification range.

Table 1: Elemental analysis of AlSi10Mg powder

<table>
<thead>
<tr>
<th>Sample</th>
<th>Al (at.%)</th>
<th>Si (at.%)</th>
<th>Mg (at.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlSi10Mg-new</td>
<td>93.2 ± 0.07</td>
<td>5.77 ± 0.03</td>
<td>1.02 ± 0.02</td>
</tr>
</tbody>
</table>

The built cubes are grouped based on the laser power and scanning speed as presented in Figure 2. The as-polished samples were analysed under an optical microscope to determine the microstructure and presence of pores experienced during laser processing, which are seen as black areas in the images. The presence of keyhole pores (small black spots) in Fig. 2b exhibits oxide pores at the bottom left corner. These types of pores were also observed by Thijs et al. [5], which they attributed to the heat accumulated at these points of the scan path. After etching, the samples showed patterns consistent with the melt pool created by laser scan tracks during the melting of the powders followed by rapid cooling. These patterns can be attributed to the laser-processing pattern where an overlap in the laser path is expected based on the hatch spacing, which was set at 0.12 mm overlap in these experiments. Finer microstructures were observed at lower scan speed while higher scan speeds showed combinations of fine microstructure and bigger melt pool areas.

Figure 2
Optical images of the as-polished and etched AlSi10Mg samples processed at varied laser power and scanning speeds resulting in energy densities of; (a) 167, (b) 133 and (c) 111 J/mm³
3. Conclusion
The microstructure of cubes produced by the SLM process was investigated. The microstructures consisted of laser scan path patterns in varying sizes, reflecting the rapid heating and cooling of the laser during processing. Due to the moving heat source, the thermal gradients and growth rate varied over the melt pool revealing cell size distinguished by melt pool tracks. A more homogeneous and fine microstructure was obtained for the lower energy densities, with more oxide and keyhole pores observed for the medium energy densities.

REFERENCES

*National Laser Centre, Council of Scientific & Industrial Research, South Africa (nmathe@csir.co.za)*
EVALUATION OF A CARBON FIBRE POWDER SCRAPER USED IN METAL ADDITIVE MANUFACTURING

D. Bester¹*, H. Wichers², H. Moller¹

ABSTRACT
Powder bed fusion is an additive manufacturing process, which builds parts, layer-by-layer, by melting the cross-section of the part onto a powder layer. Aeroswift is a PBF machine, designed and built in South Africa. A powder scraper was designed which would be flexible, work for extended periods of time and have the ability to operate at high temperatures. In this study, the process of development toward carbon fibre scrapers and the evaluation for comparison to commercially available scrapers is explained. Results showed that the carbon fibre powder scraper is comparable to commercially available scrapers such as those produced by EOS, and is a viable solution for Aeroswift.

1. Introduction
Powder bed fusion (PBF) is an additive manufacturing (AM) process that produces a part by building it layer by layer. This is done by melting the cross-section of the part onto a powder layer, using a laser beam and scanner. The build platform moves down by one layer thickness (typically between 20 and 50 µm), a new powder layer is added and the next cross-section is scanned. This process is repeated until all the cross-sections are scanned and a completed component printed. The cross-sections are obtained by running the computer-aided design (CAD) model through slicing software.

Aeroswift is a PBF machine, designed and built in South Africa, which has a build volume of 2000 x 600 x 600 mm³. Due to the large width of the build platform, a custom powder scraper was designed. The quality of a powder layer is very important in PBF processes and influences the surface roughness of a built part and, to a certain extent, its dimensional accuracy. This powder scraper had to fulfil the following specification:
1. Operating temperature of 600oC: the machine has a preheat temperature of up to 600oC.
2. Flexible: due to known defects in PBF, such as warpage and balling, a flexible powder scraper is required that would be able to deal with these defects without failing.
3. Durable: the powder scraper should be able to operate for extended periods, as at full capacity, a build could be as much as 12 000 layers.
4. Consistent powder layers: consecutive powder layers should not differ much from the previous layer.
5. Smooth surface: the powder layers produced should have a good surface roughness and should be uniform throughout.

After implementing the powder scraper, test builds were conducted for parameterisation. Excessive roughness of consolidated layers caused premature failure of the powder scraper. It was uncertain whether the failure was due to unsatisfactory powder layers or due to the lack of optimised parameters. Thus, a quantitative method to determine the quality of the powder layer was needed, to show if the layer produced by the powder scraper was sufficient or not. The quality of the powder layer refers to the flatness of the layer.
Therefore the research objectives are:

- Devise a method for a quantitative evaluation of the performance of a powder scraper.
- Use the devised method to evaluate the developed powder scraper of the Aeroswift system.

2. Methodology and results

A literature study was conducted to investigate possible solutions to the first research objective. In the study conducted, no literature could be found on the qualification of powder scrapers used in AM. However, two viable solutions were identified. The first being that from the research done by Craeghs et.al. [2], which uses a camera and lighting to look at the shadows cast by defects in the powder layer, and the second being a Laser Line Scanner (LLS). After further investigation it was determined that the Laser Line Scanner is the better option, as the camera and light method is not as accurate.

A LLS obtains the line profile of a surface by using triangulation to calculate distance from the sensor to the points in the laser line projected onto the surface. The particular LLS that was used is Micro-Epsilon’s ScanCONTROL 2960-50/BL, which has a z-resolution of 4 µm. The laser line has 1280 points over a width of 60 mm and results in an x-resolution of 40 µm. For every point in the line profile the x- and z-values are given.

2.1 Experimental set-up

The preliminary tests were done inside the Aeroswift machine. The LLS was mounted on a motorised translation stage, for linear movement in the x-direction, and the powder deposition system used for the y-direction travel of the powder scraper to scrape the layers of powder. A laptop was used to run the LLS’s software and motion control for the translation stage. The powder deposition system was moved with the machine control panel. Spherical titanium (Ti6Al4V) powder was used with a particle size distribution of 20-60 µm. Three different powder scrapers were tested: a solid blade scraper, an EOS produced carbon fibre brush scraper and the Aeroswift custom carbon fibre brush scraper. The blade scraper was included to give a baseline for comparison because it produces a near perfect powder layer. The EOS scraper was chosen in order to make a comparison with a commercially used carbon fibre brush scraper.

2.2 Experimental procedure

The powder used in the tests was dried at 120oC to ensure optimum flowability for the tests. The scraper height was set to scrape a layer more or less 0.5 mm thick. The LLS was set-up so that the laser line is parallel to the powder scraper and level with the build plate. A small amount of powder was dropped in front of the scraper and scraped over the build platform with the powder deposition system. Six line profiles were captured with the LLS to cover 360 mm of the 640 mm bed due to travel limitations of the translation stage. The data obtained was processed in Excel and the following was obtained:

- Median line equation for each line profile (to allow for misalignment of the laser line with the build plate).
- The distance for each point in the line profile to the median line.
- Determination of whether a point in the line profile is a peak or a valley.
- Total amount of peaks and valleys.
- The distribution of peak and valley sizes given inside 20 µm intervals (0-20 µm, 20-40 µm, etc.).
The results for all six line profiles were combined to give an overall result. These results were then compared with one another.

2.3 Discussion of results

Preliminary test results showed that in some sections the Aeroswift scraper achieved equal performance and in some instances improved performance compared to the EOS produced scraper. However, in other sections it performed worse. The reason for the inconsistency could be tied to the method of manufacturing, as the EOS scraper is manufactured in large quantities in an automated process, whereas the Aeroswift scraper is manufactured in-house by hand. None of the scrapers had defects larger than 80 µm.

3. Conclusion

It is thus concluded that a LLS can be used to quantitatively evaluate the performance of a powder scraper and that this method can be used to evaluate the custom carbon fibre brush powder scraper used in the Aeroswift system. This scraper achieved comparable performance to a commercially used carbon fibre brush scraper. However, some improvements can still be done regarding the manufacturing process, which would further improve the powder scraper’s performance. This project did not take into account the durability of the powder scraper and it is suggested that this is done in future work.
REFERENCES


*National Laser Centre, Council for Scientific and Industrial Research, South Africa (dbester@csir.co.za)*

*Department of Mechanical Engineering, North-West University, South Africa*
RAPID SAND CASTING TRIALS USING A LOCAL CERAMIC SAND

O. Dady*, K. Nyembwe1, M. van Tonder2, D. de Beer3

ABSTRACT
Silica sand is the preferred refractory sand used for rapid casting applications. However this moulding raw material is known to have important limitations with regard to the quality of the final casting. The present paper explored the possibility of using ceramic sand as an alternative to silica sand for additive manufacturing using a Voxeljet VX 1000 printer. The properties of the sand parts produced with the ceramic sand were found to be comparable to the one obtained with silica sand.

1. Introduction
Rapid sand casting refers to the application of additive manufacturing (AM) for the production of sand moulds and cores used for metal casting [1]. Silica sand is the refractory sand of choice in most of the existing AM technologies. This is essentially due to the large availability of the silica sand material, its low cost and good quality of general castings. Special sand casting applications require alternative refractory sand in place of silica sand due to its technical limitations including low refractoriness, high thermal expansion and low reclamation yield [2]. The popular non-siliceous sand for foundry applications include among others chromite sand, olivine sand and zircon sand. Recent advances in the field of foundry refractory sand relates to the production and use of alumino-silicate based ceramic sands. These synthetic sands have spherical shaped grains and better anti-burn-on, thermal expansion and reclamation yield properties compared to natural occurring foundry sands.

No trials have been conducted or results published in literature on the use of ceramic sands for rapid sand casting applications. The objective of this paper is to assess the mechanical properties of sand parts produced by AM using a ceramic sand locally manufactured. The achieved mechanical properties with the ceramic sand are compared to the properties of imported and local silica sands commonly used for AM.

2. Methodology and results

2.1 Experimental procedure
A four steps methodology including raw material characterisation, sand preparation, additive manufacturing and sand testing was followed for this investigation. Table 1 presents the elements of the experimental work with the related techniques and equipment used.

2.2 Sand testing results
Figure 1 shows the strength test results in terms of tensile and bending for the three different types of sands. It can be observed that the ceramic sand appears to yield a stronger tensile behaviour than the imported and local sand, possibly due to the well-rounded and high sphericity shape of the sand particles. On the other hand, the local sand seems to generate the highest mechanical property in term of bending strength as compared to the imported and ceramic sands conceivably because of its optimum sand grains size and shape.
3. Conclusion
The objective of this investigation was to assess the mechanical properties of ceramic sand parts produced by AM. The initial results seem to indicate that higher mechanical properties could be achieved with ceramic sands compared to silica sands owing to the spherical grain shape morphology of the ceramic sand. Future
RAPID SAND CASTING TRIALS USING A LOCAL CERAMIC SAND continued

studies should include three dimensional printing of full moulds to complete the performance assessment of the ceramic sand by considering its resistance to the sand defects due to the AM process.

REFERENCES

1 Metal Casting Technology Station, University of Johannesburg, South Africa (odady@uj.ac.za)
2 Technology Transfer and Innovation, Vaal University of Technology, South Africa
3 Technology Transfer and Innovation Support, North-West University, South Africa
NOTES
LENS PRODUCED BINARY TiAl STRUCTURE: EFFECT OF HEAT-TREATMENT

T. Lengopeng, S. Pityana, L. Tshabalala, M. Tlotleng

ABSTRACT
Titanium aluminides are light in weight and have good thermo-mechanical properties at elevated temperatures. Meanwhile, binary TiAl structures lack ductility at room temperature hence they are impossible to form into structures by conventional casting methods. In this work, a process development to study the binary alloy structure of the laser in-situ alloyed Ti and Al using the Laser Engineering Net Shaping (LENS) System is reported. The microstructures of the produced TiAl were initially heterogeneous and homogenised with heat treatment. The overall hardness of the samples was 444 HV0.5 (As-produced) and 582 HV0.5 (heat-treatment), respectively.

1. Introduction
The use of titanium aluminides (TiAl) as high temperature materials has become a reality since their early research and development. Their lightweight and mechanical properties at elevated temperatures make them attractive as high temperature structured materials necessary for the aerospace and automotive industries [1-2]. Binary TiAl structures lack ductility at room temperature hence they are impossible to form into structures by conventional methods such as casting and forging. According to the available phase diagrams, when Ti and Al are reacted, thermodynamically, they will form 3 stable intermetallic phases of TiAl. The relevance of the thermodynamic stable of the binary TiAl to structural engineering has been studied over the years. It has become noticeable that the $\gamma$-TiAl is more valuable when compared to $\alpha_2$-TiAl and dual phase ($\alpha_2+\gamma$)-TiAl. But there are competing arguments and hence development is now tailored towards the part being manufactured. This study looked at the possibility of using the laser melt-pool to alloy Ti and Al into a binary structure of TiAl while studying its composition, texture, appearance and heat treatment profile. Even though binary TiAl have low ductility at room temperature, the use of additive manufacturing (AM) in fabricating structure out of it is yet to be reported. Meanwhile, to improve on their ductility, research and development make use of ternary and quaternary alloys among others [3]. The idea is that the extra metal(s) added to the master alloy (TiAl) will improve on one or many properties relating to performance of the alloy being generated.

To manufacture high value components of TiAl alloys casting is still found to produce heterogenous microstructures while AM technologies like electron beam melting seem to be achieving desirable TiAl products with correct specifications. While AM technologies are able to achieve desired results, they are still dependent on the powder metallurgy (PM) routes where they still dependent on an alloy being manufactured before manufacturing. The current authors believe that the PM step in AM manufacturing can be removed when a powder blown AM platform is used. Therefore, it is our consensus that the overall process-to-market, if the PM stage is not eliminated, could be expensive and therefore limiting. The Additive Manufacturing Research Group in the Laser Enable Manufacturing Division at NLC CSIR, Pretoria is looking to manufacture and circumvent expensive production of TiAl structures by using the LENS platform. In their approach they seek to make TiAl structures from elemental powders using the laser in-situ AM alloying approach. The phenomena here is such that the laser created melt pool will be able to convectionally mix
the elemental powders into a TiAl alloy when correct thermodynamics are met. In this paper, a binary TiAl alloy was produced using the proposed in-situ alloying mechanism. The binary TiAl alloy was studied for the microstructure with light optical and scanning electron microscopes, composition using SEM-EDS and XRD while overall hardness of the produced alloy was measured using the Vickers micro-harness machines.

2. Methodology and results

2.1 Methodology
A 1 kW laser power, Optomec LENS platform was used to produce the TiAl alloy studied in this paper. The processed powders were pure aluminium and a master alloy consisting of Grade 1 and commercially pure titanium. Argon gas was used as the carrier gas and for purging oxygen off the processing chamber during manufacturing. For processing, effects of laser power (W), carrier gas (l/min), powder flow-rates and composition were investigated. The results reported here are from the optimised process parameters when the laser power output was 400 W. The manufactured samples were characterised for appearance using Olympus optical light microscope and Joel JSM-6010PLUS/LA SEM with EDS, composition using SEM-EDS and X-ray diffraction. The produced samples were heat treated at 1400ºC under Argon environment. Zwich/Roell Indetec (ZHVµ) was used for measuring the micro-hardness of the produced alloy.

