Additive Manufacturing as a key driver of the 4th industrial revolution

6 - 9 NOV 2018
PROTEA PARKTONIAN, BRAAMFONTEIN, JOHANNESBURG

BOOK OF ABSTRACTS AND PROGRAMME BROCHURE
This year, the 2018 RAPDASA conference is hosted in Johannesburg in collaboration with the University of Johannesburg and Resolution Circle. We have aimed to make this conference the biggest in this field in South Africa to date. We have also made our highly regarded exhibition space open for free to the public (upon registration), in the hope that this will increase RAPDASA’s as well the exhibitors’ exposure and footprint. Additive Manufacturing has the typical South African flavour, one of innovation in unique circumstances, which I’m sure will be demonstrated again this year at the conference.

This year theme is Additive Manufacturing as a key driver of the 4th industrial revolution and includes 50% international keynote speakers. We have 53 technical presentations running in three parallel streams and 21 exhibitors.

The RAPDASA management committee together with the University of Johannesburg and Resolution Circle would like to welcome you to this conference. We hope the conference will inspire you towards further innovation and be integral to South Africa’s 4th industrial revolution.

As always, we are most grateful to our sponsors, exhibitors, our presenters and participants without whom this event would certainly not be possible.

Prof. Thorsten Becker
Chairperson
COMPANY DESCRIPTION

Lonmin plc is a producer of platinum group metals (PGMs) operating in the Bushveld Igneous Complex of South Africa. One of the largest platinum producers in the world, it is listed on both the Johannesburg and London Stock Exchanges. It has its registered office in London and operational headquarters in Marikana, South Africa. It operates a platinum refinery in Brakpan, Gauteng. It is committed to finding ways of enabling South African and global entrepreneurs to work and use platinum group metals as a raw material input in innovative product solutions for commercial gain.

PlatForum is a collaborative venture between Lonmin, Central University of Technology, Vaal University of Technology and the North-West University aimed at exploring new applications for platinum group metals through additive manufacturing. It offers its industrial partners a unique, cost effective means of prototyping their components and objects using actual PGMs, and it also develops its own new designs and applications.
COMPANY DESCRIPTION

It is imperative to enhance the manufacturing competitiveness of South African foundries to increase local content and exports. Increased R&D levels are key requirements for competitiveness and the development of competencies. Access to knowledge and its successful use and implementation in innovative products, processes and services are increasingly important for sustainable economic growth and for securing and creating employment and income opportunities. In recognition of this imperative, the Department of Trade and Industry (the dti) established the NFTN. The National Foundry Technology Network (NFTN) has a mandate to improve the competitiveness of the local foundry industry, especially distressed foundries. The NFTN manages, coordinates and facilitates transformation and development of the casting industry sub-segment, particularly in the product supply-chains and at manufacturing level, through focused interventions, designed to enable local South African foundries to become globally competitive. Skills and supplier development are key areas of focus. The NFTN was established in 2008 at the height of the global recession. It is funded by the Department of Trade and Industry (the dti), and hosted by the Council for Scientific and Industrial Research (CSIR).

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- Foundry Capacity Building
- Technical and Regulatory Support to Industry
- Human Capital Development, Skills, and Knowledge Transfer.
- Stakeholder Relations, Awareness Raising and Communication
COMPANY INFORMATION

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COMPANY DESCRIPTION

3D Printing Systems SA opened its doors for business in 2013. Our aim was to bring the UP portable desktop 3D printer range to the South African market. The UP range had the UP Plus 2 and the UP mini, two very reliable and easy-to-use printers. This was followed by the UP BOX and UP BOX+ and this year, we have added a superb new printer to the range. We would like to introduce the all new UP300 3D printer to the RAPDASA delegates.

The UP300 is designed for users needing a large build volume (255mm x 205mm x 225mm) and consistent performance across different materials. It combines new innovations with improved UP features and renowned reliability.

New features include:

- Material-Specific Print Heads - Optimized for different materials - One for ABS and other high temperature filaments, one for lower temperature filaments such as PLA, and the third for TPU, flexible polyurethane.
- Double-Sided Interchangeable Build Plates with one side a glass surface. This new print board allows for easier print job removal because of its rigidity.
- Dual Air Filtration Version 2 - Healthier 3D Printing via two air filters.
- Control and Monitor Print Jobs with a 4.3” full-colour LCD Screen - Puts the new print queue, print job settings and print job status at your fingertips.
- Tieretime Print Queue - Any user on the network can become the queue’s administrator, controlling and reordering the print queue.
- Print directly from USB Stick.

- Ethernet Connection - In addition to Wi-Fi, the UP300 includes a LAN Port for those preferring to work in a more secure, hard-wired network environment.

This high quality production printer, at a very competitive price, fits into most budgets. Come and see this printer at our stand during the course of the conference.
COMPANY DESCRIPTION

Founded in 1985, Altair is focused on the development and application of simulation technology to synthesize and optimize designs, processes and decisions for improved business performance. Privately held with more than 2,600 employees, Altair is headquartered in Troy, Michigan, USA with more than 45 offices throughout 20 countries, and serves more than 5,000 corporate clients across broad industry segments.

The Altair solidThinking package offering is focused on simulation-driven design solutions applied early and throughout the design process for industrial design, photorealistic rendering, model-based development, generative design, concept engineering and manufacturing feasibility.

Altair is a leading provider of enterprise-class engineering software enabling innovation, reduced development times, and lower costs through the entire product lifecycle from concept design to in-service operation. Our simulation-driven approach to innovation is powered by our integrated suite of software which optimizes design performance across multiple disciplines encompassing structures, motion, fluids, thermal management, electromagnetics, system modeling and embedded systems, while also providing data analytics and true-to-life visualization and rendering.

Altair Inspire software is the industry’s most powerful and easy-to-use Generative Design/Topology Optimization and rapid simulation solution for design engineers. It enhances the concept development process by enabling simulation-driven design to increase your product’s efficiency, strength and manufacturability. This can lead to reduced costs, development time, material consumption, and product weight.

SolidThinking Units are Now Available

SolidThinking Units transform the way you obtain software by eliminating the traditional licensing hurdles; like high cost, limited access to software and multiple licensing mechanisms. This new software licensing model offers your team seamless access to a growing library of Simulation-driven Design solutions using one single pool of recyclable units.

Rich 2D & 3D data visualization
COMPANY INFORMATION

CRPM is hosted by Central University of Technology, Free State
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COMPANY DESCRIPTION

The Centre for Rapid Prototyping and Manufacturing (CRPM) at
Central University of Technology, Free State (CUT) specialises in
Additive Manufacturing (AM), better known as 3D printing. The
CRPM was established 1997 as a centre for commercial work as
well as research using Rapid Prototyping, Rapid Manufacturing,
Rapid Tooling and Medical Product Development technologies.

In Medical Implant Development, Computer Tomography (CT)
scan data is used as input, to develop 3D CAD data for AM
processes. The CT data is imported into Mimics, a general-
purpose segmentation program for grey value images,
which performs segmentation by thresholding to identify
bony structures or soft tissue (on schematic (No 1). The 3D
reconstructed data of the anatomy is exported as a STL file to
Magics software, where implants for reconstructive surgery can
be designed to fit onto the virtual model of the skeletal area
involved (No 2). The implant data is then exported as a slice file
to the AM machine, where the implant is fabricated in a layer-
by-layer process according to each consecutive virtual slice.
Medical implants can be produced directly in bio-compatible
titanium on the CRPM’s EOSINT (M280) Direct Metal Laser
Sintering machine (No 3). Post processing like polishing and
cleaning of the DMLS produced implant can be performed (No
4). Final fitment (No 5) of the implant can be done on a pre-
operative model before the operation, to identify fixation. The
DMLS produced prosthesis is implanted during surgery (No 6).

Models of any part of the skeleton can be produced from CT
data in nylon on the CRPM’s EDS INT P380 or in translucent
resin on a 3D-Systems Viper stereo lithography machine.
Surgeons can use these models for inspection, planning and
risk assessment as well as for test-fitting of surgical jigs, fixtures
and implants before the operation is performed.

3D Design software together with the flexibility of the AM
processes allow for the fabrication of custom-made medical
equipment and devices that would be difficult or impossible
through conventional machining techniques. The Product
Development Technology Station (PDTS) at CUT together with
the CRPM have already developed a number of successful
medical devices, some of which are currently being patented
and commercialised.
EXHIBITORS & SPONSORS

COMPANY INFORMATION

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COMPANY DESCRIPTION

The Product Development Technology Station (PDTS), funded by the Technology Innovation Agency (TIA), assists SMMEs in becoming globally competitive by providing them with the technological support they need to design and manufacture innovative new products.

The station makes use of first-class engineering expertise at Central University of Technology, Free State (CUT) as well as specialized prototyping equipment to support businesses and individuals through the entire new product development process.

Expert Services:

- Product Enclosure Development
- Agricultural Equipment Development
- Machine Design and Manufacturing
- Tool Development
- Short Run Production

Innovative Technologies:

- CAD designs
- Finite Element Analysis
- Rapid Prototyping
- Reverse Engineering
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COMPANY DESCRIPTION

The VUT Southern Gauteng Science and Technology Park is a strategic technology hub in the Southern Gauteng region and is based in Sebokeng in the Vaal. It is supported by a multi-disciplinary skilled workforce, with 172 hectares of land and boasts world class technology programmes in Advanced Manufacturing, all geared to support industrialisation and job creation. To capitalise on our unique value proposition, we will make an impact in the region through focusing our capabilities in driving two flagship programmes, one in Advanced Manufacturing and the other in Agriculture Revitalization.

The strategic location, available infrastructure as well as the current entrepreneurial culture makes the VUT Science Park an ideal implementing agency for driving regional government programmes within the Southern Gauteng Region. The VUT Science Park’s vision is to be a leading Science and Technology Park that makes a significant contribution to wealth creation & welfare of the Southern Gauteng region through stimulating technology-based sustainable enterprises. VUT Science Parks works with various partners to drive the Science Park’s vision.

Mission

To provide unique and flexible innovative solutions with strategic partners so as to make impact to communities through stimulating sustainable enterprises.

Vision

To be a leading Science and Technology Park that makes a significant contribution to the wealth & welfare of the people of Southern Gauteng Region.

Value Proposition

The Science Park has unique value offering which includes:

- University owns 172 hectares of land with infrastructure such as large auditoriums, office space and incubation facilities.
- Located within a community of Sebokeng and surrounded by major industrial partners such as Arcelor Mittal, Sasol, etc.
- Easy access to road and rail services.

Operates a unique world class Advanced Manufacturing Precinct to assist entrepreneurs develop product prototypes and employs engineers, scientists, design and Additive Manufacturing specialists.

Strategic Focus Areas

Our strategic focus areas align with government priorities and with our competitive advantage. We will service clients in various sectors such as fashion, hospitality and tourism and Information and Communication Technology (ICT), however, our selected focus areas include:

- Advanced Manufacturing Precinct
- Agriculture and Agro-processing
- Green Technology Unit
- Footwear and Leather
- Enterprise Development Unit

Strategic Goals

- To support enterprise and regional industrial development
- To foster research, innovation and technology development
- To foster partnerships and communicate impact
- To develop an efficient and financially sustainable organisation
COMPANY DESCRIPTION

The National Advanced Plastic Injection Moulding (NAPIM) network was initiated at the CUT during February 2018. The mission of NAPIM is to establish a national simulation network of Higher Educational Institutes and industrial partners to support local toolmaking enterprises to provide improved tools and services cost-effectively to the manufacturing industry. Such enhancements could improve the global competitiveness of local manufacturing companies and will assist in skills development for the injection mould manufacturing industry.

COMPANY INFORMATION

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COMPANY DESCRIPTION

The vision of the Department of Science and Technology (DST) is increased well-being and prosperity through science, technology and innovation (STI). Its mission is to provide leadership, an enabling environment and resources for STI in support of South Africa’s development.

The DST’s interventions are based on the 1996 White Paper on Science and Technology, the 2002 National Research and Development Strategy and the 2008 Ten-Year Innovation Strategy, as well as the National Development Plan, which sees STI playing a central role in the achievement of its goals. A new White Paper on STI is being developed.

Most of the DST’s programmes are implemented by science councils and public entities such as the National Research Foundation (NRF), the Human Sciences Research Council, the Academy of Science of South Africa, the Technology Innovation Agency, the South African Space Agency, and the Council for Scientific and Industrial Research (CSIR).

The CSIR hosts the Collaborative Programme in Additive Manufacturing (CPAM), which represents the initial implementation of the research, development and innovation (RDI) elements of the South African Additive Manufacturing Strategy.

The Strategy, formally adopted by the DST in November 2016, was developed to guide role players in identifying opportunities, addressing technology gaps, focusing development programmes, and informing investment decisions that will enable local companies and industry sectors to become global leaders in selected areas of additive manufacturing (AM). It identifies four priority areas for the development of AM in South Africa, including qualifying processes/parts for the medical and aerospace industries, and introducing AM technology to small, medium and microenterprise (SMME) industries in the country.

The CPAM aims to increase the manufacturing readiness of AM, in order to advance the adoption and utilisation of additive manufacturing as an accepted and viable manufacturing technology. The programme focuses on RDI support for the additive manufacturing of titanium medical implants and aerospace components, polymer additive manufacturing, and design for additive manufacturing.

Another DST-supported initiative is the Aeroswift project, a collaborative partnership between the National Laser Centre at the CSIR and the Aerosud Innovation and Training Centre. The aim is to develop a metal powder-bed system that is about five times faster than current machines, with a potential printing volume about 10 times greater than existing machines.

Since 2015, the DST has also supported a DST-NRF SARChI Research Chair in Medical Product Development at the Central University of Technology’s Centre for Rapid Prototyping and Manufacturing. The research focus is the use of additive manufacturing for the design and manufacture of medical equipment, assistive devices for people with disabilities, and patient-specific implants.

These additive manufacturing initiatives contribute to the DST’s goal of socio-economic development through new knowledge and technological innovation, and to a better life for all South Africans.
COMPANY DESCRIPTION

AMTC Pty Ltd specialise in supplying innovative AMT (Additive manufacturing Technology) and services to our clients, enabling them to benefit from AMT to simplify manufacturing process throughout all business divisions and departments. In short SIMPLIFIED MANUFACTURING!!

Services

- AMT Consulting, development of business cases that include, cost models, Supply chain disruption and Performance factors

- Design for additive manufacturing (DFAM or DFAM) is design for manufacturability as applied to additive manufacturing (AM). We use general type of design methods or tools whereby functional performance and/or other key product life-cycle considerations such as manufacturability, reliability, and cost can be optimized subjected to the capabilities of additive manufacturing technology used.

- We have partnered with ABB Robotics to provide customers a complete “Turn Key” solution for their automation needs.

Equipment Supplier

Metal 3D Printers

Desktop Metal Studio+, Studio Fleet and Production Systems. 17 Core Metal Materials.

FDM Printing systems for Composts and engineering plastics.

ABB Robotics arms and end effectors design and manufacturing equipment.