2.2 Results
Figure 1 presents the produced results of the laser in-situ alloyed Ti-Al before and after heat treatment.

Figure 1 shows the microstructures of the LENS manufactured TiAl alloys. Figure 1 show the (a) as-produced and (b) heat treated binary TiAl. The microstructure after heat treatment is similar to that of a gamma phase (γ-TiAl) alloy [2]. According to the EDS analyses (atomic, %) our alloy had a composition of 48Al and 52Ti after heat treatment at 1400ºC and was homogenous when compared to the As-produced TiAl structure as depicted. The As-produced structure had a composition of 35Al and 65Ti and had a fuzzy microstructure that was inhomogeneous. This structure is similar to that of the Ti-46Al-9Nb alloy that is reported by Clemens et
LENS PRODUCED BINARY TiAl STRUCTURE: EFFECT OF HEAT-TREATMENT continued

al [2] at the GKSS Research Centre. XRD diffraction pattern of this alloy conclude that the major peak was of a duplex nature (α2/γ). The overall hardness of this alloy was 444.4 HV0.5 and 582 Hv0.5 before and after heat-treatment, respectively.

3. Conclusion
We have successfully studied the laser in-situ alloying technique in the quest to producing TiAl alloy(s). A dual phase TiAl binary alloy was produced which was then homogenised with the use of heat-treatment. The observed grains are ≥200 microns and no crossed lamellar [2] could be identified within them. The observed lamellar are finer within coarser grains leading to an inference that this alloy is not ductile. Meanwhile a hardness value of 580HV was reported for the heat treated structure.

REFERENCES

Additive Manufacturing Research Group, Laser Enabled Manufacturing, National Laser Centre, Council of Scientific & Industrial Research, South Africa (mtlotleng@csir.co.za)
2 Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, South Africa
3 Department of Mechanical Engineering Science, University of Johannesburg, South Africa
EVALUATION OF TUNGSTEN-TITANIUM COMPOSITE CARBIDES AND THEIR VIABILITY FOR PRODUCTION USING SELECTIVE LASER MELTING APPLICATIONS

M.C. Van Coller1*, C.M. Olivier1, D. Du Toit1, G.A. Oosthuizen1, N. Sachs2

ABSTRACT

Metal matrix composites have garnered interest from several industries in recent years. They offer an exceptional balance of mechanical and physical properties, which can be varied to include beneficial traits offered by both metals and ceramics. Originally, tungsten (W) and titanium (Ti) composites were researched in the 1980’s in an attempt modify the material characteristics of tungsten carbide. Today they are widely used in the production of high performance hard metals, due to their improved high temperature characteristics and resistance to diffusion and oxidation. It is also well known that tungsten carbide coated titanium alloys have significantly improved tribological properties compared to that of titanium itself. These composites are capable of catering to a diversity of applications in specialist industries i.e. dental, tooling, aviation, and electronics. These sectors operate with customised materials that continuously evolve in complexity as manufacturers innovate their products. Additive manufacturing, when compared to standard manufacturing applications, has superior process flexibility and can produce highly complex parts with relative ease. Thus, the manufacturing of tungsten carbide and titanium composites via selective laser melting may improve the current supply chain capabilities for part production and refurbishment within the above-mentioned industries. This study aims to investigate the current state of technology regarding tungsten titanium composites and evaluates the feasibility of producing such components with selective laser melting.

1. Introduction

The most distinct advantages of selective laser melting (SLM) is the versatility of compatible materials, which has resulted in multiple new metallic powders being developed for use in SLM machinery within recent years. SLM allows for part production without any tools, whereas conventional manufacturing methods require dedicated tooling such as moulds and dies. The technology may open up new avenues for innovative manufacturing methods and material composites to satisfy niche requirement markets [1].

Titanium has a high strength-to-density ratio sought after by aerospace industries and exceptional resistance to halides which is beneficial for chemical plant applications [2]. These industries often have strict quality control standards in terms of material wear and heat resistance. Although titanium possesses good high temperature load bearing characteristics, it has low thermal conductivity. If heat is induced at its surface it will not dissipate through the rest of the part, which may cause microstructural weak points from which cracks can propagate [3]. Poor tribological properties are also prevalent in titanium alloys, affecting their performance when subjected to stark friction conditions. This renders material composite modifications as a necessity to improve wear resistance [4].

Tungsten, however, provides excellent wear resistance characteristics, good strength, thermal stability and low levels of thermal expansion. These features contribute to its extraordinary reliability, which is also a necessity in the above-mentioned industries. A drawback of the material is that its strength decreases
drastically with an increase in temperature. For instance, compared with that at room temperature, the strength of tungsten at 1000°C decreases by approximately 60%. Several successful studies have been conducted regarding the improvement of tungsten’s mechanical properties by addition of dispersed second particles to form metal matrix composites (MMC). The particles have a restricting effect on tungsten’s dislocation motion and grain growth, leading to increased strength and controlled creep rates at high temperatures [5].

This paper will focus on tungsten–titanium composites in an effort to highlight research avenues where the exceptional hardness and wear resistance of tungsten carbides may be combined with titanium’s strength and versatility at high temperatures. For example, this material combination has been found useful in structural applications by increasing the compressive toughness of titanium alloys through the addition of tungsten wire supports [6]. Furthermore, for tungsten carbide surface modifications, titanium coating layers have been added to the cermet via electrical discharge coatings (EDC). The results yielded an improved surface finish which eliminated micro cracks and in turn increased the surface hardness of the carbide from 990 HV to 1750 HV [7].

The production of composite parts utilising SLM has not been researched thoroughly as of yet. This review will evaluate current industry norms regarding the manufacturing of these composites and consider advances in SLM technology that may facilitate the emergence of newly proposed process chains for producing tungsten–titanium composites.

2. Methodology

2.1 Overview of tungsten titanium composites and SLM
Selective laser sintering (SLS) technology was developed in 1987 at the University of Texas, the process is nearly identical to that of SLM, although the machinery utilised is subject to a different patent, which legally requires alternate naming. The technology has evolved significantly in recent years, especially since additive manufacturing (AM) technology has become popular among mainstream consumers. Due to the flexibility of materials and complex geometries compatible with SLM, it may be the most effective solution in many niche industries including that of composite materials [1]. MMCs were still an emerging technology in the first half of the 20th century. Hereafter development was accelerated due to the primary motivation of advancing military systems. As engineers and manufacturers gained experience within the field, commercialisation took its toll and the sector flourished into a dynamic industry wherein titanium and tungsten have been the subject of various research efforts due to their unique material properties [8].

2.2 Identify current powder metallurgy manufacturing processes to produce composite parts
Before new technologies are investigated, the current industry preferences must first be identified and thoroughly understood. The paper will focus on powder metallurgy manufacturing processes currently in use to produce composite parts and coatings. This includes varying powder gradings between processes and any necessary operations postproduction.

2.3 Identify existing SLM procedures of producing composite parts
The production of composite materials utilising SLM technology is a relatively novel field, especially
pertaining to research conducted on abrasion resistant coatings. In some cases, the coatings were first manufactured with SLM in a shell-like fashion and then applied onto the substrate material via brazing [1].

2.4 Evaluate SLM capabilities to produce tungsten titanium composites
The production of tungsten titanium composites via SLM technology will be evaluated in terms of:
- Powder availability
- Powder grading and particle size
- Process efficiency compared to conventional process chains

3. Conclusion
From the results employees were exposed to detectable levels of various metals in powder form (as total inhalable dust) during pre-processing, processing and post-processing tasks. Several metals were detected in respiratory exposure samples, which included aluminium, cobalt, chromium, copper, iron, nickel, titanium and vanadium in powder form. AM operator exposure to individual metals will be compared to permissible legislative exposure levels. The results from the direct read instruments indicated that airborne particles are emitted in the workplace atmosphere during pre-, processing and post-processing. It was found that exposure to different metals smaller than 300 nm in size is also evident in some instances.

4. Conclusion
The main contribution of this paper was to review the current manufacturing technologies available for producing popular tungsten titanium composites and to compare them to the SLM process chains in order to determine the feasibility of the proposed AM alternative for future applications.

REFERENCES


"Department of Industrial Engineering, Stellenbosch University, South Africa (17693195@sun.ac.za)
School of Chemical & Metallurgical Engineering, University of the Witwatersrand, South Africa"
QUALIFICATION OF ADDITIVE MANUFACTURING PROCESSES USING IN-PROCESS MONITORING AND NDT

T. Craeghs*, S. Cornelissen¹, M. Pavan¹, P. van den Ecker¹

ABSTRACT
Additive manufacturing has a bright future for manufacturing of complex high-end functional applications. An important challenge is, however, in the qualification of the additive manufacturing processes, especially for critical parts in for instance aerospace or the medical industry. Qualification can be defined as ‘the collection of sufficient data to demonstrate that a material or process will function as expected’. For additive manufacturing two different sources of data are seen as important, namely data captured during the process data (so called ‘in-line measurements such as melt pool measurements, acoustic signals,...’) but also ‘post-build’ part and material quality data measured with non-destructive testing techniques such as computed tomography. The Materialise software platform enables to collect and analysis these data, in order to perform an important task in qualification: determine meaningful correlations between different signals. This work will first present the overall principle and different components of the platform and second how the platform can be used via description of case studies.

1. Introduction
Additive manufacturing (AM) is an excellent manufacturing technique for manufacturing complex functional parts. Recently, large companies in aerospace and the medical industry have shown interesting cases of how AM can be used to generate e.g. large cost savings in terms of fuel consumption. These examples clearly illustrate that the current state-of-the-art of AM processes allows the manufacture of excellent materials, and accurate parts with good functional requirements. Also many academic groups show consistently good results for the different material attributes of AM materials such as the density [1], static and dynamic properties [2,3].

The main challenge is however in the qualification of the processes: how to ensure in a cost efficient manner that during the whole manufacturing period, in any of the circumstances, a consistent quality over the build process can be guaranteed. This is extra complex because of the fact that (internal) features are difficult to inspect. Once all processes have been qualified the manufacturer should have a complete understanding of the process design and have a framework in place to routinely monitor operations.

An important goal in qualification is in understanding and quantifying variations in a given process. There are two types of variations: natural variations (always present, but stochastically) and non-natural variations (sometimes present, but deterministic). It is important to understand sources of non-natural variations and to quantify the amount of natural variation. This paper will first of all define a methodology of how to capture data in a systematic manner, and which data analysis can be done for AM. This approach will be illustrated with two case studies where the methodology has shown to understand two important effects: porosity at vector start-up and local warpage due to thermal stress.
2. Methodology and results

2.1 Software platform

Figure 1 shows the typical workflow in AM, which comprises design of the part, platform preparation (positioning of the part on the build platform), data preparation (determination of the tool path), building of part including monitoring of the process and the post-build quality control using non-destructive evaluation (NDE). For qualification and validation purposes, data need to be collected from all the different process steps. Data are stored in the process database. The software tool Inspector then operates on the process data to make meaningful correlations between data.

2.2 Case studies

2.2.1 Melt pool monitoring: detection of porosity due to overheating at the start of a vector

Figure 2 shows data that have been captured during printing of 4 subsequent scan lines. The signals represent the melt pool area (measured with a high-speed thermal camera, using real-time image processing on the field-programmable gate array (FPGA) of the mode control panel (MCP)) and the real-speed of the laser (determined on the FPGA of MCP). The black block-like signal represents the laser on-off signal: when it is high, the laser is ON. It can be see that the melt pool area is high at the start of the vector, which is due to the acceleration of the laser in that area. However, this leads to a too high energy input at the start of the vector, which subsequently induces porosity as can be observed in the microscope picture on the right. This example clearly illustrates the approach: the systematic collection of process data and correlation of these data with both post-build quality data (in this case microscopic images) and tool path leads to a profound understanding of the process and its variation.
QUALIFICATION OF ADDITIVE MANUFACTURING PROCESSES USING IN-PROCESS MONITORING AND NDT continued

2.2.2 Camera images: detection of horizontal cracks
A difficulty in the build preparation of AM parts is the design and positioning of support structures. Sometimes support structures are not designed strong enough. Figure 3 illustrates another way of using the overall workflow, in this case using visual images taken after the recoating process and post-build visual inspection. The crack in the part was seen in the after recoating images, since it appears as a white bright spot.

3. Conclusion
Qualification is an important domain to enable the full potential of AM in future. Specifically for this task, Materialise has developed a software framework (currently in development and being used in Materialise research) to collect systematically data from the different building blocks of the software workflow.
REFERENCES


[6] Foster, B.K. et al. 2015, Optical, layerwise monitoring of powder bed fusion, Solid Freeform Symposium, Austin, Texas, USA.

† Materialise, Belgium (tom.craeghs@materialise)
EFFECT OF ALPHA CASING ON THE MECHANICAL PROPERTIES OF Ti-6Al-4V COMPONENTS MANUFACTURED BY DIRECT METAL LASER SINTERING

S.T. Chingowo*, P. Mendonidis1, I. Adebiyi

ABSTRACT
The heat treatment Ti-6Al-4V is one of the main methods devised to modify the strength and ductility of titanium alloys. However, during heat treatment of Ti6Al4V at high temperatures formation of alpha case is evident in an argon atmosphere. To investigate alpha case’s influence on mechanical properties heat treatment was performed in a muffle furnace using argon gas on Ti-6Al-4V tensile samples at 650°C and 1100°C and hardness and tensile tests were performed. The results indicated that the formation of brittle solid solution alpha case exerted significant influence on yield strength and ductility of Ti-6Al-4V components.

1. Introduction
Numerous studies carried out around the world dealing with new methods of manufacturing compared to traditional methods of manufacturing have incorporated the use of titanium and titanium alloys due to their advantageous weight to density ratio [1]. Direct laser metal sintering is one of the new additive techniques used to produce components from metal powder deposited in a thin layer by laser scanning. The resultant brittle α’ martensitic structure due to high cooling rates is unfavorable for application by decreasing the fatigue life of the component [3].

Heat treatment of metals and alloys has been the main area of research for past decades as it plays a major role in metal working processes used to alter the physical and sometimes chemical properties of the material. But when it comes to alpha beta alloys ambiguous to heat treatment of steels developmental and optimising heat-treating conditions are relatively limited. Heat treatment above the beta transus is a high temperature heat treatment and Ti-6Al-4V tends to oxidise at high temperatures in the presence of oxygen and hydrogen [4]. Exposure of Ti-6Al-4V to air not only results in thermodynamic reaction, but also results in solid solution hardening of the surface because of inward diffusion of oxygen leading to the formation of a surface hardened zone known as the alpha case [2]. This paper aims to investigate and evaluate the material properties derived from the generation of a new surface hardened phase. Mechanical tests such as yield strength, elongation and hardness were obtained using tensile tester machine and Vickers hardness tester respectively.

2. Methodology and results
2.1 Methodology
Ti-6Al-4V tensile specimens were manufactured at the Centre of Rapid Prototyping and Manufacturing in Bloemfontein using the direct metal laser sintering process. The specimens were built in the z-direction with respect to the building platform. Ti-6Al-4V tensile test specimens (50 mm long x 12 mm wide x 5 mm thick) were run in laboratory Fathom GR muffle argon furnace at 650°C and 1100°C temperatures for 2 hours using a ramp up rate of 5°C per min and furnace cooled in argon. The furnace was first purged to eliminate any oxygen present.
Hardness testing was performed with Innovatest hardness tester equipment using 100kgf loading (HV100) as per ASTM E 384 requirements for hardness profile. A hardness profile on the polished specimen surface was produced from the edge through the centre. Following the ASTM E8M, tensile tests were carried out with an Instron 8516 servo-Fathom GR muffle furnace to determine the yield strength, ultimate tensile strength and elongation to failure. A 10 mm/min crosshead speed was employed.

2.2 Results
Etching using Keller’s reagent revealed a martensitic microstructure on as received Ti-6Al-4V sample, a martensitic structure in sample heat treated at 650°C and sample heat treated at 1100°C revealed a Widmanstatten alpha in a beta matrix after furnace cooling. The outer surface of heat-treated sample at 1100°C showed the alpha case phase and an average hardness value was 419HV compared to the bulk section 368HV. Sample heat treated at 650°C had no discrepancy in hardness between the surface and bulk material of 355HV average. The yield strength varied from 1202 Mpa on the as built to 906 MPa on sample heat treated at 650°C and 760 Mpa on sample heat treated at 1100°C respectively. Percentage elongation on as built was approximately 14.00%, heat treated at 650°C was 11.22% and on sample heat treated at 1100 was 8.93%.

3. Conclusion
In the present study, different yield strength values and hardness were obtained during heat treatment of Ti-6Al-4V alloy at different temperatures. Alpha case formation influence on mechanical properties were investigated and compared to that of as built Ti-6Al-4V mechanical properties. The microstructural evolution in the heat treated sample at 650°C exhibited the similar microstructure as the built sample of a martensitic structure supporting that at 650°C there is no change of phases as well as oxidation during the stress relieving process. Heat treatment above the Beta transus at 1100°C results in a colony type coarse microstructure forming as well as an alpha case layer on the surface. It conforms to literature that oxidation in titanium alloys is prominent at high temperatures and the present study showed that even in argon atmosphere alpha case still forms. Therefore, we suggest from the gathering up of yield strength values and hardness values that alpha case reduces ductility as well as yield strength. Further work is to be done in vacuum furnace to investigate if it is totally inert.

REFERENCES

* Department of Metallurgy, Vaal University of Technology, South Africa (tadhzwawanyasha@gmail)
ASSESSMENT OF RESIDUAL STRENGTH OF ADDITIVE MANUFACTURED SAND PARTS

S.M. Ngoie¹, E.M. Gonyana¹, K. Nyembwe*²

ABSTRACT

Three-dimensional printing (3DP) is an additive manufacturing technology that has been successfully used for the direct production of sand moulds and cores for metal casting applications. The technology uses 3D digital data to print additive manufacturing parts using a layer-by-layer approach. The mechanical properties of additive manufacturing sand parts that have been assessed in the literature include tensile and bending strength. The residual strength property has not been evaluated despite it being critical with regard to the reclamation yield ability of the additive manufacturing moulding process. This study investigates the variations of residual strength of three-dimensional printed parts subjected to various temperatures.

1. Introduction

The three-dimensional printing (3DP) technology is currently being applied to directly produce sand moulds and cores in metal casting [1]. This technology has brought various benefits including major cost cutting in certain areas, particularly in foundries. The direct production of sand moulds using 3DP technology has eliminated complex manufacturing limitations, however little is known about the behaviour of mechanical properties of additive manufacturing (AM) parts. Very few studies have been conducted in an effort to understand mechanical properties of AM parts, and this has been cited as a barrier to effectively transfer 3DP technology to some foundries [2]. This study seeks to address this gap, and determine the residual strength of AM parts subjected to different temperatures.

2. Methodology and results

2.1 Experimental procedure

The raw material used in the experimental work was a sulfonic acid coated silica sand imported from overseas and recommended by the manufacturer of the Voxeljet 3DP. Three grades of the sand were used during AM including virgin sand, 40% recycled/60% new sand and 100% recycled. The following steps were conducted in the methodology:

- Sand characterisation for size distribution, gas evolution, loss on ignition, acid demand, grain shape and pH.
- AM of sand test specimen including tensile, bending and compressive according to AFS specifications. A Voxeljet VX 1000 was used for AM.
- Heat treatment of test specimen at different temperatures i.e. 500, 600 and 800 degrees celsius
- Sand testing of test specimens with Ridsdale-Dietert equipment.
Table I below shows the sand characterisation results comparing the virgin silica sand to the recycled sand. The effect of AM process can be seen in the results of the recycled sand.

Table 1: Sand characterisation results

<table>
<thead>
<tr>
<th>Properties</th>
<th>100% new sand</th>
<th>100% recycled sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss on Ignition (L.O.I.)</td>
<td>0.53%</td>
<td>0.45%</td>
</tr>
<tr>
<td>pH</td>
<td>4.7</td>
<td>4.21</td>
</tr>
<tr>
<td>Acid demand (ml)</td>
<td>0.00</td>
<td>6.1</td>
</tr>
<tr>
<td>Gas evolution (ml)</td>
<td>6.7</td>
<td>5.6</td>
</tr>
<tr>
<td>Size distribution</td>
<td>65.56</td>
<td>64.97</td>
</tr>
</tbody>
</table>

Table 2 below shows the mechanical test results of the tests specimen with variation of new sand content from 100% to 0%. The strength values decrease as the content of the new sand decreases.

Table 2: Mechanical Properties results (uncured)

<table>
<thead>
<tr>
<th>Properties</th>
<th>100% new sand</th>
<th>40% recycled sand / 60% new sand</th>
<th>100% recycled sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (N/cm²)</td>
<td>77</td>
<td>98</td>
<td>65</td>
</tr>
<tr>
<td>Bend strength (N/cm²)</td>
<td>127</td>
<td>163</td>
<td>65</td>
</tr>
</tbody>
</table>
ASSESSMENT OF RESIDUAL STRENGTH OF ADDITIVE MANUFACTURED SAND PARTS continued

Table 3 below shows the residual strength test results for the different test specimens. The effect of the temperature is evident as the strength properties decrease as the temperature increases. This effect is more pronounced as the content of the new sand decreases.

### Table 2: Mechanical Properties results (uncured)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Temperature</th>
<th>100% new sand</th>
<th>40% recycled / 60% new sand</th>
<th>100% recycled sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500°C</td>
<td>47</td>
<td>44</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>600°C</td>
<td>13</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>800°C</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Tensile strength (N/cm²)</td>
<td>500°C</td>
<td>90</td>
<td>106</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>600°C</td>
<td>33</td>
<td>52</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>800°C</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Bend strength (N/cm²)</td>
<td>500°C</td>
<td>90</td>
<td>106</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>600°C</td>
<td>33</td>
<td>52</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>800°C</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

3. Conclusion
The preliminary test results of residual strength indicate that a decrease in sand mechanical properties with an increase in curing temperature is due to destruction of the binder during heat exposure. The 40/60 grade showed superior mechanical properties after heat treatment of the sand. The sand specimens cured at 800°C for five minutes were destroyed because of the instability of silica sand at 800°C, which led to linear expansion and also because the binder from the sample was consumed after being exposed to the heat of the muffle furnace. The investigation has shown that out of the three silica sand grades, the 40% recycled and 60% virgin sand grade demonstrated that it is more apt to retain strength. Future investigations should possibly compare the performance of various silica sands and different AM technologies.

REFERENCES


* Department of Metallurgy, University of Johannesburg, South Africa (dnyembwe@uj.ac.za)
STEPPING OUT ON A LIMB: THE DESIGN AND MANUFACTURE OF A 3D PRINTED TITANIUM PROSTHESIS

L. Dean¹, J. Els², N. Minnaar³, H. Grimsehl⁴, Van der Walt, P.²

ABSTRACT
This paper highlights the potential of direct metal 3d printing in the design of prosthetic devices through a live project case study. The project has two thrusts, technical (what we can achieve with digital design and manufacturing technology) and social (customisation to create something desirable and personal). Technically the paper considers a three-way balance between structural optimisation, additive manufacturing criteria and aesthetic vision. From a social perspective, the paper describes a custom response tailored to an individual’s needs and personal taste: a couture device for special occasions and something the wearer is confident.

1. Background
Recent decades have seen huge advances in both the engineering of prosthetic devices and the social empowerment of their users. Para-sport has played a big part with Paralympic participation rising from 400 in 1964 to over 4,250 at London 2012. The summer games now attract a cumulative TV audience of 3.8 billion and during London 2012 1.3 million tweets mentioned ‘paralympic’ [www.paralympic.org]. Despite these advances however, ‘everyday’ prosthetic devices are developed largely irrespective of gender and styled to appear reassuringly robust. What options are there for the young, the feminine and the fashion conscious? In sports at least, there has been move away from the disguise of a false limb to almost a celebration of technology. Could the geometric freedoms of additive manufacture and the flexibility of production it offers provide something decorative and couture that one would be proud to display?

This project centres upon a leg prosthesis for an above the knee female amputee and employs an ‘off the shelf’ mechanical knee mechanism and carbon fibre blade foot. Direct Metal Laser Sintering, DMLS titanium was used in the construction and accounts for the entire structure between knee pivot and blade foot. The decision was taken to expose the carbon fibre blade rather than house it within a rubberised imitation foot and regular shoe as is usually the case in non-sports applications. Indeed, the intention is for the whole leg to remain exposed rather than disguising it beneath clothing. Rather than a matching pair of shoes the device is worn with one shoe and the blade. The surface pattern of the ‘off the shelf’ shoe selected by the amputee is reflected in the carbon fibre socket that provides the interface with the residual limb. This patterning on the three-dimensional form is achieved by a hydrodipped graphics process.

2. Structural analysis and topological optimisation
Thorough virtual prototyping of the assembly enabled the team to not only target weaker areas of the geometry for reinforcement, but to reduce areas of over engineering. Software stress analysis highlighted areas of concern under simulated loading and with appropriate safety factors. Importantly the visualisation highlighted not only a significant area of weakness towards the ‘ankle’ of the design but also indicated that the upper cage around the knee damper was stiffer than required. Without such detailed visualisation it would have been tempting to address structural concerns by simply increasing section thickness throughout
the design. This would have been both unnecessary and counterproductive; further stiffening the over-engineered upper section would simply deliver forces more efficiently to the critical area. Maintaining or even reducing the rigidity of the upper section would allow compliance in this region and thereby lower stresses elsewhere.

Topological optimisation software has been employed in the development process as a guiding factor. Ultimate engineering performance was not the aim in this project where style and fashion have such significant influence. It was important however to understand and visualise the load paths in the structure and to achieve a balance between “form follows force” and “form follows fashion”. Allowing the software an open solution space resulted in a not particularly aesthetic and volumetrically substantial ‘pipe’. Adjusting software parameters to open up this structure indicated structural advantage in a radial network of vertical spars. This ‘crude’ (the computer is not tasked to consider aesthetics) software derived structure proved not too dissimilar in concept to the existing design. Comparing the two indicated a need to spread the original design lattice work radially in order to improve strength. In this way topological optimisation was used to guide and improve structural performance without inhibiting creativity.

3. Design for additive manufacture
Conceptualising the structure began with a consideration of build orientation and constraining the geometry within certain angles to the vertical. The importance of such considerations at the concept stage this has been discussed by the author as far back as 2008 (Dean 2008). The difference in this project has been the scale of the prosthesis. To best satisfy the necessary load paths and aesthetic considerations the part would be built vertically from blade foot mounting to thigh socket adaptor. Build volume limitations meant building the design in two sections that would be laser welded together. The need for this separation placed a constraint on the geometry and the need to minimise the number of separate contact points at the join. The two DMLS titanium halves were printed along with an SLS polyamide jig to align the sections until the welding fastened them in place. A small test section either side the join was printed to prove the welding ahead of the full height builds. The investment required for the direct metal printing of substantial volumes required design work to be right first time.

A further consequence of scale was concern over unsupported lengths. The design is a lattice work of relatively fine strands generally running top to bottom. During the build process unsupported lengths will only be anchored at the base. In particularly thin sections this brings the danger of deflection as the build height progresses, a slight force from the recoater arm for example (part of the mechanism that delivers powder to the build area and that sweeps over the built material as it fuses) may cause the entire build to fail. To alleviate this risk it was necessary to ensure a balance of section thickness and cross branching between strands.

REFERENCES

1 De Montfort University, United Kingdom (ldean@dmu.ac.uk)
2 Centre for Rapid Prototyping and Manufacturing, Central University of Technology, South Africa
3 Altair Corporation, South Africa
4 Medical Ortotist Prosthetist, South Africa
SLM-PRODUCED Ti6Al4V: NOVEL ANNEALING STRATEGIES TO IMPROVE DUCTILITY

G.M. Ter Haar*, T.H. Becker

ABSTRACT
This paper presents two novel post process heat treatments to improve selective laser melting-produced Ti6Al4V ductility to match that attained by wrought samples. Due to the martensitic α’ microstructure inherent to the selective laser melting technique, selective laser melting-produced Ti6Al4V parts achieve a poor ductility. While many researchers have successfully demonstrated heat treatments that decompose the unfavourable α’ phase into a more ductile (α+β) lamellar phase, the achieved tensile ductility is still below that achieved by wrought samples. This study demonstrates that a bi-modal microstructure allows for both a high ductility and good strength to be obtained. Results of the study show that it is possible through post-process heat treatments to attain tensile properties that can compete with that of wrought samples.

1. Introduction
A characteristic that is fundamental to all metals’ mechanical properties is its microstructural morphology. Due to the rapid part cooling during the selective laser melting (SLM) process (the most popular laser powder bed fusion additive manufacturing technique today), a fine martensitic α’ microstructure is produced. This microstructure contributes to a high ultimate tensile strength (UTS) of up to ~1200 MPa, at the cost of ductility (2–8%) [1, 2]. Post-process heat treatments are incorporated to alter microstructure and thereby improve ductility, usually at the cost of part strength. Most contemporary heat treatments developed by researchers, with the aim to optimise strength and ductility, achieve a fracture elongation of 10–12% and a UTS of 950–1000 MPa. While this is satisfactory according to the ASTM standard F2924–14, it is still below that which is achieved by wrought samples [3, 4]. SLM-produced Ti6Al4V microstructural morphology is hugely different to that of the starting microstructure of wrought samples. Furthermore, SLM parts do not go through a thermomechanical process route and therefore grain fragmentation and globularisation, allowing the optimisation of mechanical properties [5], is not achievable. Therefore, the same annealing strategies applied to wrought samples do not have the same effect on the microstructure of SLM-produced Ti6Al4V. While research has been able to improve ductility of SLM-produced Ti6Al4V, great potential exists in optimising mechanical properties through microstructure. This paper is aimed at re-engineered annealing strategies to obtain optimal mechanical properties in SLM-produced Ti6Al4V.

2. Methodology
Ti6Al4V (ELI) powder was supplied by TLS Technik GmbH & Co. Average particle diameter was measured to be 33 µm. Cylindrical specimens were manufacturing using a Concept Laser M2 SLM machine using default process parameters (listed elsewhere [6]). Specimens’ longitudinal axis were orientation in the Z-axis with reference to the build plate. Five samples were put aside for tensile testing in the as-built condition. Annealing of the rest of the samples was done in a Gallenhamp muffle furnace. Two annealing strategies were carried out as tabulated in Table 1. After annealing, samples were machined into ‘dog–bone’ shaped specimens according to ASTM E8.
3. Results

Group A on Figure 1(c) represents the ultimate tensile strength (UTS) and fracture elongation achieved by as-built samples. Annealing strategy 1 achieved the expected lamella colony through furnace cooling from just above the $\beta$ transus. The cooling rate throughout the furnace was not identical and therefore some samples cooled slower than others. Slower furnace cooling had a thickening and globularisation effect on the $\alpha$ lamellar colonies, Figure 1(a). Group C on Figure 1(c) indicate the UTS and fracture elongation achieved by samples from annealing strategy 1. Samples with an elongated lamella colony achieved the best strength in the group while the globularised sample (C2) achieved the lowest in the group. Sample C2 achieved the best fracture elongation in the group (27%).