Printing as a service Via AME Pty Ltd

Proto type printing, Molds, Jigs, Dies & Fixtures, Functional parts, Bridge Manufacturing 10 to 500 units, Custom Parts, Sand casting and Investment casting patterns.
COMPANY INFORMATION

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COMPANY DESCRIPTION

BunnyCorp Pty Ltd is a Rapid Product Development Company in South Africa with more than a decade’s worth of experience in Product Development and Additive Manufacturing, working with FDM, SLA and specialising in Design for SLS processes. Our experience gives us a unique understanding of the different 3D Printing processes, the Design Advantages and the Restrictions that comes with each of these Additive as well as Subtractive Technologies.

Our Services Include:

- Concept Development, Design, CAD Modelling & Digital Sculpting, Prototyping for Product Development for various industries ranging from aerospace, defense, toys to medical products, medical being the predominant industry with focus on prosthetics for humans and animals. We incorporate 3D printing as a tool to communicate with clients, fast track product development with various applications from prototypes to tooling and in some cases the actual product.

- Design, 3D Modelling & Digital Sculpting and Manufacturing for the Jewellery industry in South Africa, UK, Australia and the United States with the emphasis on complex geometry, intricate detail and organic shapes.

- CAD training is one of our cornerstones services, being specialized in various CAD packages we also supply training to various industries and educational institutions with a growing portfolio of training material an published training manuals, clients include the Jewellery Industry, Automotive, Furniture Design, Interior Design and Virtual Reality Industry.

- Design, CAD Modelling, Digital Sculpting, prototyping and manufacturing of props for the Film, Television and advertisement industries, including marketing and other events companies.

- Design, CAD, Digital Sculpting and Compositing for the Virtual Reality Industry with projects ranging from Architectural, Corporate to Gaming.

- Design, Consultation, Digital Sculpting & Modelling for the Art Industry ranging from big public Sculptures to smaller curio products.

EXHIBITORS & SPONSORS
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COMPANY DESCRIPTION
Published since 1981, Dataweek is South Africa’s leading magazine dedicated to electronics, offering highly informed commentary to engineering and purchasing personnel involved in the design, production and maintenance of electronics equipment. Dataweek keeps pace with a highly innovative industry where continuous technology updates are vital to its readers.

Dataweek has become the premier South African publication in its field due to its solid coverage of the latest developments. Dataweek serves electronics engineers, design engineers, technicians, R&D and business professionals in Southern Africa, covering the full spectrum of electronics and communications in areas such as:

- Analogue and mixed signal, LSI
- Circuit & System protection
- Computer/Embedded technology
- Contract Manufacturing/OEMs
- Design Automation
- DSP, micros & memory
- Electronics Production, Manufacturing
- Electronics Technology
- Enclosures, Racks, Cabinets & Panel Products
- Interconnection
- Opto-Electronics
- Passive Components
- Power electronics/management
- Production technology/equipment/packaging
- Programmable Logic
- Switches & Relays
- Telecoms, Datacoms, IoT, Wireless
- Test & Measurement
- And more……

Dataweek is published in print, online and supported by twice weekly news briefs.

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COMPANY DESCRIPTION
voxeljet is one of the world’s leading manufacturers of large-format and fast 3D printing systems and operates service centers in Germany, India, China, the UK and the USA for the economical on-demand production of molds and models for industrial customers in accordance with German quality standards.

The core technology of voxeljet is powder-binder-jetting technology of sand and plastic for the production of casting components. Initially developed for the foundry industry voxeljet products now find utilization in a wide variety of applications. Printed sand molds and plastic models can be used for concrete casting and architectural visualization. The printed molds can be reused and ensure consistent concrete properties at all times since the molds can be integrated into any established process. Furthermore, sand printed components can be used for laminating and vacuum-forming processes. Architects, designers and engineers can apply the technology to realize unique ideas through the geometric freedom that 3D printing grants.

With its new polymer-based process High Speed Sintering (HSS) voxeljet developed a Binder Jetting Process which is ideal for the production of functional prototypes and end-use parts. In addition, customers can adapt their HSS system to their own materials and requirements in a unique open source program.

Due to voxeljets high degree of competence and longstanding experience in the field of powder-binder-jetting, specific part requirements can be tailored to individual customer needs. This means high-performance materials such as ceramics can also be processed using voxeljet 3D printing systems.

The customer portfolio of voxeljet includes renowned automobile manufacturers, the aerospace industry, as well as mechanical engineering, consumer goods, the film and entertainment industry and art and architecture industries. Hereby the main applications are molds and cores for sand casting, plastic models for investment casting, as well as display models, functional prototypes and end-consumer parts.
COMPANY DESCRIPTION

Materialise Software provides companies with a platform of software tools that manage and control the 3D printing process more efficiently, allowing them to meet the highest standards of the most demanding industries. Materialise Software’s suite of solutions, Materialise Magics, includes industry-leading data preparation and design optimization tools, programs to integrate 3D printing into production environments, and software and control systems used by machine manufacturers to better bridge the gap between applications and 3D printers. These solutions are open by nature, empowering co-creation and collaboration between different players in the 3D printing and manufacturing eco-system and providing the industry a solid foundation on which to expand and grow.

COMPANY DESCRIPTION

Rapid 3D is a business, originally founded by a family of engineers, is thriving due to a strong focus on workable, reliable 3D printing solutions.

Solutions that make good business sense.

Rapid 3D is proud to be the official distributors, in Southern Africa, for the world’s leading 3D printing and Additive Manufacturing brands. These principal brands include EOS (Electro Optical Systems GmbH), EnvisionTEC, Markforged, 3D Systems, 3D Platform and Zortrax. Additive Manufacturing (AM) and 3D printing are relevant to many industries. As such, one vendor cannot excel in all industries. It is for this reason that Rapid 3D have carefully chosen the best-in-class vendors for each of the industries we serve.

This strategy allows us to offer best-fit technology to each of our customers, without having to compromise due to vendor technology lock-in.

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COMPANY DESCRIPTION

Weartech offers a comprehensive range of products for the use, in wear, corrosion and hardfacing applications, as well as maintenance and fabrication. We have three divisions that offer different products, but often complement each other in the industries we serve. This allows us to offer our customers single supplier simplicity. One of our divisions, is the Speciality Metals Division, which offers Nickel, Cobalt, Iron and Titanium Powders for Additive Manufacturing. Weartech is a family business and was founded in 1984 and currently operates from Johannesburg, Durban and Cape Town.
COMPANY DESCRIPTION

The Metal Casting Technology Station [MCTS] is a technology transfer partner for the metal casting industry, pioneering development through training, research and technology support.

A non-profit initiative funded by the Department of Science and Technology through the Technology Innovation Agency [TIA]. The Technology Station operates from the University of Johannesburg in the Department of Research and Innovation and in partnership with the Department of Metallurgy.

The MCTS supports and assists the metal casting industry - foundries, suppliers, related industries - to improve the sectors innovation ability for increased competitiveness and sustainability.

**Our focus:**
- Research
- Casting Design and Simulation
- Education and Training
- Physical Metallurgy
- Rural and Emerging Foundries
- Sand Technology

**Our core services:**
- CAD Design
- Casting Simulation
- Additive Manufacturing
- Technology Demonstration
- Training
- Technology Development
- Materials Testing
- Metallurgical and Failure Analysis
- Moulding Systems Analysis and Troubleshooting
- Moulding Material Analysis and Development
- Internship

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COMPANY DESCRIPTION

The Council for Scientific and Industrial Research, commonly known as the CSIR, is a world-class African research and development organisation established through an Act of Parliament in 1945. Its executive authority is the Minister of Science and Technology. The CSIR undertakes directed, multidisciplinary research and technological innovation that contribute to the improved quality of the life of South Africans.

The organisation plays a key role in supporting government’s programmes through directed research that is aligned with the country’s priorities, the organisation’s mandate and its science, engineering and technology competences. The CSIR fosters partnerships with a network of partner organisations and clients, regionally and abroad, as part of a global sphere of influence on matters of technology.

We draw expertise from diverse research fields to provide integrated solutions and interventions to support a broad range of national development programmes, as set out in the National Development Plan. Our national footprint is testament to our commitment to serving diverse communities and sectors, with the CSIR’s main campus located in Pretoria and our regional offices in Durban, Johannesburg and Stellenbosch – in proximity to applicable industries across the country.

Impact is at the core of our business and the following objectives are crafted to ensure that we deliver on our mandate:

**Build and transform human capital** - Our scientific and technical contributions are only made possible through the skills and capabilities of our staff. The CSIR is an important part of the National System of Innovation and contributes to the national imperative to develop human capital and to the ongoing transformation of our society through the development and training of our scientific base.

**Conduct high-quality and relevant research and technological innovation to foster scientific and industrial development** - The CSIR identifies and invests in various areas of research to enable the translation of CSIR research into solid scientific outputs, such as publications, technology demonstrators and intellectual property. The organisation selects and implements a range of research and development programmes, in collaboration with various stakeholders, to identify opportunities to support new industries and improve the efficiency and competitiveness of existing industries.

**Financial sustainability and governance** - Financial sustainability and a sound track record of governance are imperative to the success of the organisation in the long term.

Key issues that the CSIR seeks to address through science, engineering and technology interventions include contributing to a vibrant economy and creating employment opportunities; building a capable state that is able to consistently deliver high-quality services for all South Africans; contributing to the development of economic and social infrastructure like transport, energy, water resources and ICT networks; transitioning to a low-carbon economy to improve our ability to understand the long-term effects of climate change by assisting government with the formulation of mitigation and adaptation strategies; transforming human settlements; improving health and building safer communities.

Our ability to contribute to a better future for all is illustrated in our unique value proposition, which is the multidisciplinary nature of our skills base. Two-thirds of our staff consists of scientists, engineers and technologists who share a passion for shaping a better future through science and technology innovation. The organisation also invests in a myriad of training interventions to foster young talent and further develop expertise by providing bursaries, studentships, internships and exchange programmes.

Research infrastructure is fundamental to the organisation accomplishing its scientific and industrial development mandate. The investment in research and built infrastructure and the implementation of the Campus Master Plan will help us achieve this.

It is this combination of excellence in research, highly skilled staff and world-class infrastructure that puts the CSIR at the cutting-edge of research and technological innovation to improve the quality of life of South Africans.
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COMPANY DESCRIPTION

The National Metrology Institute of South Africa (NMISA) was established under the Measurement Units and Measurement Standards Act No 18 of 2006. The NMISA is responsible for maintaining the SI units and to maintain and develop primary scientific standards of physical quantities for SA and compare those standards with other national standards to ensure global measurement equivalence.

The institute furthermore must provide reference analysis in the case of a measurement dispute and maintain and develop primary methods for chemical analysis to certify reference materials for SA and the region.

Who are we?

• Vision
To be a measurement centre of excellence inspired to consistently deliver outstanding, innovative and international comparable measurement solutions that support the country’s trade, people’s quality of life and enable the protection of the environment.

• Mission
To provide South African industry and environmental, health and safety sectors with fit-for-purpose measurement standards and measurements. This is achieved by keeping and maintaining the national measurement standards and units to an acceptable international standard; and by disseminating traceability to the South African industry.

• Values
- Measurement Excellence
- Social Responsibility
- Economic prosperity
- Good Governance

Our products and services

Reference Materials Production Facility
NMISA has established a reference material production facility to homogenize, package and store matrix reference materials. This includes a state-of-the-art resonant acoustic mixer (pilot and benchtop scale), 3D-mixer, pilot-scale freeze drier, shaking sieves and cutting mills. Packaging systems such as an automated powder and liquid dispensing system into custom form-fill-seal aluminium pouches, semi-automated canning system and benchtop ampouling system are also now available.

Training
The expertise residing in the NMISA staff is an important contribution to the development of a skilled and capable workforce through training in measurement science. Where and when required, the NMISA assists especially SANAS and the National Laboratory Association (NLA) with training courses. The NMISA staff is also involved as invited lecturers in graduate and post-graduate academic courses.

Africa Food and Feed Reference Material Programme
NMISA offers a Food and Feed Reference Material Programme dedicated to providing measurement support to Food and Feed testing laboratories through the provision of Certified Reference Materials. Reference measurements and Reference materials for Quality Control and Proficiency Testing Scheme purposes.

Automotive
Clothing, footwear, leather & textiles
Ship & boat building
Aerospace & defence
Rail & transportation
Toolmaking
Metal fabrication

Consulting
NMISA laboratories also provide consulting service for problem-solving and the implementation of new systems in the metrology field.

Certified Reference Materials
The highest order CRMs are usually produced and certified by a primary method and under the jurisdiction of a national metrology body (NMISA). These CRMs typically are produced under stringent manufacturing procedures and differ from laboratory reagents in their certification and the traceability of the data provided. Accredited laboratories are required to use CRMs to ensure traceability of their results.
COMPANY DESCRIPTION

EOS is the world’s leading technology supplier in the field of industrial 3D printing of metals and polymers. Formed in 1989, the independent company is a pioneer and innovator for comprehensive solutions in additive manufacturing. Its product portfolio of EOS systems, materials, and process parameters gives customers crucial competitive advantages in terms of product quality and the long-term economic sustainability of their manufacturing processes. Furthermore, customers benefit from deep technical expertise in global service, applications engineering, and consultancy.

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COMPANY DESCRIPTION

GE Additive is a world leader in additive design and manufacturing, a pioneering process that has the power and potential to transform businesses.

Through our integrated offering of additive experts, advanced machines and quality materials, we empower our customers to build innovative new products. Products that solve manufacturing challenges, improve business outcomes and help change the world for the better.

We partner with a range of industries, from aerospace to energy, automotive to healthcare, guiding their additive journeys and supporting them with our additive knowledge and experience.

GE brings an un-paralleled level of materials science and application expertise - we’ve been researching, developing and using additive technology for more than 20 years. Our knowledge and experience in the additive industry and materials science differentiates us and makes us uniquely poised to coach, guide and advise existing and new customers.

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COMPANY DESCRIPTION

Formlabs designs and manufactures powerful and accessible 3D printing systems. Headquartered in Boston with offices in Germany, Japan, and China, the company was founded in 2011 by a team of engineers and designers from the MIT Media Lab and Center for Bits and Atoms. Formlabs is establishing the industry benchmark for professional 3D printing for engineers, designers, and manufacturers around the globe, and accelerating innovation in a variety of industries, including education, dentistry, health care, jewellery, and research.

Formlabs products include the Form 2 SLA 3D printer, Fuse 1 SLS 3D printer, Form Cell manufacturing solution, and Pinshape marketplace of 3D designs. Formlabs also develops its own suite of high-performance materials for 3D printing, as well as best-in-class 3D printing software.

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Terry Wohlers
PRESIDENT OF WOHLERS ASSOCIATES, INC.