Annealing strategy 2 achieved a bi-modal microstructure, as depicted in the micrograph on Figure 1(b). Since $\beta$ phase volume percentage drastically increases with temperature in the high SST region, quenching from a higher temperature produces a higher volume percentage martensite. The second stage of the annealing strategy decomposed the martensite into lamella $\alpha$ ‘basketweave’ microstructure. This allows for the bi-modal microstructure of primary $\alpha$ grains in a matrix of lamella ($\alpha+\beta$). Group B on Figure 1(c) designate the UTS and fracture elongation achieved by samples from annealing strategy 2. The sample quenched from a highest SST achieved the lowest fracture elongation (12%) while the samples quenched from a lower SST (samples B2) each achieved a much higher ductility (20%). The fine secondary lamella structure achieved by the second heating stage allowed the samples to achieve a UTS of 940 – 960 MPa.

4. Conclusions

The as-built samples achieved a slightly higher fracture elongation than expected. (maximum expected ductility was ~8% [2]). It is likely that the compressive residual stress on the interior of the sample (found by Mercelis and Kruth [7]) contributed to a decrease in pore nucleation and repressed crack growth during tensile tests. Methods of fragmentation and globularisation of SLM-produced $\alpha$ grains were identified for the first time. The annealing strategies proposed improved sample ductility beyond ~12% achieved by current annealing strategies proposed in literature. This was due to the addition of $\beta$ phase and the large size of the $\alpha$ grains. The spread in fracture elongation of group C was due to the differential furnace cooling rates (and therefore elongated $\alpha$ grain widths) of the samples. The spread in fracture elongation of group B was due the different quenching temperatures which resulted in different amounts of primary $\alpha$ vs secondary $\alpha$ lamella.
SLM-PRODUCED Ti6Al4V: NOVEL ANNEALING STRATEGIES TO IMPROVE DUCTILITY continued

This shows the sensitivity of the volume of secondary α on the tensile ductility of samples. Secondary lamella achieved in strategy 1 increased strength to an acceptable value. Strength and ductility are not only dependant on α grain size, but also on α grain shape (lamella vs globular) and that globular microstructure has been found to be superior [4]. It follows therefore that fragmentation and globularisation of α grains is key technique exploitable for increasing ductility beyond that which is currently achieved by standard heat treatments. The results of the study show great potential for achieving excellent tensile properties in SLM-produced Ti6Al4V parts through optimising microstructure through post-process heat treatments.

REFERENCES

*Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa (gterhaar@sun.ac.za)
NOTES
THE POTENTIAL ENHANCEMENT OF COMPONENTS PRODUCED BY METAL ADDITIVE MANUFACTURING USING LASER SHOCK PROCESSING

D. Glaser¹*, S. N. van Staden², N. Ivanovic³, C. Polese²

ABSTRACT
Additive manufacturing of high performance alloys such as Ti-6Al-4V potentially allows for improved component design and manufacturing, and is of specific interest to the aerospace industry due to the enhancements in final geometry, weight, and even cost. Potential applications of metal additive manufacturing components would offer a performance enhancement compared to conventional manufacturing techniques, therefore the use of a final surface enhancement process to provide further performance improvements may be highly beneficial to achieve superior components. The use of laser shock processing is explored as a potential technology in order to generate beneficial compressive residual stresses into metal additive manufacturing components. Preliminary results reveal that the LSP process can effectively achieve compressive residual stresses to a depth of near 1 mm in Ti-6Al-4V.

1. Introduction
Additive manufacturing (AM) is a general term used to describe methods of building articles directly from a computer model. Typically, AM products are built up layer by layer to produce a complete or near net shaped component [1]. The AM process is specifically attractive for the manufacturing of high-value metal components as the geometric flexibility from a design and manufacturing perspective offers potential benefits in overall component performance in terms of weight and production cost. There is currently significant interest in the aerospace industry regarding the use of AM for component production, due to the perpetual pursuit of the aerospace industry to deliver components with reduced weight and improved performance at lower cost while maintaining high reliability. Since a large drive to develop metal AM technology is based on the requirement for superior component performance, the consideration of potential enhancements due to post-processing techniques is a vital consideration for successful technology adoption.

Peening technology is a well-established technique in order to enhance the mechanical performance of metal components by introduction of beneficial compressive residual stresses. Crack-based failure phenomena such as fatigue or stress corrosion cracking can be drastically affected by the presence of residual stresses. Essentially cracks initiate and propagate under tensile stresses, therefore the introduction of compressive residual stresses into the surface of the component can lead to significant performance enhancements.

Laser shock peening or laser shock processing (LSP) is one of the most advanced forms of peening technology with superior performance compared to conventional techniques such as mechanical shot peening (SP). Typically the depth of compressive residual stresses achievable by with LSP technology are on a millimetre range (often 10 times deeper than conventional SP) with virtually no surface roughness introduced. The implementation of LSP to high value components can result in order of magnitude life enhancements in terms of fatigue performance. The schematic in Figure 1 illustrates the LSP process.
mechanism, which uses a pulsed laser beam in order to generate a high pressure plasma expansion on the component surface. The plasma reaches Giga-Pascal magnitudes in a nano-second time frame, which drives a shock wave through the metal work-piece with sufficient strength to yield the metal and hence generate beneficial compressive residual stresses through the target surface [2].

![Figure 1](image1.png)

**Figure 1**

*A schematic of the LSP process (left) and a photograph of the LSP process (right)*

2. Methodology and results
This research has been conducted in the context of AM of Ti-6Al-4V by the selective laser melting (SLM) process. There is currently substantial development of the SLM process within South Africa and the CSIR National Laser Centre with a strong focus on Ti-6Al-4V due to significant interest from the aerospace and biomedical sectors. In order to obtain optimal mechanical performance in terms of fatigue, it is anticipated that AM components implemented in the aerospace industry will be in a machined state in order to adhere to tight manufacturing tolerances, and to improve the surface finish which is known to affect fatigue performance. The LSP research is therefore primarily on a machined AM surface.

2.1 Experimental approach
SLM has been used to produce samples of 30 x 30 x 10 mm3 using an EOSINT M280 system at the Central University of Technology (CUT, South Africa) from EOS GmbH, which incorporates a fibre laser with a power of 200 W, spot size of 80 microns and power density range of ~ 40 kW/mm2. Samples have been stress relieved and are to be machined. The LSP processing is to be performed at the CSIR National Laser Centre on an in-house developed processing platform which incorporates an Nd:YAG pulsed nano-second laser operating at 1064 nm. A thin water layer is used as inertial confinement, and LSP parameters such as power intensity and coverage were first optimised on wrought Ti-6Al-4V plate using a deflection based technique referred to as an Almen strip approach. Preliminary residual stress analysis has been performed using a SINT MTS3000 incremental hole drilling instrument in order to evaluate the through thickness stress field due to LSP processing. Residual stress analysis using X-ray diffraction will also be conducted using a Proto iXRD in order to evaluate the surface effect.

2.2 Discussion of initial results
The initial residual stress results showing an in depth profile of stresses within the AM coupon (after stress relieving) before and after application of the LSP process is shown in Figure 2. As expected, the residual stresses within the AM coupon after stress relaxation are very low. It is clear that the LSP process has effectively introduced beneficial compressive residual stresses to a depth of almost 1 mm in the SLM build Ti-6Al-4V coupon.
THE POTENTIAL ENHANCEMENT OF COMPONENTS PRODUCED BY METAL ADDITIVE MANUFACTURING USING LASER SHOCK PROCESSING continued

3. Conclusion
Preliminary results indicate that the LSP process may be an effective technique in order to introduce beneficial compressive residual stresses into high performance materials such as Ti-6Al-4V. Further analysis will include comprehensive residual stress analysis using the X-ray diffraction technique.

REFERENCES

1 National Laser Center, CSIR, South Africa(dglaser@csir.co.za)
2 School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, South Africa
CHARACTERISATION FOR QUALIFICATION OF Ti-6Al-4V ELI PARTS BUILD BY SLM

N.M. Baloyi1*, P. Mendonidis1, W. Du Preez2, A.P.I. Popoola3

ABSTRACT
Ti-6Al-4V parts produced for orthopaedic applications must have microstructures that are essentially pore free and comprise proper phases that can offer strong and ductile properties. Porosity affects the hardness, tensile, and fatigue properties of parts produced via selective laser melting on the Ti-6Al-4V. After deposition, selective laser melting parts are characterised by acicular α’ martensite microstructure, residual stress and the yield strengths greater than 1300 MPa and elongation below 10%. This disqualifies the selective laser melting fabricated Ti-6Al-4V and, accordingly, post-selective laser melting heat treatment is often applied to improve these properties to meet these standards. The study assessed the metallurgical characteristics of the products produced by the process for qualification.

1. Introduction
Selective laser melting (SLM) is an additive manufacturing (AM) process that is increasingly being used in the production of orthopaedic implant. This method can produce close to fully dense parts that have properties similar or better than those achieved from wrought parts. In order for SLM to be accepted as a sustainable processing method for orthopaedic implants, it is necessary to assess the metallurgical characteristics of the products produced by the process. Ti-6Al-4V parts produced for orthopaedic applications must have microstructures that are essentially pore free and comprise proper phases that can offer strong and ductile properties. Porosity affects the hardness, tensile, and fatigue properties of parts produced via SLM on the Ti-6Al-4V [1].

During manufacturing, parts can experience incomplete wetting and balling effects associated with insufficient energy input resulting in pores or voids in SLM parts [2,3]. Similarly, when energy input is not sufficient, successive scan tracks do not properly fuse together and defects appear along the scan lines [2,4,5]. After deposition, SLM parts are characterised by acicular α’ martensite microstructure, residual stress and the yield strengths greater than 1300 MPa, but the tensile elongation is noticeably below the minimum threshold of 10% suggested for critical structural applications (ASTM f 136; ASTM F 1472). This disqualifies the SLM fabricated Ti-6Al-4V and, accordingly, post-SLM heat treatment is often applied to improve these properties to meet these standards.

The samples that were received were metallurgically characterised for microstructure and mechanical properties. X-ray diffraction (XRD), optical microscope (OM), scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS), hardness and tensile testing were conducted. The samples were cross sectioned both transversely and along the building direction, to investigate any delamination or poor layer bonds. Similarly a CT scan was conducted and the porosity was found to be about 99% for both orientations, with micro-pores observed at the edges of the samples. The microstructure of the sample consists of lamella (varying from colonised plate-lite α to basketweave morphology) and an inter-platelet β phase, which seems to be orientation related. According to Ding, R. et al [6], the Ti-6Al-4V samples should be heat-treated above the β-transus temperature and cooled under slow intermediate cooling rate
respectively; to homogenise and ultimately stress relieve. Corresponding to the microstructure; the hardness varied from 241 HV-373 HV. Hardness testing evaluates the toughness of the material by piercing the surface, which means that materials with the highest HV are the toughest. When comparing heat-treatment outcomes with the achieved values; it is evident that slow cooling rates would lower the hardness. High hardness corresponds with basketweave to widmanstatten structures.

2. Methodology and results
In this investigation, parts produced from SLM EOS M270 where characterised to investigate the presence of defects and properties repeatability. SLM parts, as produced, contain thinner and longer \( \alpha' \) martensitic laths without the occurrence of \( \beta \) phases \([7,8]\). The mechanical properties of the SLM-fabricated Ti-6Al-4V depend largely on its constituent phases and their morphologies and characteristic length scales, as well as the size and orientation (texture) of the prior-\( \beta \) grains \([9]\). Previous studies have shown that thermomechanical processing (TMP) of the \((\alpha + \beta)\) titanium alloy above the \( \beta \) transus temperature leads to a ‘lamellar’ microstructural morphology, consisting of \( \alpha \) platelets with an inter-platelet \( \beta \) phase \([6]\).

It is fairly challenging to achieve tensile properties from in situ SLM parts as their yield strength (YS)> 1100 MPa \([2,9]\), which is high compared to the ASTM F 136 and F 1472 because of the \( \alpha' \) martensite structure it contains. The microstructures seen in this investigation are similar to those reported by Christensen, A. et al \([10]\) from samples produced from electron beam melting (EBM) followed by hot isostatic pressing (HIP). For their parts, YS of 803 MPa at a 17% elongation were overserved, which conforms to the ASTM F 136.

3. Conclusion
Since microstructures are predictors of mechanical properties, the microstructures observed in this study suggest that the tensile properties of the investigated sample could be within the ASTM F 136 standard. It may be difficult to produce orthopaedic parts with properties corresponding to the standard by AM, but subsequent thermomechanical processing could transform them into qualifying parts.

REFERENCES
CHARACTERISATION FOR QUALIFICATION OF Ti–6Al–4V ELI PARTS BUILD BY SLM continued


1 Department of Metallurgical engineering, Vaal University of Technology, South Africa (nheleb@vut.ac.za)
2 Department of Mechanical and Mechatronics Engineering, Central University of Technology, South Africa
3 Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, South Africa
NOTES
EVALUATION OF Ti15Mo ALLOY MANUFACTURED BY DMLS FROM ELEMENTAL POWDERS

T. Dzogbewu¹, W.B. du Preez²

ABSTRACT
The method used to produce a metallic material has a decisive effect on the microstructure and the mechanical properties. Direct metal laser sintering, which directly converts powder to functional objects by laser beam, is gradually gaining momentum as a method of choice for producing biomedical objects. Ti6Al4V has been used extensively for biomedical applications with laudable success. However, there are well-known inherent limitations such as high elastic modulus, low ductility etc. compared with human bones. Samples of Ti15Mo were manufactured by direct metal laser sintering and their mechanical properties were investigated for structural biomedical applications in comparison with Ti6Al4V alloy.

1. Introduction
Ti6Al4V has been used extensively for biomedical applications, however its high elastic modulus and low ductility limit its used as a structural biomedical material. For replacing a critical damage load bearing structure such as the femur, the implant must have a good combination of low elastic modulus and high ductility, and Ti6Al4V is not mechanically the most ideal biomaterial [1-3]. The investigation for a more suitable alternative alloy for manufacturing direct load bearing structural implants has triggered the current research of in-situ alloying 85 wt.% of pure titanium with 15 wt.% of molybdenum to produce structural bearing implants of more appreciable ductility and elastic modulus for biomedical applications. The current literature reveals that a host of scholars have investigated the suitability of Ti-xMo for biomedical applications with different conventional production methods [3-6], and the most suitable alloy for biomedical applications might be the binary Ti15Mo alloy [2,3,6,7].

Xie et al. [8] produce porous Ti-xMo (x=4, 6, 8 and 10 wt.%) alloys by selective laser sintering (SLS) method. It was found that the mechanical properties of the porous structure do not only depend on the pore properties but also on the microstructure. Collins et al. [9] carried out detailed studies of microhardness and microstructural evolution of Ti-xMo alloys by laser engineered net-shaping (LENS) process. It was concluded that the alloy is very sensitive to the Mo compositions. Recently Vranchen et al. [10] conducted in-situ alloying with mixture of Ti6Al4V (ELI) and Mo (10 wt.%) powders and focused on the solidification mechanism, microstructure, mechanical properties and response to heat treatment of the novel alloy and compare the results to Ti6Al4V (ELI). The elastic modulus of 73 GPa and remarkable elongation to 20% was found as compared to 7.3% for Ti6Al4V.