Terry Wohlers is president of Wohlers Associates, Inc., an independent consulting firm he founded 31 years ago. He has authored more than 400 books, articles, and technical papers on product development and manufacturing and has given 150 keynote presentations on five continents. Wohlers was a featured speaker at manufacturing-related events at the White House in 2012 and 2014. He has appeared on many television and radio news programs, including Al Jazeera, CBS Radio News, Bloomberg TV, CNBC, CNN, Fox Business, MSNBC, NPR, and Australia’s Sky News. Wohlers is a principal author of the Wohlers Report, the undisputed industry-leading report on additive manufacturing and 3D printing worldwide for 23 consecutive years. In 2016, he became an adjunct professor at RMIT University in Melbourne, Australia. Wohlers was elected to the SME College of Fellows in 2005. In 2004, he received an Honorary Doctoral Degree of Mechanical Engineering from Central University of Technology in Bloemfontein, South Africa.
Dr Phil Mjwara has served as the Director General of the Department of Science and Technology (DST) since April 2006. In this capacity he is responsible for all policy development in the science and technology sector in South Africa, as well as the portfolio management and governance of South Africa’s systems of government laboratories. His responsibilities further include the management of South African science and technology official development assistance and the driving of the implementation of South Africa’s National Research and Development Strategy and the management of South Africa’s new DST 10 Year Innovation Plan.

Prior to his appointment at DST, Dr Mjwara was the Group Executive: Research and Development; Strategic Human Capital Development at the Council for Scientific and Industrial Research (CSIR). At the CSIR, he was responsible for assisting the CSIR strengthening its Science and Technology base including Human Capital Development. In 2001, Dr Mjwara joined the National Laser Centre (NLC) as its head, where he has been instrumental in growing the centre’s activities since its inception and in creating a network of centres in Africa, i.e. African Laser Centre (ALC).

He has also held positions at the then Department of Arts, Culture, Science and Technology; as Director of Technology; at the University of Pretoria as professor of S&T policy and at the Universities of the Witwatersrand, South Africa and Fort Hare as a physics lecturer. He has been involved in a discipline of Management of Technological Innovation as well as in processes for policy formulation. He has led a team that conducted the South African Technology Foresight project. He has published and presented numerous papers on physics, technology analysis and foresighting related topics.

Dr Mjwara has served on various advisory councils and review boards. He currently serves on the Board of the World of Platinum of South Africa. He also served on the Council of the University of Johannesburg. He was also a Co-Chair for the Group on Earth Observations (GEO) between 2006 until 2017.

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Dr. Karsten Heuser

VP OF ADDITIVE MANUFACTURING, COMPETENCE CENTER IN SIEMENS DIGITAL FACTORY DIVISION

Dr. Heuser has been with Siemens for nearly 20 years in various management positions within Siemens businesses including Corporate Technology, OSRAM, Energy and is now the VP of Additive Manufacturing with a Competence Center in Siemens.

Dr. Heuser has a Ph.D. in solid state physics from the University Augsburg as well as a Postgraduate Diploma in Advanced Management from ESMT.
Dr. Jorge Vicente Lopes da Silva  
COORDINATOR OF 3D RESEARCH GROUP / CTI RENATO ARCHER

Jorge Vicente Lopes da Silva has a Ph.D. degree in Chemical Engineering, and MSc and BSc degrees in Electrical Engineering. He is a senior researcher joined the Renato Archer Information Technology Center (CTI) in 1988, a Brazilian research center from the Science, Technology, Innovation and Communications Ministry. He coordinated the Robotics Division at CTI for some years and in 1997 he created and has coordinated the Tridimensional Technologies Research Group at the same center as a pioneer in this area in Brazil. Under his supervision the team develops application and research projects with funding agencies, industry and universities in Brazil and abroad. He is member of many scientific committees and invited speaker of the most relevant conferences in the area of Additive Manufacturing.

He has cooperated with more than 300 hospitals in Brazil and some others abroad. In his laboratory computer tools for medical imaging, currently in use in 150 countries as open-source solutions have been developed. He cooperates with many universities supervising or co-supervising master and PhD thesis. Dr. Silva has been invited for lectures in many national and international conferences, including the organization of the special session on Information Technology in Biofabrication 2016. Currently he holds a four years special scholarship in Technological Development Productivity 1D from the National Council for Scientific and Technological Development (CNPq).

Dr. José Greses  
REGIONAL DIRECTOR AT EOS GMBH  
PHD, MSC

Dr. J. Greses is Regional Director Export North at EOS GmbH, with responsibility for the subsidiaries in United Kingdom and Ireland, Nordic and Baltic, plus EEMEA (Eastern Europe, Russia, Middle East and Africa). He is leading a sales and service team focused on developing and supporting innovative Additive Manufacturing applications in the medical/dental, aerospace, automotive, industry and high-end design fields, among others.

He had different sales and management roles within EOS GmbH since 2006 and previously, managed the Macroprocesses Unit of the Laser Dept. of AIDO (Spain) and worked at The Welding Institute (U.K.). He holds a PhD on laser welding from the Univ. of Cambridge (U.K.) and a MSc in Marine Technology from Cranfield Univ. (U.K.). He is also a graduate on mechanical engineering from the Polytechnic Univ. of Valencia (Spain).
Gerrie Booysen
CENTRE FOR RAPID PROTOTYPING AND MANUFACTURING

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.

Prof Ian Campbell
LOUGHBOROUGH UNIVERSITY

After graduating from the Special Engineering Programme at Brunel University in 1985, Ian Campbell worked as a design engineer, first in Ford Motor Company, and later in the Rover Group. In 1989, he was appointed as a Senior Teaching Fellow for CAD/CAM at the University of Warwick. This gave him the opportunity to raise his awareness of CAD/CAM technology and practices. He remained in this position for four years, during which time, he undertook a part-time MSc degree by research. In 1993, he obtained a lectureship at the University of Nottingham and gained his PhD, again through part-time study, in 1998. He moved to Loughborough University in October 2017, where he was appointed as a senior lecturer. His current position, since April 2017, is Professor of Computer Aided Product Design at Loughborough Design School. He is currently supervising a number of research projects, mainly in the area of design interaction and 3D printing technologies. Prof Campbell is a Fellow of the Institution of Mechanical Engineers and Editor-in-Chief of the Rapid Prototyping Journal. He is also a Visiting Professor at Vaal University of Technology in South Africa.
Mr Sechaba Tsubella

ACTING DIRECTOR: ADVANCED MANUFACTURING TECHNOLOGIES, DST

Mr Sechaba Tsubella holds a BTech Polymer Technology (Tshwane University of Technology), BSc (Hons) Chemical Technology (University of Pretoria), B.Com Economics (University of South Africa) and a MSc (Eng) Chemical Engineering (Witwatersrand University). He began his career in the manufacturing industry having worked for Dunlop Tyres and Reunert before joining the Technology Innovation Agency as Portfolio Manager: Advanced Manufacturing. He was previously the Deputy Director: Manufacturing Sector at the Gauteng Department of Economic Development, prior to his appointment at the Department of Science of Technology as Deputy Director: Advanced Manufacturing Technologies. Sechaba was also a part time mentor of the Innovation Hub Maxum Enterprise Development Programme. He is currently the Acting Director: Advanced Manufacturing Technologies at the Department of Science and Technology.

Gideon Potgieter

CEO OF RESOLUTION CIRCLE

Gideon has extensive experience in Operations Management in the corporate world and in a consulting role, including Supply Chain Management, Quality Management and Project Management applying tools, methodologies and philosophies like ISO9001, Kaizen, Lean, Six Sigma and Theory of Constraints. He has worked in several industries ranging from High-Tech Electronics and Information Technology to Automotive, Education and Medical Insurance in South Africa and abroad. Most recently he has become involved with Product- and Technology development for Startups in the Bio-Tech, Clean Tech and High Tech areas through Resolution Circle.
Prof Tshilidzi Marwala
VICE-CHANCELLOR AND PRINCIPAL OF THE UNIVERSITY OF JOHANNESBURG

Tshilidzi Marwala is the Vice-Chancellor and Principal of the University of Johannesburg beginning on 1st January 2018. From 2013 to 2017 he was the Deputy Vice-Chancellor for Research and Internationalization and from 2009 to 2013 he was the Executive Dean of the Faculty of Engineering and the Built Environment both at the University of Johannesburg. From 2003 to 2008, he progressively held the positions of Associate Professor, Full Professor, the Carl and Emily Fuchs Chair of Systems and Control Engineering as well as the SARCHi Chair of Systems Engineering at the Department of Electrical and Information Engineering at the University of the Witwatersrand. From 2001 to 2003, he was the Executive Assistant to the technical director at South African Breweries. From 2000 to 2001 he was a post-doctoral research associate at the Imperial College (then University of London).

He holds a Bachelor of Science in Mechanical Engineering (magna cum laude) from Case Western Reserve University (USA) in 1995, a Master of Mechanical Engineering from the University of Pretoria in 1997 and a PhD specializing in Artificial Intelligence and Engineering from the University of Cambridge in 2000. Marwala completed the Advanced Management Program at Columbia University Business School in 2017 and completed a Program for Leadership Development at Harvard Business School in 2007.

His research interests are multi-disciplinary and they include the theory and application of artificial intelligence to engineering, computer science, finance, social science and medicine. He has published 12 books in artificial intelligence, one of these has been translated into Chinese, over 300 papers in journals, proceedings, book chapters and magazines and holds four international patents. His writings and opinions have appeared in the magazines New Scientist, The Economist and Time Magazine.
BACKGROUND

Based on South Africa’s position as the world’s second largest producer of titanium raw material, 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 was published in 2016 (see http://www.rapdasa.org) and 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.

Early in 2015 the national Collaborative Program in Additive Manufacturing (CPAM), funded by the DST, was initiated to pursue implementation of this strategy. 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, University of Cape Town, University of Johannesburg and University of the Witwatersrand, Rapid3D and Altair. An important sub-program of the CPAM is aimed at 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. It provides an opportunity for postgraduate students from the collaborating institutions to present their research to an international audience. Through their participation many of these students get their first exposure to the process of preparing and submitting conference papers for peer review and subsequent presentation in the seminar.

For more information regarding the seminar, contact:

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Dr Kobus van der Walt
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### TIME PROGRAMME DIRECTOR: DR KOBUS VAN DER WALT

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<td>9:30</td>
<td>Registration, Tea and Coffee</td>
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<tr>
<td>10:00</td>
<td>Welcoming Address: Dr Kobus van der Walt CRPM, CUT</td>
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<tr>
<td>10:05</td>
<td>Opening Address: Mr Sechaba Tsubella Acting Director: Advanced Manufacturing Technologies DST</td>
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**Theme: ADDITIVE MANUFACTURING OF TITANIUM PARTS**

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<td>Progress towards qualifying additive manufacturing of Ti6Al4V for medical implants and aerospace parts</td>
<td>Willie du Preez, CRPM, CUT</td>
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<tr>
<td>10:40</td>
<td>Investigation of microstructural characteristics of heat treated high speed selective laser melting fabricated Ti6Al4V components</td>
<td>P Lekoadi, N Maledi, M Tlotleng, BN Masina</td>
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<tr>
<td>11:00</td>
<td>Evaluation of hatch distance and powder feed rate effects in Ti6Al4V alloy developed by LMD technique</td>
<td>PN Sibisi, API Popoola, NKK Arthur, SM Kubjane, AS Ngoveni, LR Kanyane</td>
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<td>11:45</td>
<td>Laser powder bed fusion of 55Ni-Ti shape memory alloy for biomedical applications</td>
<td>T Mphafudi, TC Dzogbewu, HK Chikwanda, I Yadroitsev</td>
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<td>12:05</td>
<td>Investigation of in-situ alloying Grade 23 Ti with Sat.6%Cu by laser based powder bed fusion for biomedical applications</td>
<td>E Newby, P Krakhmalev, I Yadroitseva, D Kouprianoff, I Yadroitsev</td>
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<td>12:25</td>
<td>Laser powder bed fusion process defects and mechanical properties of Ti6Al4V ELI mandible implants</td>
<td>JA Wessels, A du Plessis, J Els, I Yadroitseva, I Yadroitsev</td>
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<td>12:45</td>
<td>Discussion of the morning’s presentations</td>
<td>All</td>
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<tr>
<td>13:00</td>
<td>LUNCH BREAK</td>
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<tr>
<td>14:00</td>
<td>Design lessons for additive manufactured small radial flow Ti-6Al-4V turbines for application in organic rankine cycles</td>
<td>ME Cogho, GG Jacobs, JJ du Preez</td>
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<td>14:20</td>
<td>Design considerations for developing an additive manufactured Ti6Al4V compact counter-flow heat exchanger for application in organic rankine cycles</td>
<td>SC Venter, GG Jacobs, JJ du Preez</td>
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<td>Time driven activity based costing</td>
<td>AF van der Merwe</td>
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<td>15:00</td>
<td>Innovation and commercialisation of additive manufacturing</td>
<td>DJ de Beer</td>
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<td>15:20</td>
<td>CLOSURE</td>
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Investigation of microstructural characteristics of heat treated high speed selective laser melting fabricated Ti6Al4V components

P. LEKOADI¹, N. MALEDI², M. TLOTLENG³ AND B.N. MASINA∗

ABSTRACT

This study presents an investigation of the effect of different heat treatments on the microstructure of Ti6Al4V fabricated components produced by high speed laser melting. 20 mm³ cubes were heat treated in an inert oven at temperatures of 700ºC and 950ºC. The samples were heat treated at their respective temperatures for 2 hours before air cooling to room temperature. Subsequent to heat treatment, the microstructures of the heat-treated samples and the as-built were studied. The as-built samples show a martensitic alpha phase which is due to high temperature and rapid cooling during the selective laser melting process. Columnar elongated grains were also observed on the as-built test coupons. Similar grain growth was observed on the 700ºC sample, however the grain sizes were decreased.

1 INTRODUCTION

Selective Laser Melting (SLM) process is of interest because of its advantages over conventional manufacturing processes. The process has the ability to produce high geometrical components at reduced manufacturing lead times, Thijs et.al. & Beibei et.al. [1-2]. Several studies indicate that SLM produced Ti6Al4V parts has martensitic alpha phase due rapid cooling and solidification, thus adversely affecting the produced part for aerospace application. According to Wanying et. al. & Semiatin et. al.[3-4], heat treatment can improve the microstructure and mechanical properties of TiAl4V components. The aim of this paper is to investigate the effect of heat treatment on the microstructure of Ti6Al4V produced by a high speed SLM system.

1 METHODOLOGY AND RESULTS

1.1. Methodology

Gas atomized Ti6Al4V powder with a particle distribution of 20-60µm was used in this study. The powder was supplied by TLS and used as received. A high speed SLM system available at CSIR NLC was used to produce the samples. During the printing process, a high-power fibre laser at high scanning speeds was used to produce 20 mm³ cubes of Ti6Al4V samples. The Ti6Al4V samples were then heat treated to temperatures of 700ºC and 950ºC and held at that temperature for 2 hours before they were allowed to air cool to room temperature. Metallurgical samples (as-built and heat treated) were analysed for microstructural evolution using Joel JSM-6010PLUS/LA Scanning Electron Microscope (SEM).
1.2. Results

Figure 2 indicates the microstructure of as-built and heat treated at 700°C Ti6Al4V samples, respectively.

The as-built samples show martensitic α phase as expected due to rapid cooling and solidification during the SLM process, Ter Harr et al. [5]. In addition, elongated columnar grains were observed for the as-built samples. Similar grain growth was observed for the 700°C samples, however the grains of these samples were decreased in size. Minor agglomerated lamella was observed in the microstructure of the 700°C heat treated sample, this might be due to rapid cooling of the sample.