2. Methodology and Results

2.1 Methodology
A preliminary analysis was conducted to determine the optimum process parameters for the selected alloy (85wt% of pure Ti + 15wt% of Mo) by forming and studying single tracks and single layers according to well-known procedures described in the literature [11,12]. The optimum process parameters were used to produce as-built samples for microstructural and mechanical properties investigation. The microstructural analysis
was conducted with optical and electron microscope. The tensile tests samples were rectangular in shape with 10 mm gauge length, 2 mm width and 1 mm thickness, which is described as a mini sample [13]. MTS Criterion model 43 Universal Test machine was used for the tensile test. EOS M 280 DMLS machine was used for producing all the experimental samples.

2.2 Results
A cross-sectional analysis of the microstructure reveals that the 15 wt.% of Mo has significant effect on the microstructure. The Ti-15Mo microstructure presents unmelted Mo particles distributed randomly in the β-titanium matrix. The Mo was not able to melt completely due to the thermophysical difference between the two materials. Mo has a melting point of 2623°C [14] while Ti has a melting point in the range of 1650–1670°C [15]. Secondly, the laser reflectance of Mo is higher than that of Ti [16]. Ti would absorb more laser radiation than Mo. These thermophysical differences were responsible for the incomplete melting of the Mo, which lead to the formation of Mo particle – Ti matrix microstructure. The Ti15Mo microstructure is quite different from what is normally observed in Ti6Al4V manufactured by DMLS [17]. An energy dispersive spectroscopy (EDS) analysis of chemical composition of the samples reveals that the Mo concentration is not homogenous in the bulk material. The mechanical properties investigations also present values of higher ductility and low elastic modulus than Ti6Al4V as initially envisaged, since Mo is β stabilising element.

3. Conclusion
Producing implants with high ductility and low elastic modulus would greatly reduce implant failures associated with the stress shielding effect, which would translate to and improved life for implant patients. As demonstrated, using DMLS to process powder mixtures of different materials would certainly broaden the material database of additive manufacturing. It would also permit the material scientist to mix different elemental powders for specific applications.

REFERENCES
EVALUATION OF Ti15Mo ALLOY MANUFACTURED BY DMLS FROM ELEMENTAL POWDERS continued

Corrosion Science, 95, pp 117-124.

Department of Mechanical and Mechatronic Engineering, Central University of Technology, South Africa (thydzo@yahoo.fr)
USING OF THE LASER SINTERING TECHNOLOGY FOR FABRICATION OF HYDRODYNAMIC TORQUE CONVERTER ROTORS

K. Osowski¹, A. Olszak², M. Migus¹, W. Iwanicki¹, A. Kęsy¹, Z. Kęsy*¹

ABSTRACT
This paper describes application of the selective laser sintering method for fabrication of hydrodynamic torque converter nylon rotors. The fabrication process was divided into four steps: numerical calculations, solid modelling, rotors fabrication and testing of hydrodynamic torque converter with nylon rotors. The numerical calculations included computational fluid dynamics modelling and optimisation. The prototypes of hydrodynamic torque converter with nylon rotors made with the selective laser sintering method were tested on special test rigs. Based on analysis of the 3D printing processes and the test results it was identified that special attention should be paid to rotors rigidity.

1. Introduction
There is currently a great deal of research focused on improvements in mechanical power transmission systems. Therefore, a new search more frequently introduces new materials and new manufacturing technologies. A number of machine transmission systems utilise hydrodynamic torque converters due to their advantages which includes: limitation of the system dynamic loads, damping torsional vibrations, protecting the engine from load surges, starting under applied load, and working quietly and easily. The main components of hydrodynamic torque converters are: rotors, a pump, a turbine and a stator mounted in housing filled with working fluid. The rotors are not connected mechanically but through working fluid circulation. Because of the complicated geometry of the rotors additive manufacturing can be used for fabrication of hydrodynamic torque converter components. The idea of using the selective laser sintering method for fabrication of hydrodynamic torque converter parts was presented and discussed [1–3]. This paper shows progress in the idea realisation.

2. Methodology and results
Both 1D and 3D flow mathematical models of motion of a hydrodynamic torque converter working in a transmission system were carried out [4,5]. Based on these calculations solid models of rotors were built and written as STL format files (Figure 1).

![Figure 1](Link_to_image)

The rotors solid models created by means of the ANSYS Turbogrid Module: a – pump, b – stator, c – turbine
Next rotors were fabricated on a 3D Systems Vanguard SI laser-sintering machine (Figure 2).

![Rotors fabricated by means of the SLS method](image)

Due to the lower nylon’s lower rigidity, a special metal reinforcing skeleton was used. The prototyped hydrodynamic torque converters with nylon rotors were tested on the special test rigs. One of the test rigs designed for prototyped hydrodynamic torque converter testing is presented in Figure 3.

![Test rig for prototyped hydrodynamic torque converter testing](image)

3. Conclusion
The laser sintering technology can be applied to the fabrication of hydrodynamic torque converter rotors. Dimensional errors of nylon rotors should be taken into consideration when laser-sintering technology is used. Nylon rotors undergo major deformation during the converter operation, and because of that transmitted torque during the tests was limited.

REFERENCES
Using of the Laser Sintering Technology for Fabrication of Hydrodynamic Torque Converter Rotors continued


* University of Technology and Humanities in Radom, Poland (zhesy@interia.pl)
2 New Chemical Syntheses Institute, Poland
ABSTRACT

This article presents the results of durability tests of toothed wheels made of plastic with two methods of additive manufacturing: the selective laser sintering (SLS) and the Multi-Jet Modelling (MJM) method. The geometry of the plastic toothed wheels was received on the basis of measurements of steel wheels working in a typical mechanical reduction drive using reverse engineering methods. Toothed wheels, both plastic and steel, worked for a set period of time under load, and in the course of the tests the resistance movement of the reducer was measured in order to assess the degree of surface of the teeth wear. After the test accurate measurements of weight and geometry were conducted. Based on the obtained results it was found that the resistance movement is smaller for wheels made with MJM, however, they are less durable.

1. Introduction

The last decade is characterised by a dynamic development of new technologies used in the construction of machines. One of such technologies is additive manufacturing (AM). Currently, many components made with AM methods are applied in research and development, production of prototypes and even production of machine components [1-4]. The advantages of AM methods are clearly visible during production of components with complex geometry, such as gears.

2. Methodology and results

The geometry of the plastic toothed wheels was obtained on the basis of measurements done on a steel toothed wheels scanner QT Sculptor. Pairs of plastic toothed wheels are made from PA2200 (SLS, Formiga P100) and Full Cure 850 material (MJM, Eden 350V). Manner of plastic toothed wheels installation into reducer is shown in Figure 1.

![Figure 1](image-url)  
*Figure 1*  
_Gears mounted in the reducer_
Toothed wheels, both plastic and steel, worked for a set period of 500 hours under load, whereby every 10 hours the resistance movement of the reducer was measured in order to assess the degree of wear surface of the teeth. After testing was completed, the geometry and weight of toothed wheels were measured and changes in appearance evaluated. Sample research results are shown in Table 1 and Figure 2.

Table 1: Testing parameters of toothed wheels

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Mass (kg)</th>
<th>Force (N)</th>
<th>Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steel</td>
<td>0.9477</td>
<td>9.2969</td>
<td>0.1859</td>
</tr>
<tr>
<td>2</td>
<td>FullCure 850</td>
<td>1.0005</td>
<td>9.8149</td>
<td>0.1963</td>
</tr>
<tr>
<td>3</td>
<td>PA 2200</td>
<td>1.0895</td>
<td>10.688</td>
<td>0.2138</td>
</tr>
</tbody>
</table>

Figure 2
Comparison of deviation measurements before and after testing

3. Conclusion
On the basis of the results, it was found that the resistance movement is smaller for the wheels made using the MJM method, however, these toothed wheels are less durable, because of a higher drop in their weight and greater deviations from the initial dimensions. Therefore, it should be considered that further work should be focused on a selection of materials for plastic toothed wheels produced with AM methods.

REFERENCES
RELIABILITY TEST OF PLASTIC TOOTHED WHEELS MADE OF 3D PRINTING continued


* University of Technology and Humanities in Radom, Poland (akesy@op.pl)
NEW PROCESS: HIGH SPEED SINTERING

M. Yagci

ABSTRACT
A technology, which received significant interest a view years ago when Loughborough University and Evonik independently developed it, high speed sintering (HSS), is to receive its first commercial release with Voxeljet.

Voxeljet is well known as a provider of a large format and high productivity 3D printing equipment. Their material sets so far have focused on tooling and pattern making applications, but with HSS Voxeljet will be entering the thermoplastics market with the ability to directly print end products.

The basis for HSS is the same as Voxeljet’s core technology, binder jetting.

HSS works by selectively jetting infrared absorbing ink onto layers of plastic powder. Each layer is exposed to infrared light, which melts the powder to form functional plastic parts directly out of the machine. It enables printing of parts with properties similar to injection moulding.

In combination with the excellent surface quality, sharp and clear edges, as well as true-to-detail resolution, HSS parts can be directly used for functional applications in automotive, industrial equipment, and even consumer goods.

The system will be offered as an open research platform, offering the flexibility to utilise different base materials e.g. Polyamide (PA) and thermoplastic polyurethane (TPU).

REFERENCES
1*Manager sales, Voxeljet AG, Germany (tobiasking@voxeljet.de)
# CONFERENCE PROGRAMME

**Friday, 10 November**

<table>
<thead>
<tr>
<th>Session Details</th>
<th>SESSION CHAIR: Gerrie Booysen</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:00</td>
<td>Opening</td>
</tr>
</tbody>
</table>
| 08:15           | 3D Printing: gateway to virtuality's creative playground  
Lionel Dean |
| 09:00           | How we hacked my body back to life  
Jason Laing |
| 09:45           | Development of a custom Photopolymer for 3D printed Bone  
Dr David Prawel |
| 10:30           | TEA                            |

**ROOM A**

| Session Chairs | Design for Additive Manufacturing  
Dr Kobus van der Walt, Malan van Tonder |
|----------------|----------------------------------|
| 11:00          | Benchmarking of FDM printed replacement parts for rural wheelchairs  
Allan Kinnear |
| 11:20          | Utilising Additive Manufacturing to reduce time to market for valve developments  
Malan van Tonder |
| 11:40          | How 3D printing technology is shaping our orthopaedic practice  
Kyung Cho |
| 12:00          | A theoretical framework for material selection in 3D printing solutions to craniofacial reconstruction in burn victims  
Webster Gova |
<p>| 12:20          | Closing Panel                  |
| 13:30          | LUNCH                          |</p>
<table>
<thead>
<tr>
<th>ROOM A</th>
<th>ROOM A</th>
</tr>
</thead>
<tbody>
<tr>
<td>SESSION CHAIR: Gerrie Booysen</td>
<td>ROOM A</td>
</tr>
<tr>
<td>08:00</td>
<td>Opening</td>
</tr>
</tbody>
</table>
| 08:15  | 3D Printing: gateway to virtuality’s creative playground  
Lionel Dean | ROOM A |
| 09:00  | How we hacked my body back to life  
Jason Laing | ROOM A |
| 09:45  | Development of a custom Photopolymer for 3D printed Bone  
Dr David Prawel | ROOM A |
| 10:30  | TEA | ROOM A |
| ROOM A | ROOM B |
| Process Monitoring  
Francois du Rand, Sonette du Preez | Material Process  
Monnamme Tiotleng, Nana Arthur |
| Additive Manufacturing operator’s respiratory exposure to metal powders during powder bed fusion  
Sonette du Preez | In-situ alloyed LENS Additively Manufactured TiAI-Nb structure  
Monnamme Tiotleng |
| Emissions and exposure in Additive Manufacturing: The current state of knowledge  
Johan Du Plessis | Comparison of in-situ alloyed Ti-6AI-4V + 10Mo via Selective Laser Melting and Laser Metal Deposition  
Nana Arthur |
| Development of an Additive Manufacturing re-coater monitoring system for powder bed systems  
Francois du Rand | A comparative study of laser processing of commercially available Titanium Aluminide powder and in-situ alloying of Titanium Aluminide  
Shaik Hoosain |
| 12:00  | A theoretical framework for material selection in 3D printing solutions to craniofacial reconstruction in burn victims  
Webster Gova | ROOM A |
| 12:20  | Closing Panel | ROOM A |
| 13:30  | LUNCH | ROOM A |
BIOGRAPHY
Dr Lionel T Dean’s specialism in Additive Manufacture (AM, aka 3D printing) began in 2002 with a one-year residency at the University of Huddersfield UK. The project, considered at the time to be blue-skies research, set out to explore the application of what were then termed Rapid Prototyping technologies in end-use manufacture and though that, mass customisation.

The project proved timely and quickly developed into a PhD thesis and from there to Dean’s formation of FutureFactories Studio in 2003. This presentation will consider 15 years of creative professional practice focused exclusively on Additive Manufacture. The projects presented range from gallery pieces to retail products for well-known manufacturers. They include works acquired by MoMA, The Museum for Modern Art in New York and DHUB, Design Museum Barcelona for their respective permanent collections.

In 2008 the MoMA piece was included in a ‘Highlights Collection’ of the Museum’s 250 most significant acquisitions since 1980. Dean’s work sits at the intersection of art, craft and design challenging traditional boundaries and definitions of practice. He employs the virtual realm as a creative playground where time plays a part and artefacts exist with past and future states. This is a space in which ephemeral designs exist beyond the physical constraints of material or process. The resulting artefacts are at once familiar and yet strange, exhibiting formal structure while defying the patterns and logic associated with industrialisation: the flora and forna of an alien landscape.

3D Printing: Gateway to virtuality’s creative playground
Dr. David Prawel
Colorado State University
Mechanical Engineering
Colorado, USA
engr.colostate.edu/me/dr-david-prawel/

Friday November 10, 2017 | 09:45 - 10:30 | Meeting Room 12 Durban ICC

Development of a custom Photopolymer for 3D printed Bone

BIOGRAPHY
Dr. David Prawel has enjoyed a 35+ year career as an entrepreneur, consultant and educator in 3D technology and digital product development. He helped build 6 startup companies, with one successful IPO and one in the works.

He earned Bachelor’s and Master’s degrees from the University of Buffalo, and a Ph.D. from Colorado State University in Biomedical Engineering. He is currently on the Research Faculty in Mechanical Engineering at CSU, where he researches biomaterials in the Biomaterials Research and Engineering Laboratory and runs a community-access center for 3D printing and personal fabrication (www.idea2product.net) which he founded in 2012.
How we hacked my body back to life

BIOGRAPHY
Learn how the power of 3d printing not only rebuild Jason’s life but also his body. Through this journey further developments have been established by merging different techniques in order to create a better future for many other peoples lives and uses for 3D technicians.
ABSTRACT

It has been identified that the South African valve manufacturing industry is currently struggling to survive due to imported valves flooding the local market. The South African government identified this as a significant problem, hence the Department of Trade and Industry’s decision to designate valves for local procurement by state-owned companies, and to fund and set up a Technology Localisation Implementation Unit to support such localisation projects. Recently Microvalve, a local company, secured two significant orders from Transnet Koedoespoort for the supply of valves with many other smaller orders. It is envisaged that the project will assist with the Department of Trade and Industry’s mandate to localise 70% of all state-owned enterprises valve purchases. The research case study as presented aims to investigate the value of incorporating additive manufacturing and additive manufacturing-based support technologies into a valve development value chain.

1. Introduction

In March 2014 the Department of Trade and Industry (dti) designated valves as a priority product, for local procurement by state-owned companies (SOCs) [1]. These valves are required to be locally manufactured to stimulate investment in key sectors, increase competition, secure technology transfer, build industrial capabilities and increase local competitiveness. This action was taken after it was determined that local valve manufacturing companies are struggling financially, due to imported valves flooding the local market [2]. Microvalve identified a number of valves that could be manufactured locally, which adheres to the dti’s policy on 70% localisation for all state-owned enterprises (SOEs) valve purchases.

Following assistance granted from the Technology Localisation Implementation Unit (TLIU) for Microvalve to support the valve manufacturing localisation process, two significant orders have been secured from Transnet Koedoespoort. The orders required the supply of valves, as well as batches of small components within a very short timeframe. The valves, identified to be produced locally include:

- 25 mm relief valve (ball) for locomotives
- 40 mm cut-out cock for locomotives
- Sander Valves for locomotives
- Relief valves for the compressors on locomotives
- Angle filling valves for Rail car tankers
- Safety Relief valves for Rail Car Tan hers
- Discharge valves for Rail Car Tan hers
- Seating valves for compressors on locomotives
- Relief valves for compressors on locomotives

Microvalve identified key partners in the valve manufacturing value chain to reduce the time to market. The value chain for the valve development process is shown in Figure 1. Microvalve using Computer Aided Design (CAD) software did the valve designs; whereafter Zimtek did the pattern and core box designs. Each of the
casting processes was simulated using Magmasoft software. Patterns and core boxes were manufactured using additive manufacturing (AM) technology for mass production runs, which allowed sand foundries to produce multiple high quality moulds and cores for casting. Investment casting patterns were produced for low volume component production runs. The foundries were selected based on their casting capabilities.

2. Study overview
The research case study to be presented investigates the value of implementing AM technologies into the valve development value chain. The performance of the manufactured core boxes and patterns, using AM, will be benchmarked in terms of cost, lead time and performance.

REFERENCES

1 Technology Transfer and Innovation, Vaal University of Technology, South Africa (malanvt@vut.ac.za)
2 Technology Transfer and Innovation, North West University, South Africa
3 Microvalve, South Africa
DEVELOPMENT OF AN ADDITIVE MANUFACTURING RE-COATER MONITORING SYSTEM FOR POWDER BED SYSTEMS

F. Du Rand, P.J.M. van Tonder, H.C. vZ Pienaar, & D.J. de Beer

ABSTRACT

In the world of additive manufacturing, specifically powder based technologies, failed prints can be very costly due to the costs and availability of the printing materials. The most common cause of failed prints on powder based technologies can be linked to recoating problems. Thus, the lack of a dedicated re-coater monitoring system has been identified as the main driver for these problems, as there is no feedback to verify the quality of the recoated layer. Re-coater errors may cause the print process to fail or cause defects in the printed part. This paper describes the identification and benchmarking of an active re-coating monitoring system, which can be implemented into existing powder based additive manufacturing technologies.

1. Study background

Currently, powder based Additive Manufacturing (AM) technologies have no recoating quality feedback into the printing system and can be identified as one of the key aspects that may cause failed prints [1]. This indicates the need for a dedicated re-coater monitoring system that can be used to monitor the recoating quality during the printing process. There are a number of scanning technologies that can be used to develop such a system. These technologies include: Computer or Machine vision, 3D laser scanning and Time-of-Flight cameras. A brief comparison between the three technologies is shown in Table 1.

Table 1: Active Monitoring Technology Comparison

<table>
<thead>
<tr>
<th>Features</th>
<th>Technology Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Computer Vision</td>
</tr>
<tr>
<td>Measurement accuracy</td>
<td>High (±150um)</td>
</tr>
<tr>
<td>Scanning speed (points per second or frames per second)</td>
<td>High (+30fps)</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
</tr>
<tr>
<td>Computing power required</td>
<td>Low</td>
</tr>
</tbody>
</table>

From the data given in Table 1, both the computer vision and 3D laser scanning techniques showed to yield the best measurement accuracy. The next factor that was taken into consideration for the selection process included the scanning speed. Since the 3D laser scanning and computer vision technologies are different in terms of their operation, they cannot be directly compared to each other. However, both these systems have a high scanning speed, which makes them suitable to be used in the active re-coater monitoring system. The last two factors that was taken into consideration included the cost and computing power requirements for each technology. As highlighted in Table 1, 3D laser scanning devices are very costly, and...
requires significant processing power as it generates a 3D point cloud data set of the surface. The computer vision showed to have a low cost and required less amounts of computing power. A major advantage using computer vision is that compact computing devices such as the Raspberry Pi or Beaglebone Black system can be used to process the images, which significantly reduces the overall system cost. However, it needs to be taken in consideration that the computer vision technology is very susceptible to lighting conditions. Due to this fact, it is very important that the lighting must be carefully controlled in order to achieve the maximum effectiveness of the technology. Considering the given specifications of the three different technologies, as shown in Table 1, the computer vision technology was chosen as a viable option to be used in the active re-coater monitoring system.

2. Experimental setup
As highlighted in the previous section, the computer vision technology was selected to be used in the active re-coater monitoring system. The experimental setup of such a system is demonstrated in Figure 1.

As shown in the figure above, the system design requires a camera to be positioned perpendicular to the powder bed, in order to avoid image distortion as well as image focusing problems. The lighting must sufficiently illuminate the powder bed so that surface defects would be detected by the camera. In the following system, the image processing will be done with a Raspberry Pi 3 micro computer using an adaptive thresholding algorithm provided by the OpenCV library [3]. The adaptive thresholding algorithm will be able to highlight or segment the areas within the specified area that show signs of surface defects. A threshold algorithm will assign a specific value to pixels by comparing the value of the pixels to a predefined global threshold value. However, using a global threshold value is not ideal for an image with varying light conditions as unwanted sections of the image may be blanked out. A solution to this problem will be to use an adaptive thresholding algorithm as it calculates a threshold value based on a small area of neighbouring pixels, and repeats this process for the entire image. This will produce a much better segmentation result compared to that of a global threshold value. Using the adaptive threshold algorithm, the threshold value can be calculated using two different methods, namely: Calculating a mean threshold value based on the neighbourhood area and using the weighted sum of the threshold values of the neighbourhood area where the weights are in a Gaussian window. Once the image has been segmented, the image can be further analysed for any defects.
DEVELOPMENT OF AN ADDITIVE MANUFACTURING RE-COATER MONITORING SYSTEM FOR POWDER BED SYSTEMS continued

3. Conclusion
The lack of an active re-coater monitoring system has been identified as one of the key aspects that may cause failed prints due to defects occurring in the powder bed. It was determined that the Computer vision technology will be suitable to design an active monitoring system. In the research presented, a dedicated re-coater monitoring system will be developed to detect surface defects during the printing process.

REFERENCES

1* Department of Electronic Engineering, Vaal University of Technology, South Africa (francoisdu@vutcloud.onmicrosoft.com)
2 Technology Transfer Innovation Unit, Vaal University of Technology, South Africa
3 Telkom Centre of Excellence, Vaal University of Technology, South Africa
4 Technology Transfer Innovation Unit, North West University, South Africa
HOW 3D PRINTING TECHNOLOGY IS SHAPING OUR ORTHOPAEDIC PRACTICE

K.J. Cho*, P.J. Erasmus

ABSTRACT
We started using a FDM 3D printer in 2015 in our private orthopaedic practice for various applications: from surgical planning to patient specific instrumentation. We would like to present some case studies to show how 3D printing technology has shaped our business.

1. Introduction
We sometimes have patients with complex lower limb deformity that require a complicated surgical procedure. With the current medical imaging technology, it is possible to view 3D virtual models and even provide a virtual surgery platform. However, having a real-size physical model has advantages in that the surgeon can have a real feel for the size and test appropriate tool set. 3D printing technology has allowed us to do better surgical planning in a time and cost-effective way.

2. Case studies

2.1 3D model building for identifying the defects
If any unusual defect is noted during a computerised tomography (CT) scan examination, 3D models were printed to check the shape before the surgery.

2.2 Knee fusion to total knee replacement
We had a patient who had a knee fusion surgery done on one of his knees after a traumatic incidence. Prior to the conversion surgery to the total knee replacement, construction of extensor mechanism was performed along with soft tissue expansion. A surgical planning was done virtually and the surgeon repeated the virtual planning on the printed model of the patient’s knee. The prosthesis size, type and the surgical approach were determined based on the trial implantation.

2.3 Patient specific osteotomy
A multi-planar deformity of the lower limb was corrected with a high tibial osteotomy. The size and angle of the osteotomy was determined virtually and a patient specific cutting guide was 3D printed.

3. Conclusion
3D printing technology has been helpful for more accurate surgical planning for complicated knee surgeries, giving the surgeon more confidence and saving surgical time in the theatre. Consultations with a 3D printed model of the patient’s own knee helped the patient understand the procedure better as well.

REFERENCES
* Stellenbosch Knee Clinic, South Africa (hyjincho@gmail.com)
MICROSTRUCTURE AND MECHANICAL CHARACTERISATION OF COATED TiAl ALLOY ON Ti64

B.N. Masina¹, T. Lengopeng¹, S.L. Pityana¹², M. Tlotleng¹³*

ABSTRACT
In this study, TiAl alloy was coated on Ti64 using 1073 nm high-energy continuous-wave laser while varying the scanning speed. This was done in order to increase the surface temperature properties of Ti64. Scanning electron microscopy, light optical microscopy and Vickers’ micro-hardness were used to characterise the microstructure, clad area, dilution and hardness of the coatings, respectively. The macro- and micrographs of the clads indicated a needle- and dendritic-rich structure for both the coating and at the interface for all the scanning speeds. The overall hardness was found to be high at low scanning speed.

1. Introduction
Ti64 is the most popularly used grade of the titanium alloy family in aerospace and health [1]. However, its use is limited to a temperature below 400oC. Several studies show that TiAl alloy coated on Ti64 would increase the temperature operation of the Ti64 [1]. TiAl alloys are high temperature intermetallics which can be used for applications in the temperature ranges of about 600-900oC [2], due to its high melting point (1440oC), low density, high elastic modulus and good structural stability. The objective of this study was to improve the properties of the Ti64 by coating it with TiAl alloy using the direct laser metal deposition technique.

2. Methodology and results

2.1 Methodology
A pre-alloyed TiAl powder (45-90µm) was coated on Ti64 base material using 1073 nm, IPG laser. During processing the laser power (W), laser beam diameter (mm) and power feeding rate (rpm) were kept constant while varying the scanning speed (m/min). Multiple tracks of 50% overlap were obtained for several scanning speeds. Argon gas was used as both a carrier and shielding gas. In order to study the microstructure and the microhardness of the coatings, metallographic samples were prepared. They were prepared using standard mechanical polishing methods and etched. Olympus light optical microscopy, Joel JSM-6010PLUS/LAM scanning electron microscopy (SEM) with energy dispersive X-ray analysis (EDX) and Zwick/Toel Indetec (ZHVµ) Vickers hardness were used to characterise the metallographic samples for the microstructure and mechanical properties.

2.2 Results
Figure 1 shows an overall optical macroscopy image of the clad indicating the interface and heat affected zone (HAZ). Surface cracks with deep penetration into the clads were observed for all samples. The HAZ was low at the high scanning speed. Both the micro- and macrographs revealed a needle-rich and dendritic structure for all the clads and at the interface. Also, the clads were well bonded. The overall images indicate that the height of the coating was higher at lower scanning speed. This is acceptable since material-laser interaction time (residence time, s) is increased. Figure 2 indicates the microhardness at the
interface. Microhardness results, as depicted in Figure 2, show that at the high scanning speed the overall microhardness at the interface is higher than the other scanning speeds.

Figure 1
Optical microscopy image indicated the overall image of the coating, interface, dilution and the heat affected zone

Figure 2
Microhardness graph indicated the microhardness across the samples that were done at the interface

3. Conclusion
Couple clads of TiAl pre-alloyed powder were produced on the Ti64 base material using a direct laser metal deposition technique while varying the laser scanning speed. The obtained TiAl clads indicated a needle-rich and dendritic rich structure for both the coating and at the interface. It was found that the HAZ was narrow at high scanning speed. The main challenge that still needs to be overcome when cladding TiAl pre-alloy powder on Ti64 is the cracking. The microhardness result shows that as the scanning speed increases the coating height decreases.
MICROSTRUCTURE AND MECHANICAL CHARACTERISATION OF COATED TiAl ALLOY ON Ti64 continued

REFERENCES


1 National Laser Center, Council of Scientific & Industrial Research, South Africa
2 Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, South Africa
3 Department of Mechanical Engineering, University of Johannesburg, South Africa (mtlotleng@csir.co.za)
IN-SITU ALLOYED LENS ADDITIVELY MANUFACTURED TiAl-Nb STRUCTURE

M. Tlotleng1,2*, S. Pityana1,3

ABSTRACT
Titanium aluminides are interesting intermetallic materials to study due to their enhanced high temperature and lightweight properties. They are necessary as structured materials, but brittle to form with conventional methods; hence big corporates are interested in developments that will lead to cost effective manufacturing technologies that are able to produce homogenous, defect free titanium aluminides structures. Additive manufacturing is one promising technology hence it was explored here in studying process development of producing TNB alloy using the laser in-situ alloying approach. The produced alloy, \( \gamma \)-TNB, appeared to be homogeneous after heat-treatment and had hardness of 580HV.

1. Introduction
Titanium alloys are necessary as aerospace structure materials. They are lightweight and have improved corrosion and wear properties. The use of titanium aluminides (TiAl) as high temperature materials is becoming a reality now since their early research and development. Their lightweight and mechanical properties at elevated temperatures make them attractive as high temperature structured materials necessary for the aerospace and automotive industries [1-2]. Binary TiAl structures lack ductility at room temperature hence they are impossible to form into structures through conventional means such as casting and forging. To improve on their ductility, research and development make use of ternary and quaternary alloys among others, e.g. GKSS and GE alloys in the manufacturing of durable, weight-reduced structures [3]. To manufacture such high value components casting is still found to produce heterogenous microstructures while additive manufacturing (AM) technologies like electron beam melting seem to be achieving desirable TiAl products with correct specifications. While AM technologies are able to achieve desired results, they are still dependent on the powder metallurgy routes as they use pre-alloyed TiAl powders in the manufacturing of TiAl structures. Therefore the overall process to market could be expensive. In realising this, the Additive Manufacturing Research Group in the Laser Enable Manufacturing Division at NLC CSIR, Pretoria are looking to manufacture TiAl structures using the laser net shaping system (LENS) platform from elemental powders using the laser in-situ AM alloying approach. The phenomena here is such that the laser created melt pool will be able to convectionally mix the elemental powders into a TiAl alloy when correct thermodynamics are met. In this paper, a TNB alloy produced using the proposed alloying mechanism is reported and discussed. The TNB alloy was studied for the microstructure with light optical and scanning electron microscopes. The composition was studied with scanning electron microscopy (SEM) - energy dispersive X-ray spectroscopy (EDS) and X-ray Diffraction (XRD) while overall hardness of the produced alloy was measured using the Vickers micro-harness machines.