3. CONCLUSION

High Speed Selective Laser Melting process was used to produce 20 mm³ cubes Ti6Al4V samples. The effect of heat treatment on Ti6Al4V microstructure was investigated. It was observed that the resultant Ti6Al4V microstructure after annealing, depends mainly on the heat treatment temperature and the cooling rate.

REFERENCES


Evaluation Of Hatch Distance And Powder Feed Rate Effects In Ti-6Al-4V Alloy Developed By LMD Technique

P.N. SIBISI, A.P.I POPOOLA1, N.K.K. ARTHUR, S.M. KUBJANE1, A.S.NGOVENI1 & L.R. KANYANE1

ABSTRACT

The present work investigates the effects of process parameters on the structural integrity and dimensional accuracy of laser metal deposited Ti-6Al-4V parts. All the process parameters were kept constant except for variations in powder feed rate and hatch spacing. The densities, heights and morphologies were evaluated to quantify their responses to variation in process conditions. Results revealed a correlation between the process conditions and the characteristics of the end-product.

1. INTRODUCTION

Laser metal deposition (LMD) provides various benefits over traditional manufacturing and has since become the research hotspot as demand for advanced manufacturing persists. Despite numerous advantages LMD has to offer, further advantages are hindered by the limited understanding of the correlation between process parameters and resultant material properties. Various literatures have indicated that success of building a component of good quality, structural integrity and relatively precise geometry lies within the proper parameter selection and heat transfer dependant solidification mechanism, as well as microstructural evolutions. The primary aim of the present work is to study and optimize LENS process parameters to improve the densification and dimensional accuracy of Ti-6Al-4V parts by LMD.

2. METHODOLOGY AND RESULTS

The laser metal deposition technique was used to fabricate a total of four samples from gas atomised Ti-6Al-4V ELI spherical powder particle size range of 40-90 µm. The test samples of 10mm X 10mm X 5mm design dimension were built on 75mm X 75 mm X 4 mm Ti-6Al-4V plate by Laser Engineered Net Shaping (LENS). Table 1 shows the process parameters.

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3 Laser Enabled Manufacturing Group, National Laser Centre, Council for Scientific and Industrial Research, Meiring Naudé Road, Brummeria, Pretoria 0185, South Africa
Microhardness and Density measurements were done by Vickers diamond-based indenter and the Archimedes method. The results revealed that both the overlap distance and powder feed rate have an influence on structural integrity of deposits as seen by density variations shown in Table 1. The effects of powder feed had significantly more effect on density as compared to hatch-spacing. Results also revealed that the higher powder flow rates produced elevated sample heights measured through Vernier Caliper, in contrast to their counter parts. Samples built at larger overlap distances produced samples with relatively shorter heights.

Illustrated in Figure 1 a)-d) are the optical micrographs of the deposit specimen captured using an Olympus BX51M optical microscope. The increase in powder feed rate resulted in evolution of pores which can be attributed to incomplete melting of powders. All the observed hardness values of the samples were above that of conventionally fabricated Ti-6Al-4V alloy (344 HV). Furthermore, the results reveal that the hardness substantially reduces with an increase in scan speed and improves with increasing hatch spacing.

### Table 1: Processing Parameters used for deposition along with their corresponding deposited heights and densities.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Laser power (kW)</th>
<th>Scan speed (mm/s)</th>
<th>Powder feed rate (g/min)</th>
<th>Hatch Spacing (mm)</th>
<th>Height (mm)</th>
<th>Overbuild (mm)</th>
<th>Density (g/cm³)</th>
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<tr>
<td>A-1</td>
<td>300</td>
<td>16,93</td>
<td>1.6</td>
<td>0.3375</td>
<td>5.18</td>
<td>0.18</td>
<td>4.4102</td>
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<tr>
<td>A-2</td>
<td>300</td>
<td>16,93</td>
<td>3.8</td>
<td>0.3375</td>
<td>6.16</td>
<td>1.16</td>
<td>4.3272</td>
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<tr>
<td>B-1</td>
<td>300</td>
<td>16,93</td>
<td>1.6</td>
<td>1.0125</td>
<td>2.57</td>
<td>-2.43</td>
<td>4.3976</td>
</tr>
<tr>
<td>B-2</td>
<td>300</td>
<td>16,93</td>
<td>3.8</td>
<td>1.0125</td>
<td>4.46</td>
<td>-0.54</td>
<td>4.2487</td>
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</table>

3. CONCLUSION

Ti-6Al-4V samples possessing hardness values higher than achieved by conventional manufacturing practices were successfully with sample A1 being most accurate sample. The relationship between process variables and deposit characteristics was established.

REFERENCES


Laser powder bed fusion of 55Ni-Ti shape memory alloy for biomedical applications

T MPHAFUDI1, TC DZOGBEWU1, HK CHIKWANDA2, I YADROITSAU1

ABSTRACT
The binary near equiatomic nickel-titanium is a shape memory alloy, an intermetallic compound material which found applications in automotive, aerospace, robotics and biomedical industry due to its shape memory effect and super elasticity. The reversible martensitic transformation property and the biocompatibility of the material have drawn significant attention. However, the manufacturing and processing complications encountered when using the conventional methods to manufacture the NiTi alloy has brought shortcomings to homogeneity in the microstructure, which affects the material shape memory and super elastic behaviour. The emerging additive manufacturing methods such as laser powder bed fusion could be used to unearth the full potential of the alloy for biomedical applications. The laser powder bed fusion method could be used to manufacture NiTi objects with tailored geometries which would enhance the biomechanical and biofunctional properties of the material and translate into quality life for implant patients.

1 INTRODUCTION
The NiTi alloy, popularly known as Nitinol, is a shape memory alloy that displays reversible thermomechanical behaviour in its crystal structure when induced by stress or temperature. Nickel-titanium application in biomedical devices has become a research focus for material scientists. The attraction was instigated by the material’s biocompatibility as well as its unique functional properties, which are known as the shape memory effect, super elasticity (pseudoelasticity) and good damping effect [1-2].

Probably, the major limitation of Ti6Al4V for skeletal reconstruction biomedical applications is its high elastic modulus (110 GPa). The elastic modulus of NiTi is <31.2 GPa which could perhaps make it more suitable for structural biomedical applications as compared to Ti6Al4V. The mechanical properties of biomaterials are dependent on the microstructure. The method used to manufacture the material has a decisive effect on the microstructure which determines the mechanical properties. The manufacturing and processing complications encountered when using the conventional methods to manufacture the NiTi alloy has brought shortcomings to homogeneity in the microstructure, which affects the material Shape memory and super elastic behaviour [3-4].

Using the versatility of additive manufacturing (AM) technology such as laser powder bed fusion (LPBF) could improve the homogeneity in microstructure while maximizing the material properties. The use of a computer-aided design (CAD) file in LPBF process, which permits freedom of design, would also eliminate the daunting task of cutting and shaping to get a net shape. The LPBF process could help to unearth the full potential of the NiTi alloy for biomedical applications and other engineering purposes [5].

1 Department of Mechanical and Mechatronic Engineering, Bloemfontein, Central University of Technology, Free State, South Africa
2 Light Metals, Materials Science and Manufacturing, CSIR
2. METHODOLOGY AND RESULTS

A preliminary analysis will be conducted to determine the optimum process parameters for the selected alloy (55Ni-Ti) by forming and studying single tracks and single layers on a Titanium substrate [6], according to well-known procedures described in the literature [5, 7]. The optimum process parameters will be used to produce as-built samples for microstructural and mechanical properties investigation. The microstructural analysis would be conducted with an optical and scanning electron microscope. Then the mechanical property results that will be obtained using LPBF will be compared to the properties of NiTi produced by the classical methods. Based on the outcome of the comparison conclusions will be drawn on the feasibility of using LPBF for producing NiTi samples for biomedical applications. The tensile test would be performed using a MTS Criterion model 43 Universal Test machine. The surface roughness of the samples would be measured with Surftest SJ-210 portable surface roughness tester accordingly to ISO 1997. EOSINT M 280 machine would be used for producing all the experimental samples.

3. CONCLUSION

From the literature review, it was revealed that the conventional methods have been used to manufacture NiTi for biomedical applications. However, the unique characteristic that gives Nitinol its super elastic properties are adversely affected due to the manufacturing limitations encountered when using the conventional methods of manufacturing. To solve the shortcomings brought by the conventional methods of manufacturing additive manufacturing would be employed in an anticipation of producing biomedical objects with excellent biomechanical and biofunctional properties with complex shapes without contaminants.

The study intended to compare the mechanical properties of the LPBF NiTi samples to that of the conventionally manufactured samples. It is expected that the samples produced with the LPBF process would yield preferable biomechanical properties. The success of the study will in the future help produce implants with appreciable mechanical properties to improve life of implant patients.

REFERENCES


Investigation of in-situ alloying grade 23 Ti with 5at. % Cu by laser based powder bed fusion for biomedical applications

E. NEWBY*, P. KRAKHMALEV, I. YADROITSAVA, D. KOUPRIANOFF & I. YADROITSEV

ABSTRACT

The formation of in-situ grade 23 Ti alloy (Ti6Al4V ELI) with Cu by Laser powder bed fusion 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 investigated for in-situ alloying of Ti6Al4V-5 at.%Cu to form dense parts with suitable microstructural and surface quality. Relations between microstructure and process parameters are studied.

1. INTRODUCTION

Infection is one of the reasons for post-operative complications after bone replacement surgery. After orthopaedic replacements, the most common complications are: infection, impaired healing, and bleeding affected by surgical and patient specific risk factors [1]. Bacterial infection of a prosthesis is a severe complication because the infected prosthesis has to be removed in order to cure the infection and re-implantation is needed [2, 3]. Ti6Al4V Extra Low Interstitial (ELI) alloy is commonly used for medical implants because of its biocompatibility and suitable mechanical and corrosion resistant properties. Manufacturing implants from materials with antibacterial properties such as Cu-bearing alloys is a promising approach for infection prevention [3, 4]. Cu additions at the bone-implant interface reduce the risk of bacterial infection and implant failure [3-5]. The goal of this work is to find optimal process-parameters for LPBF Ti6Al4V-5 at.%Cu in-situ alloyed material for biomedical applications and to study the microstructure.

2. METHODOLOGY AND RESULTS

2.1. Methodology

Argon atomized Ti6Al4V (ELI) and Cu powder, spherical in shape, were used. Chemical composition for Ti6Al4V (ELI) being 89.26 wt% of Ti, 6.31 wt% of Al, 4.09 wt% of V, 0.12% of O, and Cu powder 99.9 % purity. The 10th, 50th and 90th percentiles of equivalent diameter (weighted by volume) were 12.6 µm, 22.9 µm, 37.0 µm, respectively for Ti6Al4V (ELI) powder and 9.45 µm, 21.9 µm and 37.5 µm, respectively for Cu powder. To produce the Ti6Al4V-5 at.%Cu powder mixture, the elemental Cu and Ti6Al4V(ELI) powders were mixed for 1 hour. Before laser processing, the powder mixture was dried at 80°C for 2 hours to increase powder flowability. To determine optimal laser power and scanning speeds, single tracks with length of 20 mm and 10 mm x 10 mm squares which were 5 layers high were manufactured by an EOSINT M280 machine. Three tracks were...
produced at each set of process parameters: 170 W laser power and 0.4-1.4 m/s scanning speed and the set at 340 W had an increase in scanning speeds by two times accordingly. The powder layer thickness was about 50 µm. The build chamber was filled with an Ar atmosphere. Experiments were done on Ti6Al4V substrates with 3 mm thickness.

2.2. Results

Results include analysis and discussion about morphology and geometrical characteristics of single tracks and their dependence on laser power and scanning speeds, laser-matter interaction time and linear energy input. Investigations of cross-sections perpendicular to the scanning direction of single tracks were done to estimate the penetration depth of the molten pool and LPBF mode. Keyhole, transition and conduction modes were found at the laser process parameters used. Defects in 3D samples were analysed at different process parameters. Optimal process parameters for in-situ alloyed Ti6Al4V(ELI)-5at.% Cu material for biomedical application are discussed. A comparison of the microstructures between Ti6Al4V(ELI)-1at.% Cu and 5at.%Cu material is made.

3. CONCLUSION

The purpose of this paper was to identify optimal process parameters for in-situ alloying of Ti6Al4V-5 at.%Cu. Better homogeneity is achieved at higher energy input. Further work that would be carried out includes investigation of the distribution of the elements in the single tracks the effect of differing layer thickness with similar parameters.
ABSTRACT

Ensuring additive manufactured metal-based components are free of major defects is crucial to their uptake for industrial and medical applications. Random porosity, high roughness and deformation during processing are the main current drawbacks in laser powder bed fusion parts. The prediction with numerical simulations of mechanical properties of defected samples is highly important for understanding the effect of these defects. A step-by-step systematic approach of determining defects in laser powder bed fusion and their influence on mechanical properties will be used for the current research.

1. INTRODUCTION

The need for new implant, treatments and prosthesis as well as prolonging the lifespan of current implants has increased and has brought a robust change in people’s quality of life [1]. Additive manufacturing of metals is growing steadily, producing parts with higher complexity with many applications including medical and aerospace, and are far more widespread and offers exciting possibilities for future development [2, 3]. The endoprosthesis replacement of the lower jaw with an artificial implant is performed in the case of traumatic gunshot injuries, or when a large section of bone is destroyed by chronic infection, caused when malignant neoplasms growth develops, and also in connection with osteomyelitis lesions, etc. The Ti6Al4V alloy is one of the most suitable materials of choice for such implants, due to its incredible strength, low weight ratio and outstanding corrosion resistance. Quality control in metal based additive manufacturing is extremely important, from dimensional accuracy and for minimizing or eliminating defects [2].

2. METHODOLOGY AND RESULTS

2.1. Biomechanics of mandible

This section describes how mastication and muscles serve in the movement of the mandible jaw, loadings, directions and bone properties as factors that must be taken into account for modelling of mastication. Material properties of different bones found in the human mandible are also shown.
2.2. Strategy of LPBF manufacturing of mandible

Laser powder bed fusion (LPBF) process-parameters, scanning and manufacturing strategies of complex objects can lead to fractures, warps, and pores within the LPBF part as it was shown by defect analysis by computed tomography scans and cross-sectioning of LPBF samples. This section describes approaches for the supports and building strategy of manufacturing the mandible implant by LPBF.

3. METHODOLOGY AND RESULTS

3.1. Methodology

Spatial distribution, size and shape of the defects of AM parts can be done by microCT to predict the effect of the pores on the mechanical properties of the part. Failure location prediction by FEA for LPBF mandible implant could serve as a tool for optimizing the design of mandible implants, as well as quality control of produced implants having some porosity or other differences from the CAD model. The methodology and main stages of the study are presented.

3.2. Porosity in LPBF parts

Pore’s shape, size and 3D distribution are shown in rectangular bars for mechanical testing and customised parts such as facial and mandibular implants. Detailed analysis of defects and their reasons are described.

4. CONCLUSION

A conclusion in the early stages of this work can be done on the basic expected outcomes of the research project:

- When conducting mechanical testing for the validation of the numerical simulations, all joints and forces during mastication must be tracked and included in both experiments and simulations, by assuming the right boundary conditions.