2. Methodology and results

2.1 Methodology
A Optomec, 1 kW laser power, platform was used to produce the TNB alloy studied in this paper. The processed powders were pure aluminium and a master alloy consisting of Grade 1, commercially pure
titanium and niobium. Argon gas was used as the carrier gas and for purging oxygen off the processing chamber during manufacturing. For processing, effects of laser power (W), carrier gas (l/min), powder flow-rates and composition were investigated. The results reported here are from the optimised process parameters when the laser power output was 400 W. The produced samples were characterised for appearance using Olympus optical light microscope and Joel JSM-6010PLUS/LA SEM with EDS, composition using SEM-EDS and X-ray diffraction. The produced samples were heat treated at 1400°C under Argon environment. Zwick/Roell Indetec (ZHVµ) was used for measuring the micro-hardness of the produced alloy.

2.2 Results
Figure 1 presents the produced results of the laser in-situ alloyed TiAl-Nb before and after heat treatment. Figure 1 shows the macro- and micro-images of powder (a) and TNB alloy that was produced (b) and its heat treatment images (c and d). The sample is characterised of micro pores and unidentifiable structure before heat treatment (b). Post heat treatment the macrostructure of the alloy could be identified (c and d). Hexagonal grains with lamella inside were obvious at higher magnification (d). It would seem that the grains are small which could mean the chosen process conditions and the heat treatment done at 1400°C led to a refined macrostructure. The EDS composition indicated that this alloy composed of 52Al, 38Ti and 10Nb (at, %) making it an early gamma γ-TNB alloy. This structure is similar to that of the Ti-46Al-9Nb alloy that is reported by Clemens et al [2] at the GKSS Research Centre. XRD diffraction pattern of this alloy conclude that the major peak was of a duplex nature (α2/γ). The overall hardness of this alloy was 580HV.

![Image of LENS synthesised γ-TNB alloy](image-url)
IN-SITU ALLOYED LENS ADDITIVELY MANUFACTURED TiAl-Nb STRUCTURE continued

3. Conclusion
We have successfully studied the laser in-situ alloying technique in a quest to produce TiAl alloy(s). γ-TNB alloy was produced and with heat-treatment was homogenised and refined. The observed grains were small [1] and no crossed lamellar [2] could be identified within them. The observed lamella structures were fine, leading to an inference that a ductile, fully lamella γ-TNB was achieved. A hardness value of 580HV was reported.

REFERENCES

1 National Laser Center, Council of Scientific & Industrial Research, South (mtlotleng@csir.co.za)
2 Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, South Africa
3 Department of Mechanical Engineering, University of Johannesburg, South Africa
ADDITIVE MANUFACTURING OPERATOR’S RESPIRATORY EXPOSURE TO METAL POWDERS DURING POWDER BED FUSION

S. du Preez*, D. de Beer2, J. du Plessis1

ABSTRACT
Various powder bed fusion methods make use of laser or electron beams to melt and fuse metal powders together. These metals powders include titanium and various forms of stainless steel alloys. Despite the fact that additive manufacturing is an enclosed process, workers may potentially be exposed to the powders and other chemicals. The aim of this study was to assess additive manufacturing operator’s respiratory exposure to metal powders associated with powder bed fusion by making use of standardised occupational hygiene measurement methods. It was found that additive manufacturing operators are exposed to various metals present in inhalable dust and in size fractions smaller than 300 nm.

1. Introduction
The expansion of AM worldwide continues to show endless possibilities of this technology, although information on the potential health effects of materials used during AM is lacking [1]. Currently the existing literature is limited to emission studies of desktop fused deposition modelling (FDM) printers in test chambers or unoccupied rooms. It is therefore essential to gain an understanding of personal exposures in industrial workplaces. Powder bed fusion (PBF) is one of the highly used technologies which uses titanium and various metal alloys to manufacture metal parts [2,3]. Exposure to powders is expected to be primarily through inhalation, and exposure to submicron particles is also of interest due to their potential acute and chronic health effects. An operator’s exposure to different metal powders takes place in three major steps, which includes pre-processing, processing and post-processing tasks. Metal powder dust can be generated during pre-processing and post-processing tasks and can also be accompanied by the formation of metal fumes arising from the molten metal as well as by the emission of metal fumes of variable composition depending on the metal powders used. Inhalation of materials used during different AM may cause respiratory irritation, coughing, nose and throat irritation [4,5] This study aimed to assess AM operator’s respiratory exposure to various metals present during pre-processing, processing and post-processing stages of PBF at three South African institutions.

2. Methodology
Sampling was carried out at three different AM facilities in South Africa utilising PBF. The assessment of occupational exposure was done by making use of standardised occupational hygiene measurement methods to assess respiratory exposure to titanium and stainless steel metal powder materials. Personal sampling was conducted by means of GILAIR constant flow sampling pumps calibrated at 2 l/min before and after sampling along with MCE filters (37 mm diameter, 0.8 micron pore size), using the NIOSH 7300 method. All sample analysis was conducted by a SANAS accredited testing laboratory. Nanoparticle respiratory deposition (NRP) samplers were used to collect particles smaller than 300 nm. Field blank and area samples were also collected to ensure quality control. Airborne particle number and respirable mass concentrations were measured with two direct-read instruments: a condensation particle counter (CPC) airborne particle counter (APC).
3. Results
From the results employees were exposed to detectable levels of various metals in powder form (as total inhalable dust) during pre-processing, processing and post-processing tasks. Several metals were detected in respiratory exposure samples, which included aluminium, cobalt, chromium, copper, iron, nickel, titanium and vanadium in powder form. AM operator exposure to individual metals will be compared to permissible legislative exposure levels. The results from the direct read instruments indicated that airborne particles are emitted in the workplace atmosphere during pre-, processing and post-processing. It was found that exposure to different metals smaller than 300 nm in size is also evident in some instances.

4. Conclusion
The findings of this study indicate the AM operators are exposed to submicron particles that are emitted from industrial PBF machines into the manufacturing facilities. Emissions during all three stages of AM resulted in operator’s exposure to aluminium, cobalt, chromium, copper, iron, nickel, titanium and vanadium metals in powder form. Although personal exposure is low there is a need to provide important information for training employees on health effects associated with exposure, and to deliver control measures necessary to eliminate or reduce employee exposure, during every stage of AM.

REFERENCES

1 Occupational Hygiene and Health Research Initiative, North-West University, South Africa (dupreezonette@gmail.com)
2 Department of Technology, North-West University, South Africa
In situ alloying is an important topic in terms of alloy development and improvement of mechanical properties in additive manufacturing [1]. With the scarcity of getting most commercial titanium alloys in powder form, development and qualification of such techniques are essential [2]. This work therefore investigates the microstructural differences and mechanical properties of Ti-6Al-4V+10Mo manufactured by selective laser melting and directed energy deposition. It was found that the alloy manufactured by directed energy deposition exhibited better melting of molybdenum particles and hence a more homogeneous microstructure compared to the high power, high speed selective laser melting process.

1. Introduction
Both the selective laser melting (SLM) process and the directed energy deposition (DED) process have been studied for the manufacturing of aerospace components. Although both processes build parts according to computer-aided design (CAD) files and in a layer-wise profile, the SLM process is a powder bed technique while the DED process is a blown powder technique. Most investigations aimed at in situ alloying using the SLM process include the addition of refractory metals such as rhenium, molybdenum, niobium and tantalum to titanium or titanium alloys [3]. These metals are known for their high melting points, resistance to wear, corrosion and deformation [3]. Studies conducted on the addition of refractory metals to titanium alloys reported as-built microstructures characterised by undissolved refractory particles [2-5]. This often leads to inhomogeneity of the alloy composition therefore producing a composite-like microstructure [2-5]. This is mostly due to the high powers and speeds used in SLM processing which leads to insufficient interaction times between the metal powder and the laser.

Conversely, Collins et al. (2002) successfully performed in situ alloying of molybdenum with CP titanium using the DED process and reported no un-melted particles or inhomogeneity. The microstructure was composed of short alpha precipitates in a beta matrix [6]. It is therefore important to further investigate the suitability of the different techniques in producing homogeneous microstructures. This study investigates the additive manufacturing (AM) of Ti-6Al-4V+10Mo employing both techniques for comparative purposes, and characterising the resultant microstructures.

2. Methodology and results
Powder samples were prepared and mixed in a tubular mixer for 30 minutes, then processed on a SLM machine fitted with a 5kW Nd:Yag laser at powers ranging from 3kW to 2kW and at speeds ranging from 2m/s to 4m/s to make 10x10x10(mm³) samples. The mixed powder was also used for processing on the laser net shaping system (LENS) fitted with a 1kW IPG laser at powers ranging from 360W to 400W and at speeds ranging from 0.008m/s to 0.011m/s. Sample metallography was performed, and samples etched with Kroll's reagent to reveal the microstructures before optical microscopy and scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDS) could be performed.
Figure 1(a) shows numerous un-melted Mo particles and light and dark bands indicative of the uneven distribution and melting of Mo particles. Before melting, the scraping mechanism can affect the distribution of Mo in the mixed powder and at the high speeds used in this process and there is insufficient time for Mo to fully melt due to its high melting point (2623°C) compared to the lower melting point of Ti-6Al-4V (1660°C) [5]. The main difference between the two processes is that the LENS is capable of manufacturing samples at much higher energy densities than the SLM machine. The low speeds used on the LENS allow for better Mo melting and therefore a more homogeneous microstructure was obtained (Figure 1(b)).

The EDS results revealed that the amount of molybdenum dissolved in the matrix of the sample produced on the SLM machine was ~5%, while LENS samples revealed ~8%. This further proves the better melting and homogeneity obtained from this process. The melt pool shape and track are clearly visible in the SLM microstructure while the LENS samples show no evidence of the melt pool track. The characteristics of Ti-6Al-4V are columnar grains growing parallel to the build direction for SLM produced parts but the addition of molybdenum shortened the grains considerably (Figure 2(a)). The LENS samples show a different microstructure characterised by alpha precipitates in a fully beta matrix (Figure 2(b)) – also reported by Collins et al.[6].

Figure 1
Micrographs of Ti-6Al-4V+10Mo: (a) produced on an SLM machine at 2kW and 2m/s and (b) produced on the LENS at 360W and 0.008m/s (Mo appears light on backscattered electron images because of high atomic number)

Figure 2
Micrographs of Ti-6Al-4V+10Mo: (a) produced on SLM machine and (b) produced on LENS machine.
3. Conclusion
Although the SLM process is faster and uses higher powers compared to the DED process, it is not suitable for obtaining homogeneous microstructures in the as-built condition for in situ alloying. Thus, DED is a preferred technique for in situ alloying to produce homogenous microstructures.

REFERENCES

1 National Laser Center, Council of Scientific & Industrial Research, South Africa (cmadikizela@gmail.com)
2 School of Chemical and Metallurgical Engineering, University of the Witwatersrand, South Africa
EMISSIONS AND EXPOSURE IN ADDITIVE MANUFACTURING: THE CURRENT STATE OF KNOWLEDGE

J.L. du Plessis1*, S. du Preez1, D.J. de Beer2

ABSTRACT
Scientific publications on health and safety in additive manufacturing are sparse. This study aims to provide a summary of research on emissions and exposures associated with additive manufacturing, to analyse the methods used to quantify emissions and exposures, and to identify future research opportunities. Sixteen research papers investigating health and safety issues (two papers) or emissions and exposure (fourteen papers) have been published. Emissions of particles and volatile organic compounds from desktop fused deposition modelling printers using acrylonitrile butadiene styrene and polylactic acid have been characterised the most extensively by making use of various measuring instruments and analytical methods.

1. Introduction
Additive manufacturing (AM) is the process of joining materials using layer-on-layer methodologies to make objects [1]. Although AM has been used in the industry for several decades, the use of desktop 3D printers is becoming common in offices, universities, schools and at home. The increased use in industrial and non-industrial settings now raises concerns for user health and safety. However, thus far scientific publications on health and safety are surprisingly sparse. The question raised therefore is, what is the current state of knowledge regarding emissions from different AM technologies and the subsequent exposure of users to these emissions?

2. Methodology and results

2.1 Methodology
A systematic review of literature was conducted to identify scientific (peer reviewed) articles published. Databases included in the systematic search included: Scopus, EbscoHost, Pubmed, ScienceDirect and Google Scholar.

2.2 Results
The first publication on safe work practices for AM was published in 1999 [2], and after a void of 14 years, Short et al. [3] addressed environmental, health and safety issues. Since 2013, fourteen papers on emissions and exposures from AM have been published in peer reviewed journals. The majority of papers (58%) originated in the United States of America. Twelve (86%) of the papers investigated emissions and exposures from desktop fused deposition modelling (material extrusion technology) printers mostly in chambers or in small rooms using predominantly acrylonitrile butadiene styrene (ABS) and/or polylactic acid (PLA). However, at least 20 other materials have also been used. Particles, in the nanometre to micrometre scale range, and volatile organic compounds (VOCs) emissions have been investigated. However, emissions of ozone, volatile carbonyl compounds and polyaromatic hydrocarbons have also been investigated. A wide array of measuring instruments from different manufacturers and analytical methods have been used to quantify emissions and exposures.
3. Conclusion
Emissions of particles and VOC’s from desktop fused deposition modelling printers using ABS and PLA have been characterised the most extensively by making use of a wide variety of measuring instruments and analytical methods. There is, however, ample opportunity to investigate emissions and exposures associated with other AM technologies. Also, (personal) exposure of users to emissions should be conducted. Standardised use of measuring instruments and analytical methods will ease comparison of research findings between studies.

REFERENCES

1 Occupational Hygiene and Health Research Initiative, North-West University, South Africa (johan.duplessis@nwu.ac.za)
2 Technology Transfer and Innovation Support Office, North-West University, South Africa
BENCHMARKING OF FDM PRINTED REPLACEMENT PARTS FOR RURAL WHEELCHAIRS

W.A. Kinnear¹*, J.G. van der Walt¹, V. Rossouw², G.J. Booysen³

ABSTRACT
Paraplegic and other patients rely on wheelchairs for mobility to participate as equal citizens within society. Wheelchairs supplied through state healthcare are often not well suited to especially rural conditions and often break down. This study investigates if entry-level fused deposition modelling can be used to produce parts that commonly fail on wheelchairs at reduced cost compared to commercially available parts while still retaining good durability.

1. Introduction
A wheelchair is one of the most commonly used assistive devices, enabling many patients to become mobile and thus participate fully in community life. An estimated 1% of the world’s population (65 million), need a wheelchair [1] while this number is roughly 2.3% (1.2 million) in South Africa [2]. Due to a lack of governmental funding and the large demand, therapists are forced to prescribe cheaper less effective wheelchair designs. This problem is further highlighted in the rural areas where the basic folding frame wheelchair design is supplied to patients. These wheelchairs are for low activity, indoor environments and not rural settings often with dirt roads. These factors imply a high turnover of wheelchairs thus increasing the load on supply. Imported wheelchairs are not supplied with spare parts and local spares often do not fit them. Importing the missing component sometimes costs more than purchasing a new locally produced wheelchair [3]. Presently wheelchairs in the governmental sector are maintained by therapists or local hospital maintenance personnel, depleting their already limited time and resources. A lack of repairs leads to many wheelchairs being discarded. The front caster wheels and seat post guides have been found to be the two parts that mainly fail on wheelchairs in a rural environment.