- Defects will be included in the Ti6Al4V test samples with different design geometries, thus to indicate which size and shape of pores will cause any significant defect in the functioning of the jaw. Test samples will be subjected to microCT scans to analyse porosity during LPBF and then will be mechanically tested. Comparison between numerical simulations and experimental data will be used to validate the model and to use it for prediction of mechanical properties of customised Ti6Al4V mandible implants.

REFERENCES


Design lessons for additive manufactured small radial flow Ti-6Al-4V turbines for application in organic rankine cycles

M.E. COGHO*     G.G. JACOBS1     J.J. DU PREEZ1

ABSTRACT
To improve efficiencies in current technology used to provide power in industry, the Organic Rankine Cycle (ORC) is a technology that recovers energy from waste heat. For small systems, it can be difficult to conventionally produce small intricate turbines. Additive manufacturing (AM) is an attractive technology used to produce turbines for such systems. In order to design more complex turbines, it is important to first characterise simpler small turbines produced using AM to set a baseline. This baseline can then be used in future studies.

1. INTRODUCTION
It is desirable to improve the efficiency of current technologies relying on fossil fuelled power. One such a method is the ORC, that can be used to recover low grade heat from exhaust gas [1].

This study focuses on small scale ORC systems that can easily be integrated into current systems for the recovery of waste heat. AM is considered an attractive method to produce components for such systems. To produce intricate small radial inflow turbines for these smaller applications poses significant challenges using conventional tooling. AM can be used to create more complex features and profiles for small turbines, which is expensive or impossible with conventional tooling and machining methods [2]. A small radial inflow turbine will be produced through AM and will thereafter be characterised.

Once there is a good understanding of the characteristics of the small AM produced turbines, the designs can be optimised in further studies. It is expected that this study will demonstrate the advantage of employing AM for the construction of small radial inflow turbines over conventional production methods. AM will allow the turbines’ shapes and profiles to be altered in ways conventional tooling cannot achieve [3].

2. METHODOLOGY AND RESULTS

2.1. Methodology
To characterise the turbines an experimental approach will be used. Test turbines will be produced using AM and then tested. The test turbines were designed using optimal design conditions, after which the design was finalised by adjusting the parameters due to restrictions to produce practically functioning turbines.
Parameters that influenced the design of the turbine include size constraints, as the premise of the study is for small radial flow turbines. The rotor diameter was restricted to 40mm and limited by safe operation of rotational speeds which were estimated as 80 000 revolutions per minute for testing. Ti-6Al-4V was selected to be the material for the turbine due to its high strength to weight ratio, as well as its resistance to corrosion [4].

Three turbines with three different sets of guide vanes, were designed. This was done to determine the effect of these variables on the turbine characteristics. Losses that were considered included inter alia:

- Losses from the tip clearance
- Loss of kinetic energy at the exhaust
- Impeller losses
- Losses due to friction
- Other losses like leakage, flow and bearing losses

### 3. DESIGN LESSONS

During the design process, in conjunction with the Centre for Rapid Prototyping and Manufacturing (CRPM), at Central University of Technology, Free State, certain design lessons were learned. One hurdle was that support structures were required for guide vane passages. This was due to the width of the passage that supplied the working fluid to the turbine.

The passage height was too small to allow the support structures to be removed afterwards. The solution was to manufacture the guide vanes as two parts, eliminating the need for support structures completely.

Another limitation from the AM process was manufacturing the screw thread required at the bottom of the rotors. This will be overcome by manufacturing guide holes with screw thread where the screw thread will be manually tapped afterwards to clean up the screw thread.

Manufacturing of the impeller profile of the turbine, through selective laser melting, is expected not to render problems due to the selected blade profile, as depicted in Figure 1. In future studies, more complex profiles will be researched and developed in order to maximise turbine efficiency.

### 4. CONCLUSION

The study thus far highlighted limitations using AM to produce components for small radial inflow turbines. Most of the manufacturing obstacles can be overcome through selection of configurations suitable for AM. This research will create a baseline for future research and development of more complex impellers; and to reduce the parts count of these turbines.

### REFERENCES


Design considerations for developing an additive manufactured Ti-6Al-4V compact counter-flow heat exchanger for application in organic Rankine cycles

S.C. VENTER*, G.G. JACOBS1, J. DU PREEZ1

ABSTRACT
Additive manufacturing has the ability to produce parts not previously possible with conventional methods. While this technology enables the production of highly complicated parts there are still design considerations to conform to. A literature study indicated that there is little information available on how to design compact heat exchangers for additive manufacturing. This paper discusses the design considerations for producing compact counter-flow heat exchangers by means of additive manufacturing for application in Organic Rankine Cycles.

1. INTRODUCTION
Additive manufacturing (AM) is a viable method for producing microchannel heat exchangers [1]. The ability to fabricate fins and walls with a thickness thinner than 200 μm in any profile allows microchannel heat exchanger design to evolve from its former basic designs [2]. A mathematical model was used to theoretically develop a preliminary design. Design considerations were then suggested by experts from the Centre of Rapid Prototyping and Manufacturing (CRPM) at Central University of Technology, Free State. A final design will be selected for production through additive manufacturing.

2. METHODOLOGY AND RESULTS
2.1. Theoretical Design
For the preliminary design the effectiveness-NTU method was used, which is generally preferred for analysis or design of heat exchangers [3].

The effectiveness of a heat exchanger is determined with equation 1 [4]:

\[ \text{Effectiveness} = \varepsilon = \frac{\text{Actual Heat Transfer}}{\text{Maximum Heat Transfer}} \] (1)

The actual heat transfer is calculated by either determining the energy lost from the hot fluid or the energy gained by the cold fluid, using equation 2. Maximum heat transfer may be calculated with the maximum temperature difference within the heat exchanger as shown in equation 3 [4].

\[ q = \dot{m}_h c_h \left( T_{h_i} - T_{h_f} \right) = \dot{m}_c c_c \left( T_{c_i} - T_{c_f} \right) \] (2)
The core pressure drop across the heat exchanger is calculated with equation 4. This equation incorporates entrance-, core friction-, flow acceleration- and exit-losses [3]:

\[ \Delta p = \frac{G^2}{2\rho_i} \left[ \left( -\alpha_1^2 + K_e \right) + f_F \frac{4L}{D_h} \left( \frac{\rho_i}{\rho_m} \right) + 2 \left( \frac{\rho_L}{\rho_g} - 1 \right) - \left( -\alpha_2^2 - K_e \right) \left( \frac{\rho_L}{\rho_g} \right) \right] \] (4)

2.2. Design and design considerations

A review of the preliminary design, by CRPM, led to suggested improvements to the design to make it compatible with AM. These changes are described below.

Manufacturing of the part in a horizontal orientation (cf. Figure 1), will cause the channels to deform during the selective laser sintering process as indicated with red in Figure 2. To prevent this from happening, it was decided to manufacture the part in an upright orientation (cf. Figure 3).

The inlets and outlets were also changed as the angle at which it was connected to the heat exchanger was too small and will cause the section to deform, see Figure 4. Any section such as this with \( \theta > 35^\circ \) will require supports; otherwise the material curls up during the selective laser sintering process due to the heat applied as shown in red in Figure 4.

3. CONCLUSION

Using the design considerations provided by CRPM and other sources, the heat exchangers will be produced for testing and characterisation. This research will produce design considerations, design lessons and thermo-hydraulic characteristics for additive manufactured compact counter-flow heat exchangers for application in Organic Rankine Cycles.

REFERENCES


**Time Driven Activity-Based Costing**

**A.F. VAN DER MERWE AND A. ANDERSON**

**ABSTRACT**

The purpose of Time Driven Activity-Based Costing (TDABC) is to improve the utilisation of resources in the additive manufacturing (AM) environment. The AM system cost parameters are identified for a time driven activity-based costing system. Time driven activity-based costing is based on resource unit time cost. Standard times linked to value chain activities multiplied by resource unit time cost is then used to predict product cost. Costing is one of the indicators of the Commercial Readiness Index, that forms part of the larger Collaborative Program in Additive Manufacturing (CPAM) initiative in South Africa.

A platform is proposed for determining real cost of production of future projects and ensure AM sustainability. The TDABC system will be a hierarchical decision-making model that can be taught to employers and employees in order to adjust their path of thought to benefit the business. The base parameters identified forms the foundation for this model. TDABC can help the AM sector to improve on their cost management systems. The system is fed from accounting systems such as Sage and Pastel to analyse historic costs. Standard times for activities are measured using known Time Study, Work Sampling and MTM (MOST) techniques.

At this stage the system strategy will in the end lead to reduced metal AM product cost to the end user in the medical sector.
Innovation And Commercialisation Of Additive Manufacturing

DJ. DE BEER

ABSTRACT

Since the inception of additive manufacturing (AM) in South Africa in the early 90’s, excellent progress has been made in terms of building an ecosystem, developing own approaches, technology platforms and novel products and/or applications. Whilst innovative new applications, products and processes are being reported constantly, there is still a lack of commercial successes. Much of these may be attributed to the traditional “Innovation Chasm”. In parallel, funding mechanisms used or applied for mostly also refer to the Technology Readiness Level (TRL) of the anticipated product, service or process. It has now become evident that TRL on its own does not offer a full picture, and Commercial Readiness Levels or Indices (CRI/CRI) should be used in parallel with conventional descriptors such as TRLs.

The new DST Chair in Innovation and Commercialisation of AM at the Central University of Technology, Free State (CUT), supported by merSETA and the Vaal University of Technology (VUT), aims to provide support to further develop and refine an applicable CRI system; apply existing knowledge and data towards complete qualification of AM products; develop and implement AM-specific commercialisation approaches, practices and procedures, and commercialise specific AM-produced products such as medical implants and aerospace components. The intention is to find novel / own ways to bridge the innovation chasm, replicate learning / experience in other industry sectors, and in parallel, to grow skills and expertise in AM commercialisation, as part of creating an AM Entrepreneurial Ecosystem and related industry in South Africa and the rest of Africa.
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## VENUE: MERIDIANS ROOM

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<td>Printed RFID Tags on Paper and Flexible Substrates Towards Low-Cost Connected Sensor Systems</td>
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**Metal Body Armour: Biomimetic Engineering Of Lattice Structures**

**A. DU PLESSIS *1**

**ABSTRACT**

Biomimicry in additive manufacturing often refers to topology optimisation and the use of lattice structures, due to the organic shape of the topology-optimised designs, and the lattices often looking similar to many light-weight structures found in nature such as trabecular bone, wood, sponges, coral, to name a few. Real biomimetic design however involves the use of design principles taken in some way from natural systems. In this work we use a methodology whereby high resolution 3D analysis of a natural material with desirable properties is “reverse-engineered” and the design tested for the purpose. This allows more accurate replication of the desired properties, and adaption of the design parameters to the material used for production (which usually differs from the biological material). One such example is the impact-protective natural design of the Glyptodont body armour [1]. In this previously published work, the natural body armour was analysed for energy absorption and hence impact protection using high resolution microCT, reverse engineering of simplified models, simulation and mechanical testing of polymer models produced by laser sintering. In this paper we report on the production of these same models in Ti4Al4V and analyse the resulting mechanical properties of these metal body armour units.

1. **INTRODUCTION**

In this work a biomimetic approach is used to find suitable dimensions for a desired property, in this case impact protection. The idea is that a natural system with desirable properties can be analysed in detail using microCT and reverse engineered, which provides detailed design guidelines for the application required. To demonstrate this principle an impact protective design is used in this example. The selected natural material for this purpose is an animal’s body armour. Despite many animals having body armour, one example in particular is relevant, being similar to the shell of a tortoise, but much larger and thicker. Most importantly, this animal is known to have been involved in fights with large tail-clubs, so the protective role of the shell units was highly important in this animal. For more information on this animal and the reverse-engineering process using microCT scans and detailed image analysis, the reader is referred to [1]. In this work a series of simplified models based on the natural body armour unit was designed, using a combination of a solid shell and lattice core. This type of system is already well known as impact protective material in general, especially for metal foams [2], but the use of an additive manufactured system for this purpose was not investigated before to our knowledge. The biomimetic design values are varied and the obtained mechanical properties reported, which provides insight into the use of this design for impact protective devices using additive manufacturing.

2. **METHODOLOGY AND RESULTS**

Samples were produced according to the designs in [1], with a single body armour unit being 28 mm in its widest dimension in the form of a hexagon, with height 12 mm: shell thickness was varied and lattice strut thickness and density was varied in 8 different models. Two of these models are shown in Figure 1, with the shell version having holes added to allow unconsolidated powder to be removed. Samples were produced on an EOS M280 using standard process parameters and stress relief heat treatment after the build.

![Figure 1: Two of the produced Ti6Al4V biomimetic samples - to the left the lattice-only model and to the right the lattice-shell combination.](image-url)

1 * Department of Physics, University of Stellenbosch, South Africa (Corresponding author)
Detailed microCT analysis of the produced parts demonstrate the successful production of diamond-lattice struts with mean diameter of 0.2 mm as shown in Figure 2, which is impressive - the single track width is only 0.12 mm.

Compression testing was performed using an Amsler compression machine with 250 kN max, and displacement sensor attached to measure crosshead displacement. Figure 3 shows that first yielding for the lattice-only sample occurs at 12 kN. This is followed by the typical yield-recover cycles for layer-by-layer yielding of the lattice with a mean plateau force around 7 kN, before full densification. This typical response for lattice failure is useful for energy absorption and protection applications.

3. CONCLUSIONS

- Accurate production of biomimetic impact protection samples in Ti6Al4V
- MicroCT validates the production strut thickness, which can be used as guideline for other designs
- Mechanical properties are reported and show good strength and energy absorption

REFERENCES


Can Additive Manufacturing Help Win The Race?

CH. HANDS, A. DU PLESSIS², N. MINAAR³, BA. BLAKEY-MILNER¹

ABSTRACT

This paper provides an overview of the newly established CPAM Project on Additive Manufacturing design and simulation, focusing on topology & lattice structure optimization for a light-weighting advantage. This collaboration project between industry and academia aims to utilize existing hardware and software tools, and investigate the practical limits of these technologies, providing eventual guidelines for their general use. This will provide a solid foundation for the practical use of metal AM optimized solid and latticed structures especially for Ti6Al4V parts. Two case studies are demonstrated here, one a purely topology optimized design, and one both topology and lattice optimized design, both constructed from Ti6Al4V and both load-bearing components to be utilized in the NMU Eco-Car Project for competition in late 2018. This paper presents the design for additive manufacturing (DfAM) process, the challenges met in applying a DfAM design mindset, and a unique final voxel-based smoothing step utilized in the design process. Detailed structural integrity assessment of these parts are included, but the question remains: will Additive Manufacturing help win the race?

1. INTRODUCTION

Topology Optimised design is a topic of intense research and application at the moment, which results in an efficient design by expanding available design space and allowing greater complexity of design as a result of the design freedom offered by additive manufacturing [1,2]. Its main purpose is to produce an efficient design by either light-weighting the part or maximising the stiffness; this is achieved by using pre-defined inputs (loads, constraints, materials, joints & contacts) via simulation to determine which areas of the design space require material as a result of the load paths, while not affecting the strength or deformation of the structure. This process is then iterated to result in an optimised structure. As a next step, it is possible to add lattice structures to the optimised design space where low stresses are found, or where the stiffness can be tailored to suit the application. The output structure often requires some data post-processing in the form of smoothing and defined solid support material regions, to deliver a practical design input for additive manufacturing. All of this is typically done in Topology Optimisation software such as in Altair Inspire 2018, in tandem with specialised AM preparation software, all of which was used in this work.