This study aims to determine if low cost fused deposition modelling (FDM) and additive manufacturing (AM) can be used to produce custom made durable parts to replace parts that commonly fail on wheelchairs. FDM process parameters (orientation, layer height, raster angle, print speed and air gap) has a major effect on the mechanical properties of parts produced [4]. Lužanin et al. [5] studied the influence of layer thickness, deposition angle and fill density on flexural strength PLA Fused Deposition Modelling (FDM) samples and showed that this has a significant effect. A study conducted by Es Said et al. [6] examined tensile strength, modulus of rupture, and impact resistance for different layer orientations of ABS models. The 0° orientation samples displayed superior strength (20.6MPa) and impact resistance (44.4Mpa) compared to all other orientations. Lee et al. [7] employed the Taguchi method to find the optimal FDM process parameters for ABS, concluding that layer thickness, raster angle and air gap significantly affect the material’s elastic performance.
2. Methodology and results

2.1 Methodology
The entry level Wanhao I3 plus was selected as the FDM machine to conduct this study. It can be readily purchased at low cost in South Africa, it is easy to setup and use and produces high quality parts for its price range. The following experimental procedure was followed to test the suitability of this FDM printer for printing wheelchair parts:

- A standard test geometry was printed in Wanhao supplied ABS and PLA material using the machine’s standard process parameters. The dimensions of the various features on the test geometry were measured with a digital Vernier calliper.
- The mechanical properties of ASTM D638 Type IV tensile samples that was FDM printed in ABS and PLA were determined. Different percentages of fill density (25, 50, 75, 100%) and shell thicknesses (0.8, 1.2 mm) were compared at different part orientations to find the settings best suited for printing wheelchair parts.
- A finite element analysis was performed on a case study caster wheel using data from the mechanical properties of the ABS and PLA materials used.
- A cost comparison was performed between FDM printed wheelchair parts and commercially available parts.
- FDM printed caster wheels were installed on a wheelchair and tested in a real-world environment as a case study to demonstrate the durability of the parts.

2.2 Results
Table 1 shows initial results on mechanical properties of ABSA test pieces manufactured at different fill densities and shell thicknesses.

<table>
<thead>
<tr>
<th>% Fill</th>
<th>Shell thickness (mm)</th>
<th>Yield strength (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation</th>
<th>Young’s modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>25</td>
<td>1.2</td>
<td>28.875±0.75</td>
<td>28.9±0.7</td>
<td>1.883±1.139</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.8</td>
<td>29.214±0.847</td>
<td>29.2±0.8</td>
<td>1.432±1.099</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.2</td>
<td>29.52±1.083</td>
<td>29.5±1.1</td>
<td>2.210±0.749</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>0.8</td>
<td>28.74±4.885</td>
<td>31.8±0.3</td>
<td>1.953±0.76</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.8</td>
<td>30.54±4.68</td>
<td>41.1±1</td>
<td>2.7±1.6</td>
</tr>
</tbody>
</table>

3. Conclusion
At the time of submission of this abstract, all experimental work has not been completed. Initial mechanical testing of FDM printed test pieces however showed encouraging results in terms of the intended application. Initial geometrical test samples also showed good accuracy. All experimental results will be presented in a full paper.
BENCHMARKING OF FDM PRINTED REPLACEMENT PARTS FOR RURAL WHEELCHAIRS continued

REFERENCES


1 Department of Mechanical and Mechatronics Engineering, Central University of Technology, South Africa (wahinnear@cut.ac.za)
2 Department of Occupational Therapy, Free State Department of Health, South Africa
3 Centre for Rapid Prototyping and Manufacturing, Central University of Technology, South Africa
A THEORETICAL FRAMEWORK FOR MATERIAL SELECTION IN 3D PRINTING SOLUTIONS TO CRANIOFACIAL RECONSTRUCTION IN BURN VICTIMS

W. Gova1, A. van der Merwe1*

ABSTRACT
Thermal injuries affect over a million people in South Africa annually. There are currently limited solutions focussed on reconstructive tissue regeneration of craniofacial thermal injuries involving cartilaginous tissue such as the ear and nose. The potential of 3D printing producing scaffolds to assist with reconstruction of complex three-dimensional tissue such as the ear and nose has been demonstrated by some scholars. The current paper systematically identifies novel materials, synthesis techniques and suitable 3D printing technologies to be further developed for production of tissue scaffolds for reconstructive regeneration of cartilaginous craniofacial tissue for a PhD project.

1. Introduction
In South Africa, almost 3.2% of the population is affected by thermal injuries in one way or the other [4]. Hospital admissions because of burns is approximated at 18% of total admissions, with around 6% of these cases being reported to the private sector, due to hospital cost limitations. The rest of these cases are managed by provincial facilities. The cost of managing burn wounds is estimated to be around R4000 per patient per year [5]. The management of burn wounds affecting cartilaginous tissue is currently still limited to replacement with synthetic implant materials, ear prostheses and autologous implants derived from rib cartilage [2,4]. These approaches only allow for application of an epidermal autograft to regenerate permanent composite skin over the burn. In cases where the thermal injury includes the cartilage framework of the nose and ear, current reconstructive surgeries do not result in recovery and regeneration to the morphology of craniofacial cartilaginous tissue to reverse the mutilating effects of thermal injuries needed to better the quality of life of burn victims [4].

The use of 3D printing has been demonstrated to have great potential in assisting to produce the extracellular matrix required for cartilage tissue scaffolds to facilitate reconstruction of the complex shape of the ear and nose [1,3]. The current submission discusses current developments in 3D printing with a specific focus on its application to craniofacial reconstruction of cartilaginous and other hard tissue. This paper will outline challenges that will be addressed in the PhD project for the design of prototypes that can be scaled up to clinical solutions.

2. METHODOLOGY AND RESULTS

2.1 Fishbone analysis and manufacturing readiness assessment
Fishbone analysis and manufacturing readiness level (MRL) assessment of 3D printed scaffolds for use as frameworks in three-dimensional reconstruction of craniofacial tissue to assist in identifying suitable novel research focus areas for a PhD project currently underway.
Wu et al. [6] successfully demonstrated the applicability of the technology and manufacturing readiness level model (TRL and MRL) of the U.S. Department of Defence to assess manufacturing maturity in bioprinting research. The study managed to address technology readiness level (TRL) and MRLs of engineering challenges and gaps associated with translation of bioprinting from laboratory to large scale manufacture of tissues and organs. Fishbone analysis of the various MRL sub-threads for 3D printing of scaffolds for craniofacial reconstruction will be conducted as shown in Figure 1. The fishbone analysis will be conducted to evaluate all the MRL and TRL threads and sub-threads on a 9-point scale to determine the extent and scope of current research to appraise focus areas for the current study in respect of craniofacial reconstruction after thermal injury.

Materials is one of the key focus areas for current research identified by an MRL assessment conducted by Wu et al. [6] on bioprinting. However, this approach excludes evaluation of 3D printing techniques involving non-biological materials such as titanium. A similar approach will be conducted for selection and production of materials for 3D printing specifically focused on production of scaffolds for reconstruction of craniofacial tissue following mutilation by thermal burns.

![Fishbone diagram](image)

**Figure 1**

*Fishbone analysis of MRL sub-threads for 3D printing of scaffolds in craniofacial reconstruction applications*

The sub-threads of material selection and MRL challenges and gaps to be assessed in more detail and addressed in the current study before scaling is possible are shown in Table 1.
A THEORETICAL FRAMEWORK FOR MATERIAL SELECTION IN 3D PRINTING SOLUTIONS TO CRANIOFACIAL RECONSTRUCTION IN BURN VICTIMS continued

Outcomes of this paper will assist in the development of a theoretical framework for selection criteria of materials for use in 3D printing of scaffolds reconstruct craniofacial cartilaginous tissue.

3. Conclusion
The current study will specifically focus on TRL and MRL assessment of materials for production of 3D scaffolds for reconstructing the complex three-dimensional framework of craniofacial tissues after thermal injury. The assessment will highlight gaps and challenges that need to be immediately addressed to bring research in this field a step closer to fullscale clinical production.

REFERENCES


1* Department of Industrial Engineering, Stellenbosch University, South Africa (16353315@sun.ac.za)
A COMPARATIVE STUDY ON LASER PROCESSING OF COMMERCIALIY AVAILABLE TITANIUM ALUMINIDE POWDER AND IN-SITU ALLOYING OF TITANIUM ALUMINIDE

S. Hoosain¹*, L. Pityana¹,², M. Tlotleng¹,³, T. Legopeng¹, B. Masina¹

ABSTRACT
Laser cladding or laser metal deposition involves the deposition of any weldable material onto the surface of a metal substrate by means of a laser beam. The process uses a high power laser beam focused onto a metallic substrate to generate a molten pool to which a stream of powder is fed. This way, the material volume increases leading to the formation of a solid layer. Titanium aluminide is acknowledged as a promising high temperature structural material due its high melting point, high strength to density, high elastic modulus and high creep strength. Due to its low ductility it is difficult to machine using conventional manufacturing techniques. Titanium aluminide components have been successfully produced using the cast methods but prove to be very expensive and time consuming. In situ alloying using laser processing is a potential method of manufacture of these alloys as elemental powders can be fed separately from different powder feeders and the feedrate can be controlled and hence the composition can be controlled. Using this method, in situ alloyed powder and commercial General Electric (GE) powder was processed on a 3kW IPG laser. The goal was to determine if suitable parameters could be found to produce an in situ alloy as close as possible to the commercial alloy in terms of composition and microstructure.

1. Introduction
Dual phase gamma titanium aluminides (γ-TiAl) is a promising candidate material in high temperature aerospace and automotive gas turbine engines to replace Ni-based superalloys for its high specific strength, high stiffness, good corrosion resistance, high creep resistance between 600 - 750°C, and oxidation resistance. Casting metallurgy methods followed by hot isostatic pressing (HIP) are commonly accepted by industry for raw γ-TiAl material production before mechanical processing but prove to be very expensive and time consuming [1]. The brittleness and low fracture toughness of γ-TiAl makes it difficult to manufacture using conventional methods. Direct energy deposition using laser processing is a potential method of manufacture of these alloys as elemental powders can be fed separately from different powder feeders and the feed rate can be controlled and hence the composition can be controlled to develop the γ-TiAl [1,2]. Using this method, in situ alloyed powder and commercial GE powder was processed on a 3kW IPG laser. This study looks into the effect of the processing parameters on the in-situ alloy composition and microstructure and compares this to the commercial alloy.

2. Methodology and results
An IPG Nd:YAG 3kW laser was utilised in these experiments for the deposition of single clad tracks onto Ti6Al4V substrates. The clad metal was commercially available Ti-48Al-2Cr-2Nb powder with -90 +45 µm particle size. It was carried to the workpiece by means of a GTV powder feeder together with an ILT three-way cladding nozzle. The same set-up was repeated on in-situ alloyed powder. Pure titanium powder was mechanically alloyed with Nb and Cr powders. This powder was then alloyed in-situ with the
aluminium powder using two powder feeding hoppers. The feed rate of the hoppers were varied to evaluate its effect on composition and microstructure. Samples were cut, polished, and etched according to standard metallographic procedures for titanium alloys. Microstructures of the commercial alloy are shown in Figure 1 showing the lamellae microstructure typical of this alloy. Energy Dispersive X-ray Spectroscopy (EDS) scans were also conducted in these samples shown in Table 1.

| Table 1: EDS composition of the commercial Ti--48Al-2Cr-2Nb alloy |
|-----------------|------------------|------------------|
| Formula | Mass % | Atom % |
| Al | 40.7 | 54.75 |
| Ti | 55.44 | 42.67 |
| Cr | 2.56 | 1.81 |
| Nb | 1.93 | 0.77 |

3. Conclusion
Initial work was done on the commercial Ti-48Al-2Cr-2Nb alloy to evaluate the microstructure and composition as a starting point. Work still needs to be done on the in-situ alloy to acquire a composition and microstructure comparable to the commercial alloy.

REFERENCES
A COMPARATIVE STUDY ON LASER PROCESSING OF COMMERCIAL AVAILABILITY TITANIUM ALUMINIDE POWDER AND IN-SITU ALLOYING OF TITANIUM ALUMINIDE continued


1* National Laser Center, CSIR, South Africa (shoosain@csir.co.za)
2 Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, South Africa
3 Department of Mechanical Engineering, University of Johannesburg, South Africa
3D PRINT DESIGN COMPETITION

The 3D Print Design Competition is a national competition that forms part of the annual Rapid Product Development Association of South Africa (RAPDASA) conference.

The competition is aimed at encouraging designers, engineers & artists to use the latest technology, to promote awareness of Additive Manufacturing (AM) and attempts to gauge the country’s capability to design and engineer for AM.

This year’s challenge (the same as last year’s) was to design a miniature mechanical object (gadget), especially an ingenious or novel one, to make life easier, simpler, better or just more fun. The 5 categories to choose from are: Engineering, Household, Industrial Design & Functional Art, Education, & Toys.

Turbo Vacuum | Stefan Heusser | info@heusser.co.za

This small device turns a balloon into a portable vacuum cleaner. The concept of based on a turbocharger setup common on many automobiles. The advancement of 3D printing allows for the printing of complex parts of small parts, previously prohibitively expensive. The design consists of a turbine stage (with an inflated balloon attached), which converts the balloon pressure into rotational movement of the turbine wheel. This turbine wheel is connected to a compressor wheel inside the compressor stage. This compressor wheel is, in fact, a mirror image of a standard compressor, causing it to create a vacuum rather than compressing air. This vacuum air passes through a nozzle the accelerate the air flow. This small design is portable and uses no electricity. Ideal for cleaning small hard-to-reach areas such as circuit boards/heatsinks, keyboards, car cup holders, ashtrays and behind appliances.
Emma Phone Stand | Hendo Jordaan | hendo.jordaan@gmail.com

‘Emma’ is a desktop phone stand which uses a few mechanisms to allow the user to tilt and orient the smart phone as needed. It also has space for USB storage devices, pens and routing for the charger cable. It uses a Globoid worm gear for tilt and a rack and pinion system for adjusting the width of the legs/cradles. All parts are easily printed without any supports.

Visual Aid for Engineering Drawing Projections | Jessica du Toit | dutoit.jessica@gmail.com

A visual aid for high school level technical drawings students.
3D PRINT DESIGN COMPETITION continued

**Swivel Video Call Bracelet | Jeane Bresler | jeanebresler@gmail.com**

A device that allows you to make video calls while you have the freedom to move around and use both hands.

---

**Gunslinger Set | Ashley Toth | ashleydillontoth@gmail.com**

The design of the gunslinger set is to have a realistic weapon look that involves similar principles of reloading and trigger activated firing but without the danger of hurting people in the process. The set includes four types of 3D printable guns ranging from single fire (simple trigger mechanisms) to semi-automatic (complex trigger mechanisms). The intent is to create a device that is new, fun, and safe to use for all parties involved.
RAPDASA is a non-profit organisation that aims to be a platform to connect academics, industry partners and companies in the field of Additive Manufacturing (AM), with a strong focus on 3D printing.

www.rapdasa.org