2. METHODOLOGY AND RESULTS

The first example of purely Topology Optimised design is a load bearing bracket, depicted in Figure 1. It is designed to withstand forces determined from existing competition data, over multiple load cases to simulate real-world conditions. Topology Optimisation is then used to reduce the mass and increase stiffness of the bracket without exceeding design constraints. No defects were found from subsequent microCT scanning tests, and the mass of each Ti-6-4 metal printed bracket is 27 grams saving 45% compared to the original design, which was an already very light carbon-fibre part.
A second example of a Topology Optimised steering arch was then designed with optimised lattice structures, using minimum lattice strut thickness of 2 mm as limited by printer constraints, but with varying lattice strut lengths to minimise mass. The final design structure achieved is depicted in Figure 2.

In a unique application of microCT-based voxel software, the part was then further smoothed using image processing methods. This is depicted in Figure 3, with the yellow envelope line showing a smoothed model compared to the original design (white). This effectively removes sharp corners and ridges, which may act as stress raisers and may also make final production challenging. The final smoothed part is then subjected to Wall Thickness Analysis to ensure no parts are thinner than 0.5 mm, a further constraint of the printer.

### 3. CONCLUSIONS

- First examples of Topology Optimised and Latticed Structured parts demonstrated
- Topology Optimised brackets produced successfully with full density
- An Image Processing method used for final smoothing of model
- Image Analysis features used for further wall thickness analysis of the optimised model

### REFERENCES


Maxillofacial Prostheses Production Through Computer-Aided Design And Manufacturing Technologies - Review Of State Of The Art

I. VÁN HEERDEN1*, A. FOSSEY1 & J.G. VAN DER WALT1

ABSTRACT

Many patients suffer facial disfigurements, causing significant psychological trauma. In the past, external maxillofacial prostheses were produced through fabricating wax models and applying carving techniques. Digital imaging technologies, computer-aided design, computer-aided manufacturing and additive manufacturing have opened new approaches to the production of maxillofacial prostheses. In South Africa, the uptake of the newer techniques has been slow, because of a lack of skilled practitioners and limited funds, particularly because many patients are government funded. A project is currently underway to revise and customise the production process chain for the manufacturing of maxillofacial prostheses to address the South African challenges.

1. INTRODUCTION

In the medical world, numerous patients suffer one or other disfigurement. These disfigurements may be as a result of birth defects, cancer or accidents. Maxillofacial defects are of particular concern, because these patients often suffer significant psychological trauma and tend to withdraw from their social environments. Therefore, patients suffering facial disfigurements usually visit medical practitioners requesting some or other reconstructive intervention. Many of these interventions require the reconstruction of external anatomical body parts such as ears, noses or eyes. In these cases, patients require the production of external maxillofacial prostheses, in an attempt to improve their aesthetic appearances.

2. CONVENTIONAL MAXILLOFACIAL PROSTHESES DESIGN AND PRODUCTION

The conventional production of external maxillofacial prostheses has been accomplished mainly through fabricating wax models and applying carving techniques. These conventional techniques include several complex steps and rely on the exceptional artistic ability of a designer and the skills of a clinician [1]. Maxillofacial prosthesis production consists of a number of production steps. Firstly, a duplication of the affected area is created by taking an impression of the area; secondly, the building of a clay or wax model of the anatomical structure(s) for which a prosthesis will be constructed; thirdly, the production of a three-piece-mould of the clay or wax model; and finally, the fabrication of the prosthesis in the desired material. In the case of an external prosthesis, such as a maxillofacial prosthesis, the human likeness is hand painted onto the silicone prosthesis.

Conventional carving techniques are difficult and time-consuming, and cause undue discomfort to patients. Also, these techniques require that patients are present for extended periods. The application of newer technologies such as, digital imaging technologies, computer-aided design (CAD) and computer-aided manufacturing (CAM) in the field of maxillofacial reconstruction has opened up new approaches to the fabrication of maxillofacial prostheses [2]. The application of CAD and AM technologies in the design of maxillofacial prostheses has largely replaced conventional carving techniques, although some medical practitioners still apply these techniques. These newer technologies are less invasive for the patient, less time consuming and are fast gaining popularity. Furthermore, the introduction of the CAD design is one of the greatest advances in the manufacturing of medical devices [3]. These technologies brought about more accurate design products that can be visualised before the final manufacturing process of prosthesis commences. The process is further enhanced by its high level of repeatability [4].

The production of external maxillofacial prostheses is an interdisciplinary process requiring a team of specialists, all participating in a production process chain from the generation of digital data to the manufacturing of external maxillofacial prostheses. These specialists include medical practitioners, designers and engineers. The major events of such a production process chain include the acquisition of 3D digital data, the processing of the 3D digital data, the designing of the 3D digital geometry of external maxillofacial prostheses and the manufacturing of external maxillofacial prostheses.

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2.1 Review of medical editing and design software

A literature review was undertaken to obtain some understanding of which software packages were mostly used in maxillofacial reconstruction. Several search terms and combinations of search terms were used to source the literature in ScienceDirect, Elsevier's leading platform of peer-reviewed scholarly literature. Search terms included, medical design software, medical imaging software, medical editing software, digital design for facial reconstruction, digital design for facial prostheses, maxillofacial facial prostheses and CAD. During the literature searches, leads presented by the searches were also followed. The literature search revealed 348 literature sources, which were scrutinised to identify those literature sources that mentioned the use of medical image editing and design software in craniofacial reconstruction in the board context. This subset of literature sources was further scrutinised to identify, where possible, whether software was used for the construction of internal facial prosthesis or external facial prosthesis.

The literature search revealed several literature sources, which contained information about medical image editing software. A total of 64 literature sources referred to 20 different medical image editing software packages that were used in craniofacial reconstruction. Of these 20 editing software packages, 20% appeared in 65.6% of the literature sources. The proprietary software, Mimics®, is the most popular and appeared in approximately 52% of the literature sources referring to the top five medical image editing software packages. Two open source editing software packages, 3D Slicer and InVesalius, also made the top five listing.

The literature search revealed several literature sources, which contained information about computer-aided design software. A total of 154 literature sources referred to 29 different CAD software packages that were used in craniofacial reconstruction. Of these 29 design software packages, 10 appeared in 77.9% of the literature sources. Proprietary software, developed by 3D Systems®, were the most popular and appeared in approximately 50% of the literature sources referring to the top ten CAD software packages. Two open source CAD software packages, MeshLab and Meshmixer®, made the top ten listing. Two well-known engineering design software packages, CATIA® and Solidworks®, also appeared in the list of software used in craniofacial reconstruction.

3. CURRENT STATE OF MAXILLOFACIAL PROSTHESES DESIGN AND PRODUCTION IN SOUTH AFRICA

The uptake of the newer technologies such as, digital imaging technologies, CAD and CAM, in maxillofacial prosthetics manufacturing has been relatively low in South Africa. This can be attributed to a limited number of skilled medical practitioners and technologists that are skilled in the application of these newer technologies. Also, many patients requiring maxillofacial reconstruction are government funded, thus access to these newer technologies is limited. Therefore, in the South African context, a combined approach to maxillofacial prostheses manufacturing is followed, whereby the new technologies are applied sparingly depending on the availability of skilled practitioners and funds.

4. CONCLUSION

Worldwide, CAD/ CAM are undergoing rapid uptake and growth in the medical sector. The expectations are that medical device manufacturing will become a key role player in the global medical landscape. Although the process chain for maxillofacial prostheses manufacturing cannot be replaced in its entirety by these new technologies, some components can be replaced, thereby bringing about a number of advantages. In particular, the most important of these advantages include the manufacturing of more accurate custom-made maxillofacial prostheses and the possibility of remanufacturing identical prostheses on demand, without patient participation. Although the process chain is considered to be rather expensive, particularly for developing countries, the continual introduction of cheaper and free software options will widen access to these technologies. Thus, several aspects will require consideration for a developing country such as South Africa to implement, in the future, CAD/ CAM technologies in a comprehensive way. Besides the current high manufacturing cost of maxillofacial prostheses, competences in most aspects of the manufacturing process will have to be developed. Skilled medical designers are probably the most limiting skill currently in South Africa, therefore, a combination of the conventional manufacturing and CAD/CAM technologies will persist into near future. As new CAD/CAM technologies are regularly appearing in the market place, it could be envisaged that prostheses manufacturing will become cheaper and more readily available in the near future, thereby opening up new and additional options for access to these technologies.

REFERENCES


Investment Casting Of Aluminium Alloy A356 Using Primecast® And PMMA Additive Manufacturing Materials For Sacrificial Patterns

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ABSTRACT

Investment casting is a manufacturing process that uses sacrificial patterns and ceramic shells to produce a cast part. Castings produced from this process have smooth surfaces and an excellent dimensional accuracy. The process involves pattern making, mould making, burnout and casting. In this study, aluminium alloy A356 castings were produced from patterns produced using two additive manufacturing technologies, namely Primecast® and PMMA. Metrology was performed on all the castings through Micro-CT scanning and different features of the castings from the two types of patterns were compared. The strengths and weaknesses of the two pattern making approaches are discussed.

1. INTRODUCTION

In previous work, comparison was performed on patterns built by Primecast® and PolyMethyl Methyl Acrylate (PMMA) respectively, which were produced using additive manufacturing (AM) technology. The investment casting patterns that were built in Primecast® were manufactured using an EOSINT P380 AM machine found at Central University of Technology (CUT), while those that were built in PMMA were manufactured at Vaal University of Technology (VUT) using Voxeljet 3D printing technology. The patterns had features such as thin walls, cavities, surface finish and angles that pose challenges to these AM technologies and the investment casting process. The metrology was performed on each of the patterns after being built and the Micro CT scanner results were reported. This paper is now reporting on the preparation of ceramic moulds (shell making, pattern extraction and firing), characterising of quality of the moulds, casting of the metal alloy into the moulds and metrology on the castings. Comparison of moulds and different features of the castings from the two types of patterns is reported.

2. METHODOLOGY AND RESULTS

2.1. Methodology

The mould making and casting were done at CSIR. The patterns were prepared by attaching gates and vents to the AM patterns. The gating and vents were produced by wax injection using suitable dies at CSIR. The assembly was then cleaned using wax pattern cleaner and de-ionized water to clean up any debris and carbon from the wax. The assembly was then left to air dry. Once the assembly was dry it was dipped into the primary or face coat, followed by an intermediate coat, and lastly the backup coat. Each coat consisted of dipping and stuccoing, and subsequent drying.
The pattern was then removed from the mould through a special burnout process, and the mould was fired in a high temperature furnace, leaving a clean cavity behind. The aluminium alloy was placed in a graphite crucible, heated until it melted, and the molten metal was then poured into the cavity of the mould. After the moulds were filled with molten metal, they were left to cool in air.

Four castings, two produced from Primecast® and two from PMMA sacrificial patterns, were scanned at Stellenbosch University using a General Electric Phoenix V|Tome|X L240 / NF180 Micro-CT scanner, which provides very accurate geometrical dimensions and porosity levels [1]. Measurements were done to compare the castings with the CT models and the CAD model.

2.2. Results

The CT scan data was compared with the CAD data. The data set was colour-coded according to deviations between the AM patterns and the cast part, and between the CAD design and the cast part. Deviation values ranged between -0.5 mm and 0.5 mm. Green indicates the best fit, while yellow denotes areas where the cast part dimensions are larger, and the blue indicates areas where the cast part dimensions are smaller than the pattern and the CAD dimensions. Figure 1 below shows result of one feature, freeform (sinkhole), from the cast part.

3. CONCLUSION

Aluminium A356 was successfully cast from the two types of sacrificial patterns. There were significant differences in dimensional accuracy and surface finish between the castings from the two types of AM patterns. The advantages and limitations of the castings from each AM pattern will be outlined in detail in the full paper.

REFERENCES

Investigation On The Suitability Of Polymers For Selective Laser Sintering Using Novel Mid-IR Lasers

LORINDA WU

ABSTRACT

Selective laser sintering systems comprise predominantly of 10 μm CO2 lasers to process polymer powders. However, not all polymers sinter well at this laser wavelength due to their wavelength dependent absorption properties. Mid-IR lasers emitting at 2 μm offer an attractive alternative option to process polymers such as polyolefins. This work identified the polymers likely suitable for 2 μm SLS processing through FTIR and laser transmission welding experiments. Some of the suitable materials include HDPE, PMMA and the biopolymer PLA.

1. INTRODUCTION

Selective laser sintering (SLS) is a laser-based additive manufacturing (AM) method in which a laser is scanned across successive layers of polymer powder to create a 3D object. The polymer particles coalesce together due to the heating generated from absorption of the infrared laser radiation.

In the majority of SLS systems used to produce polymer parts both commercially and in R&D laboratories, the lasers employed are predominantly CO2 lasers (λ=10.6 μm) [1]. These laser systems are convenient because many polymers exhibit significant absorption around that wavelength. Nevertheless, certain polymers such as polyolefins are highly transmissive at 10.6 μm and are not processible without the introduction of additives (e.g. carbon black) to modify its absorption behaviour. This constrains the colour choice of polymers that can be used in SLS parts. On the other hand, thermally sensitive biopolymers such as PLA exhibit such strong absorption at 10.6 μm that attempts at 10.6 μm SLS have been unsuccessful thus far as a result of rapid heating and consequent material degradation. A modified SLS using 1 μm laser was able to process PLA but required the incorporation of absorbing additives [2].

The advent of 2 μm wavelength lasers offer an attractive alternative in laser processing of polyolefins and several other polymers which exhibit absorption features in the mid-IR region. It can potentially produce higher resolution parts, as well as the printing of additive-free parts, which is particularly important for certain medical applications. By decreasing the processing laser wavelength, the minimum beam diameter can be reduced significantly and consequently, be able to process smaller features by up to 4-fold.

This work attempts to identify, amongst a large variety of polymers, thermoplastic polymers that are processible with 2 μm lasers with a view towards SLS applications.

2. METHODOLOGY AND RESULTS

Common thermoplastic polymer sheets 1 mm thick (PMMA, PC, PP, POM-C, HDPE, PA6) were locally procured for these experiments, comprising both natural/transparent and black sheets, the latter containing absorbing additives. They were selected based on their expected absorption around the laser wavelength of an 80 W Tm-doped fibre laser (λ=1940 nm) used for this study. The PLA thin film (~50 μm thick) was supplied by CSIR Materials Science & Manufacturing.

Figure 1 shows the FTIR transmission spectra of these polymer sheets. Absorption features from the -C=O 2nd overtone (λ~1.95 μm) and –OH combination vibrational modes (λ~2.1 μm) can be observed; therefore, they should be laser processible around 2 μm. The lower transmittance at shorter wavelengths is due to crystallite scattering from the semicrystalline polymers (PP, POM-C, HDPE, PA6, PLA), and is not from absorption.

A 1940 nm fibre laser was used to conduct the polymer melt and laser transmission weld (LTW) experiments. A scanning system was configured to enable sweeping of the laser beam across the polymer sheet(s). Single or two polymer sheets were clamped vertically in a xyz- translation stage, with the latter for LTW. The beam diameter was measured to be ~410 μm and remained unchanged across the length of the scanned region. The entire setup was enclosed and purged with dry air.
It was found that all the selected polymers demonstrated varying degrees of interaction with the 1940 nm laser at power levels of up to 30 W. Selected results are shown in Figure 2 (a) - (c) of laser melted PMMA, LTW of HDPE sheets and direct laser welding of PLA films, respectively.

The PLA films welded well with a seam width ~500 μm, which is somewhat larger than the laser beam width but with no apparent material degradation. PLA has a number of potential biomedical applications including tissue engineering. Using SLS will achieve a far higher resolution that is not possible with existing FDM technology.

3. CONCLUSIONS

Several thermoplastic polymers were experimentally verified to be processible with 2 μm lasers. Successful laser welds were demonstrated on amongst others, HDPE, PMMA sheets and PLA film. Further polymer characterisation, including DSC and TGA, will assist in determining the process parameter space to be used for SLS.

REFERENCES


Feasibility Of Using Lens Technology To Produce WC-Ni Alloys

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ABSTRACT

Laser Engineered Net Shaping (LENS), which is a powder blown rapid prototyping technology, was used to produce thin walls from a blend of micron-sized Tungsten Carbide (WC) and Nickel (Ni) powders. The processing parameters were altered in accordance with a three-variable full factorial design of experiments and star points. The build height, build width and hardness were measured. Variations in height and width were observed with the altering of parameters, whereas hardness was found to be parameter independent.

1. INTRODUCTION

The laser engineered net shaping process, as illustrated in Figure 1, was developed by a multi-program that includes Sandia National Laboratories and United Technologies of Pratt and Whitney (UTPW) in 1990 [1]. This technology has been used to produce a variety of alloys, with the predominant focus being on titanium alloys, Inconel and stainless steel [2]. Limited commercialisation, including scientific research, has been done using the LENS process to manufacture cemented tungsten carbides, with only cobalt (Co) being utilised as a binder phase [3]. It is well-known that the tungsten carbide (WC) phase is responsible for hardness and wear resistance while the Co binder provides the toughness and bending strength [4]. However, Co is toxic when inhaled and is under consideration for addition to the suspected human carcinogenic list [5]. Due to the apparent carcinogenic nature of Co, alternative binders, such as nickel (Ni) and iron (Fe) have been explored extensively in conventional manufacturing processes, but only to a limited extent in additive manufacturing processes. Improved oxidation and corrosion resistance has been observed when a Ni binder was used in conventional manufacturing, although the mechanical properties appeared to be lower than when Co was used [6]. In the current study, the feasibility of using the LENS process to produce WC-Ni alloys was investigated.

Figure 1: Schematic of the LENS process. (Adapted from [1]).

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2. METHODOLOGY AND RESULTS

The feedstock powder was a WC-Ni-alloy mixture with both constituent powders having a -90+45 μm particle size distribution. A LENS® 850-R system (OPTOMEC, Albuquerque, NM, USA) was used to deposit the thin walls. The computer-aided design model had nominal dimensions of 20 mm in length and 5.08 mm in height. The processing parameters were altered in accordance with a three-variable full factorial design of experiments and star points. Vickers hardness was performed at random points across the sample using a 30kgf load.

A multiple linear regression ANOVA analysis was performed on the height and width measurement results obtained from the thin walls. A quadratic model was fitted to the obtained data and the resultant equation used to determine the optimized parameters. Figure 2 shows the variation in the recorded build heights with the change in processing parameters, which included variations in power, feed rate and traverse speed.

![Graph showing variation in recorded build heights](image)

**Figure 2: Recorded build height for each thin wall sample.**

An increase in power resulted in an increase in both build height and build width dimensions, whereas a higher traverse speed resulted in a reduced build height and build width. The hardness showed no apparent differences across the processing parameters employed.

3. CONCLUSIONS

Thin wall specimens were produced from a WC-Ni powder blend using the Laser Engineered Net Shaping process. The processing parameters were found to have a large effect on the structural nature of the resulting samples although not on the material hardness.

REFERENCES


Industrialising Additive Manufacturing: The Possibilities With Siemens

H.VILJ OEN*

ABSTRACT

Additive Manufacturing (AM) offers tremendous opportunities to innovate completely new levels of competitive products, manufacturing operations and business models. Furthermore, AM is a transformative technology for adopters thereof, provided:

1. A change in mind-set to comprehend how AM creates opportunities to leap-frog the competition (products, operations and other businesses) - additive thinking.

2. The technical challenges to “industrialise” additive – in other words, to advance from “experimental” AM in workgroups to mainstream product development, serial production and core business operations - is overcome.

This paper proposes a methodology to increase competitiveness by making use of the commercially available solutions offered by Siemens PLM aimed at industrialising AM. With a focus on the Siemens Additive Manufacturing Network as a vehicle to do so.

1 INTRODUCTION

With strategic concerns rising and a constant need to improve innovation and speed while controlling costs, many organisations use lean principles and annual incremental improvements to optimize their ‘conventional’ design and manufacturing operations - but these principles were born in the 70’s and the returns are diminishing and in some industries, they have plateaued. Furthermore, this is accentuated by an increase in global competitiveness.

Through Siemens’s direct involvement with industry, they observe that incremental improvement is not enough, rather AM has emerged as a transformative technology that improves products, manufacturing and business performance in significant gains. AM therefore is a technology that reshapes everything. Siemens believes in industrialising AM so digital enterprises can incorporate it into their mainstream product development and production operations to realise the next level competitiveness.

This is achieved by offering an integrated end-to-end system. With a strong commitment to deliver a complete system and to provide users with the complete process chain, connected via a digital thread to eliminate the need for data conversion between steps and applications and driven by digital twins to create confidence in newly reimagined product designs and manufacturing processes.

A new way forward cannot be possible without a shift from conventional to additive thinking. And in order for wide-scale adoption by manufacturers taking advantage of all the new printing technology, and realising the full potential of AM, more than access to advanced product development software are required. The challenges that exist are among the following (Wu, Myant and Weider, [2]):

- High costs related to AM (machines, material, experience etc.).
- Limitation in access to technologies.
- Lack of consistency and quality management principles in the AM industry.

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• A shortcoming in design technologies in addressing the full breadth of AM capability.

• Lack of trained/experienced resources.

To address these challenges, Siemens created the Siemens Additive Manufacturing Network (SAMN) (Siemens, [1]). With the SAMN, an ecosystem is created that connects all its members to experienced users, making use of the latest technologies and printing machines, materials, part buyers and software providers.

2. METHODOLOGY

2.1. The Economics of AM

To support this vision (industrialisation of AM), this paper will focus on the infrastructure required for the large-scale adoption of AM. Figure 1 below indicates the proposed solution by Siemens and forms the heart of the SAMN.

3. CONCLUSION

Siemens is committed to making AM technology work for industrial serial production and to drive capabilities forward so companies can expand the frontier of what’s possible for products, manufacturing operations and business.

The industry trend towards making AM an industrial technology is to combine together the various necessary applications into a single continuous process chain. Siemens is a leader in this approach and offers 3 key advantages to help industrialise AM:

1. An end-to-end solution for next generation design to serial production.
2. Modular consulting services to accelerate time-to-value.
3. A global ecosystem (via SAMN) for Design for AM know-how, digital inventories and distributed production.

REFERENCES


First Advanced Open Labware Workshop And Rapid Prototyping Solutions For Research Challenges In Africa

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ABSTRACT

We report on a workshop based on open source principles to implement innovative solutions for laboratories and science applications in Africa. Specifically, 3D printed designs implemented by different research teams from Africa are highlighted. The advanced open labware workshop enabled teams to develop set-ups to solve challenges faced in their own laboratories or research environments. The workshop showed that substantial developments could be made within a two-week time frame, particularly using rapid prototyping techniques such as 3D printing and laser cutting to accelerate the development of the open labware solutions.

1. INTRODUCTION (HEADING IN ALL CAPS)

The aim of the First Advanced Open Labware Workshop was to assist researchers to develop capabilities and local expertise to accelerate research and development in Africa. The workshop was a collaboration between TReND (Teaching and Research in Natural Sciences for Development in Africa) and the Universities of Cape Town, Tuebingen (Germany) and Sussex (United Kingdom), as well as the Council for Scientific and Industrial Research (CSIR), Pretoria, and funded by the Volkswagen Foundation. Initial teachings of open source principles have been carried out in previous TReND workshops to provide a foundation of open hardware and software development [1]. Stemming from this, an advanced workshop was organised to allow for teams to utilise the foundational skills developed to build innovative solutions for challenges faced in their own laboratories or research environments. Important aspects addressed by the workshop included:

1. Providing access to equipment: 3D printers, laser cutters, as well as hardware and software components that are otherwise not available, accessible or affordable to the participants

2. Application of foundational knowledge of programming and circuit design (e.g. from previous workshops/courses) to implement solutions for unique challenges that the individual teams face in their research areas and institutes.

3. Interaction and collaboration from teams across the world and leveraging of expertise from across the groups.

4. Providing a platform on which to develop open labware solutions that can be shared and utilised across campuses and countries to solve problems; this can also be adapted to solve other problems as a result of the generic approaches followed.

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2. METHODOLOGY AND RESULTS

The workshop was held in Cape Town in April 2018, with a number of facilitators and 24 participants developing the open labware projects: 8 teams with 3 participants per team from Nigeria, Ghana, Malawi, Cameroon and South Africa, as well as two teams from Germany. A 3D printer (Zortrax M200) was utilised during the workshop to assist in development of a number of the projects. Numerous lectures and tutorials were given throughout the workshop, with focus on open source aspects, hardware and software development, and 3D printing design programs such as OpenSCAD, Google Sketchup, FreeCAD and TinkerCAD, to allow participants to design the customised parts required for their projects.

Projects that utilised 3D printed components included:

- **Analytical shaker project (Ghana):** Motor control system to shake 3D printed layers of sieves for particle sorting, specifically for pharmacology applications. 3D printed brackets were also made to cradle the motors for correct vibrations and motion to be achieved for the shaking of particles in a sample (Figure 1a).

- **Bird assessment project (South Africa):** Modified bird perch and nest with a camera and load cell system to visually assess and weigh birds. The bird nest was 3D printed (Figure 1b), along with a number of other housing and structural components.

- **Spectrophotometer project (Cameroon):** Development of a precision wide spectrum spectrophotometer for various research applications within the laboratory (Figure 1c). Housings and brackets for positioning light sources and detector arrays were 3D printed.

- **Locomotor activity testing projects (Ghana and Nigeria):** Infrared transmitter and receiver arrays in a box to detect rodent activity and speeds within the set-up (Figure 1d). One of the teams also incorporated cameras within the test set-up for visualisation and made use of 3D printed brackets and housings.

Assessment of the course success was carried out through surveys, as well as informal interactions and feedback sessions. Three different surveys were compiled to assess 1) why the participants applied to the workshop, 2) the skills and knowledge learned, and 3) the implementation of the open labware developed as part of the workshop back at the home institutions - i.e. the future goal and implementation plan. The aim was for participants to develop complete open scientific hardware, as well as be encouraged to document their efforts and deposit all project content in open repositories such as GitHub.

3. CONCLUSION

The workshop enabled participants in resource-limited settings across Africa, as well as the rest of the world, to develop functional solutions for challenges in their laboratories and areas of research. Although the participants generally did not have backgrounds in electronics or programming they were able to learn design and implementation skills to enable them to realise solutions and contribute to open labware developments, particularly through utilisation of 3D printing techniques, to integrate their solutions into functional systems. Most teams were able to successfully complete the majority of the project work during the two week period. The aim was for the teams to be able to take their developed projects back to their home institutions for use in laboratories and research projects, as well as to be able to teach others in their communities about open labware design processes and principles. Future endeavours could include follow ups to track this progress.

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REFERENCES

The Relationship Between Layer Height And Exposure Strategy In The Formation Of Residual Stresses In Selective Laser Melting Produced Ti6Al4V

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ABSTRACT

High residual stress, a martensitic microstructure and porosity pose major restriction in the qualification of Selective Laser Melting (SLM) produced Ti6Al4V parts for biomedical and aerospace applications. This study aims to investigate the relationship between layer height and exposure strategy in the formation of residual stresses in selective laser melting produced Ti6Al4V. Neutron diffraction was used to determine the distribution of residual stress in a set of rectangular SLM-produced Ti6Al4V samples. The influence of layer thickness and laser exposure strategy was investigated. The results show that an increase in layer thickness reduces the stress gradients in the part. There is also evidence that changing the exposure strategy can prevent stresses from developing along a preferential axis, making a more homogeneous stress field.

1. INTRODUCTION

SLM is an Additive Manufacturing (AM) technique which produces parts from powdered material via the consolidation of a laser beam in a layer wise fashion. AM offers numerous advantages over traditional subtractive manufacturing techniques such as lower material waste, lower lead times and the capability of achieving high part complexity. Ti6Al4V alloy is the most popular titanium alloy in the traditional manufacturing industry (wrought, rolling and CNC). This is mainly due to wrought-produced Ti6Al4V’s superior mechanical properties, particularly its high strength to weight ratio. The melting and solidification of powder results in the formation of high residual stresses. The primary mechanism is driven by a temperature gradient mechanism, which is a result of rapid, localised, heating that occurs at the impingement point of the laser on the material. Large thermal gradients form due to the slow conduction of heat away from the melt pool, which result in a mismatch in the thermal expansion experienced by the molten material and the solidified material surrounding it. The thermal expansion of the molten material is constrained by the solidified material surrounding it, resulting in compressive stress in the solid material. Upon cooling of the molten region, a secondary mechanism occurs, whereby the thermal contraction of the molten region during the state change from liquid to solid is constrained by the solid material surrounding it. This constraint induces tensile stress in the newly solidified region.

This study is aimed at investigating the through-volume residual stress distribution in a set of SLM-produced Ti6Al4V samples using neutron diffraction (ND). Investigated are the influence of layer thickness and laser exposure strategy.

2. METHODOLOGY AND RESULTS

Rectangular samples with dimensions 20 x 20 x 10 mm in X, Y and Z directions (according to ASTM F2921) were built at KU Leuven’s Department of Metallurgy and Materials Engineering using an in-house developed SLM machine. All specimens were tested in the as-built condition and were wire cut from the base plate after manufacture, before residual stress measurements commenced. The test matrix considered a 30 and 90 µm layer thickness and three exposure strategies, where the laser path would follow a parallel ([0]), perpendicular ([0/90]) and with a 30° ([0/30/60/…]) rotation to the previous layers laser path. Archimedes test according to ASTM of the samples revealed an average density of minimum of 99.42 % and a maximum of 99.58 % for all samples.

The ND measurements were performed at the South African Nuclear Energy Corporation (NECSA) using the MPI/CSI neutron strain scanning instrument. Measurements were taken through the centre of the sample, along an investigation plane (that normal to Y in the XZ plane). This plane was discretised into a 5 x 11 grid of measurement points approximately 1.67 mm apart. Strain measured for the three orthogonal directions matching the sample coordinate system were taken at each grid point to provide normal stress measurements in σxx and σyy.
A single plane is considered under the assumption that the stress distribution would be approximately symmetrical about Y due to the symmetry of the exposure strategies and sample geometry.

Figure 1a shows stress contour plots for the 30 µm and [0/90] specimen. The respective stress values indicate an approximately parabolic shaped stress distribution. Moreover, a symmetrical stress distribution is observed. Figure 1b shows the influence of layer thickness. A thinner layer thickness exhibits higher stress magnitudes, as well as steeper stress gradients. The data suggests that a larger layer thickness can offer advantages, from a residual stress point-of-view, by allowing for lower tensile and compressive stresses at the sample surface and centre respectively. Figure 1c shows the influence of the exposure strategy. The stress biaxiality ratio, defined as σxx/σyy, shows a clear effect of the exposure strategy and stress homogeneity. The directionality of stress is most evident when comparing the [0] with the [0/90] and [0,30,60,...] exposure strategies. Exposure strategy [0] resulted in a near uni-axial stress state. This is due to the contraction of the heated material being more severely constrained in the laser path direction. Exposure strategies [0/90] and [0,30,60,...] for which the laser path direction is alternated between each layer, provided a more biaxial stress state.

3. CONCLUSION

This study measured the stress distribution in SLM-produced Ti-6Al-4V samples using ND. Approximately parabolic shaped stress distributions were observed in X, Y and Z directions respectively. Stress magnitudes and gradients can be seen as a function of build layer thickness. By increasing the layer thickness, the stress magnitudes and gradients are significantly reduced. The exposure strategy used has a direct influence on the homogeneity of the stress state. A unidirectional exposure strategy results in preferentially orientated stress in the direction of the scan vector. By increasing the number of scan vector orientations, the stress components become more homogeneous and a biaxial stress state is achieved.

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REFERENCES


Conformal Cooling Channel Design For Direct Metal Laser Sintering Of Maraging Steel Injection Mould Inserts

I. ADAM¹, W. B. DU PREEZ² & J. COMBRINCK³

ABSTRACT
By lending its greatest advantage, which is the freedom of design, Additive Manufacturing (AM) has enhanced the design capabilities of tool designers.

The efficiency of injection mould (IM) tooling is positively influenced by an enhanced cooling rate achieved through conformal cooling, which in turn has a positive influence on the quality of the parts produced. The refinement of design rules for conformal cooling channels, serves to further enhance the use of AM in the IM industry. This paper reports on a determination of the limitations of conformal cooling channels built through Direct Metal Laser Sintering (DMLS).

1 INTRODUCTION
An increase in global competition has seen a general trend of cost reduction and improved product quality in the IM industry. Since the IM cycle time has a direct correlation with the manufacturing costs of plastic components, it has come under scrutiny to drastically reduce the IM cycle time, thereby increasing production and ultimately increasing profits [1]. When considering a simplified heat flow equation \( Q = \frac{A}{x} (t_1 - t_2) \) as described in Figure 1, the variable which would result in more efficient cooling is the reduction of the distance \( x \) between the mould surface and cooling channel [2].

While this holds true, another option includes making use of a mould material having better heat conduction properties. However, the physical limitations set by conventional manufacturing techniques makes the reduction of this distance \( x \) virtually impossible in tools having complex geometries.

However, with the introduction of AM to the tool making industry, tool designers now have greater freedom of design allowing for the use of conformal cooling channels that follow the contours of the part, thereby increasing the cooling potential. With the availability of this technology, not only are designers able to place cooling channels in “hard to reach” parts of the IM tool, but they can place cooling channels closer to the mould surface, which would further enhance the cooling efficiency of the moulding cycle [1].

Figure 1: Deflection of a rectangular channel, showing simplified heat transfer

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However, there are physical limitations such as the strength of the insert material, which sets a limit for the distance $x_m$ between the cooling channel and the mould surface. In developing the equation (1) below [4], the worst-case scenario was considered, whereby a rectangular channel was loaded with the injection pressure $P_n$ as shown in Figure 1. Since commonly used channels are circular in cross-section, they experience relatively smaller stresses and deflections. The stress experienced under the applied injection pressure $P_n$ can be expressed as follows [4]:

$$\frac{P_n D_h^2}{2x_m^3} \ldots (1)$$

Through manipulation of this expression, it is possible to calculate the distance $x_m$ at which the specified mould material will fail under a specified injection pressure. With this baseline a study was done to determine a minimum value for the distance $x_m$ between the cooling channel and the AM mould insert, at which the mould insert material will not fail. This is of importance as a current lack of published conformal cooling design criteria leads to tool designers over compensating for the mould material strength, thus sacrificing on cooling efficiency.

### 2. METHODOLOGY AND RESULTS

By making use of equation (1), a minimum value for the distance $x_m$ at which the mould insert is expected to fail was calculated for a channel having a circular profile. Calculations were based on an injection pressure of 260 MPa, for conformal cooling channels having a circular diameter of 4, 6, 8 and 10 mm, respectively. These values were compared and verified using SIGMASOFT® mould simulation software. CAD models were then generated, and mould inserts were manufactured using DMLS, to experimentally verify the minimum achievable value of $x_m$.

#### 2.1. Results

The calculated values for $x_m$ at which the mould material is expected to fail is given in Table 1.

<table>
<thead>
<tr>
<th>$D_h$ (mm)</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_m$ (mm)</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The deflection of a mould insert with a $D_h$ value of 4mm and $x_m$ value of 2mm is shown by the blue area in Figure 2.

**Figure 2: Simulated deflection of a AM insert using SIGMASOFT® simulation software**

### 3. CONCLUSION

The experimental verification of a minimum value for the $x_m$ distance at which the mould material will not fail is ongoing and will be published in the full paper.

### REFERENCES


**Design Of A “Large” Unmanned Aerial Vehicle (UAV) Frame For Metal Additive Manufacturing (AM) On The Aeroswift Machine**

**J.V. PRINSLOO**, N.J. MINNAAR & M. VERMEULEN

**ABSTRACT**

In order to demonstrate the capability of manufacturing a large scale aerospace part, it was envisioned to design an Unmanned Aerial vehicle (UAV) frame which would fit into the Aeroswift build volume. The Aeroswift machine is a metal powder bed fusion system with a large build volume. In this paper, the complete design process of a UAV frame will be outlined and the optimisation methodology followed to reach an optimised design solution will be covered in detail.

**1. INTRODUCTION**

The Aeroswift machine was designed and developed by Aerosud Innovation Centre in partnership with the Council for Scientific and Industrial Research (CSIR) and funded by the Department of Science and Technology (DST). The Aeroswift project was started in 2008, with the goal of manufacturing aerospace parts in Ti6Al4V for aerospace and other industries. The Aeroswift system has a build volume of 2000mm x 600mm x 600mm and is thus capable of manufacturing large scale parts. The design of the UAV frame will serve as an aerospace technology demonstrator for the powder bed fusion process on a large platform system such as the Aeroswift machine.

The key areas of the design process have been defined as UAV craft requirement specification, electronic component and drivetrain selection and mechanical design employing topology optimisation techniques.

**2. METHODOLOGY AND RESULTS**

**2.1. UAV craft and frame requirements**

The project started with specifying the requirements of the functional UAV craft and frame as the following:

- The frame should fit into a 600 x 600mm build volume
- The UAV should have symmetrical motor placement.
- Flight times of at least 15 minutes should be achieved.
- Must have autonomous flight capability, stabilised video recording and First Person View (FPV) capability.
- The fully constructed UAV should have a thrust to weight ratio of at least 2.5:1.
- Design must consider camera viewing angles in order to ensure unobstructed video footage.
- The final frame design should be producible with the powder bed fusion AM process in Ti6Al4V.
- Frame stiffness should be maximised.
- Aesthetics should be considered during the design process.

**2.2. Component and drivetrain selection**

The most important aspects to address early in the design were frame weight, the size and number of motors to use and battery size. Flight controller, cameras, camera gimbal/mounts, other control and communication electronics which would satisfy the functional requirements of the UAV craft had to be specified. Hexacopter (six motors) and Quadcopter (four motors) configurations were considered. In order to satisfy the thrust to weight and flight time requirements with the specific frame size it was decided to pursue a Quadcopter configuration for this design. All non-drivetrain electronic components required in the craft were selected in order to calculate the all up weight of the craft, to determine mount point locations and subsequent design space limitations.
To aid in the design and selection process a comprehensive calculation tool and component database, namely eCalc [1] was used. The eCalc tool benchmarks the frame, motor, propeller and battery configuration and estimates a number of performance values. The eCalc tool can be used to compare different drivetrain setups and performance metrics are based on the performance data of the actual components. The calculations performed with the eCalc tool identified the required motor thrust, frame size, battery size and weight. This information, together with the component mount positions were required inputs into the optimisation phase of the design.

2.3. Mechanical design

Due to specific structural and weight requirements, it was decided to use topology optimisation as a tool to optimise the frame design. The design methodology followed is described in the seven steps listed below. Where applicable the outputs of the steps are shown in figure 1.

Baseline concept design was generated, using primitive volumes (rectangles, cylinders, etc.) with as little detail as possible, but including position and mounting info of all components. See figure 1(a).

1. The primitive/baseline concept was imported into topology optimisation software (solidThinking Inspire in this case) and a baseline finite element method (FEM) analysis was performed to check that loading conditions are correct.

2. A baseline optimisation was run to ensure that the generated topology facilitates connections between all the components in the assembly and also that connections of the assembly to important functional interfaces are retained. The result of this step is shown in figure 1(b).

3. Checked if the baseline optimisation retained material at the boundaries of the primitive real-estate. This was indeed observed, thus indicating that the design domain needed to be increased in order to capture the load paths in the material more optimally. This is illustrated in figure 1(c).

4. Topology branch sizes were increased to reduce the computational complexity and repeated the process to produce the thickest boundaries which encompass the load paths in the material (Figure 1(d)).

5. The design space was reduced and a full-scale optimisation was completed where small branch thicknesses were considered. To form a new design space, geometry was created to capture the topology of the baseline optimisation from the previous step (See Figure 1(e)). Ad-hoc modifications to improve AM manufacturability and aesthetics was done at this step and is shown in figure 1(f).

6. The final design optimisation was completed and the resultant geometry was subsequently recreated with thin, optimised branches (See Figure 1(g)).

2.4. Results

The methodical process followed in the previous section clearly shows the transformation from a very basic design to a topology optimised design. It was even possible to adapt the aesthetics of the design to take the shape of a butterfly and make it suitable for production in metal AM. (build direction as shown figure 1(g)). The estimated weight of the optimised design is ~593g and well within specification. By focussing on high-end motors in the eCalc database, known to be efficient and optimised for this type of application, a motor, prop and battery configuration was found which should have a 2.8:1 thrust to weight ratio and an approximate flight time of 19 minutes.

3. CONCLUSION

By following the design process outlined in this paper, it was shown that all the initial UAV requirements were met, including frame weight, thrust to weight ratio and flight time, while maintaining frame stiffness. The optimised design solution for the most part minimises features that will prevent the design from being printable with the powder bed fusion process on the Aeroswift machine. Topology optimisation allowed for the development of a non-conventional frame while AM ensures manufacturability of this shape.

REFERENCES

Comparative Study Of Additively Manufactured AlSi10Mg And Maraging M300 Steel Thin Walled Structures

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ABSTRACT

The limits of width, height and overhang angle in additively manufactured AlSi10Mg and Maraging steel components were tested using the SLM 280 machine. Rectangular components with a constant length of 10mm were printed with the width varied from 0.18mm to 2.5mm. The length was varied from 1mm to 10 mm while the overhang angle was varied from 0 to 37.5º. The results revealed that the Maraging steel formed successfully at all heights, widths and overhang angles. The AlSi10Mg failed to form at all heights and overhang angles at a width of 0.18mm but formed successfully at all widths above 0.18mm.

Keywords: Additive manufacturing, Selective laser melting, Thin walling, AlSi10Mg, Maraging steel.

1. INTRODUCTION

Additive Manufacturing is a fabrication process which is able to produce complex three-dimensional components directly from a computer aided design. It is used extensively in the automotive, aerospace and biomedical industries because of its design flexibility. Thin walled structures are often incorporated in the components used in these industries because of their high strength to weight ratios (Hans, 2012).

Automotive and aerospace industries are always looking to optimise their products by using lighter and more complex components. Thin walled components which have good structural integrity and dimensional control are thus well sought out for in these industries. The discrepancies between the designed thin walled components and the fabricated product become larger as the part becomes more complex. The ability of additive manufacturing to produce three dimensional components directly from a computer aided design model makes it a suitable fabrication route for these industries.

Thin walled components are desired in industry due to their light weight advantage. These dimensions are near the limit of the width that the selective laser melting machines can manufacture. A general study on selective laser melting which was not based on any specific machine or metal powder suggested a maximum height to width ratio of 40:1. This ratio was suggested for selectively laser melted rectangular straight components. Exceeding this limit may lead to the component not forming or forming with abnormalities such as bulging. This study also suggested a maximum overhang angle of 45º to the building platform. Decreasing this angle increases the surface roughness on the down facing surface of the component and may even lead to the component not forming (Zelinski, 2016).

SLM processes create large temperature gradients in metallic components which causes the components to retain thermal stresses. These thermal stresses cause residual stresses if the they exceed the maximum yield limit of the material. Thermal stresses are responsible for delamination, cracking, warpage and reductions in the mechanical properties of printed components (Yingli Li, 2018).

2. METHODOLOGY AND RESULTS

To understand the extent of thin walling in the AlSi10Mg and M300 alloys, a total of 49 thin rectangular components were additively manufactured using the aluminium silicon alloy and the M300 steel (49 samples for AlSi10Mg, and 49 samples for M300 steel) by the SLM Solutions 280 machine. This experiment was executed in order to determine a threshold width under which either the AlSi10Mg alloy or the M300 steel will no longer form. The variables investigated were the height to width ratio and the influence of an overhang angle.
These structural components were printed at Metal Heart Additive Manufacturing at different heights, widths and overhanging angles while keeping the length constant at 10mm. The widths ranged from 0.18mm up to 2.5mm, the height ranged from 1mm up to 10mm while the overhang angle was varied from 0° up to 37.5°. This is illustrated by Figure 1 which shows the computer aided designs that will be used to form the components in this project.

2.1. Possible Experiment Benefits

It is expected that the results will show an empirical matrix, with a diagonal line separating the side which will form successfully and the side which will either not form or form with visible surface roughness and porosity. A threshold height to width ratio will thus be obtained. This will serve as a benchmark for Metal Heart Additive Manufacturing providing design guidelines for thin walled components. Components which form at the desired width and height with a limited amount of surface roughness on the down-facing side of components with overhang geometries will be deemed as successful. Components which do not form and have defects such as warping and cracking will be deemed as unsuccessful.

2.2. Results

Upon the completion of the printing session it was found that the AlSi10Mg components did not form at a width of 0.18 mm while the Maraging M300 steel alloy formed at all widths, heights and overhang angle. This was expected as the Maraging steel has a higher hardness than the AlSi10Mg alloy. This result was also expected as the AlSi10Mg alloy has a higher reflectivity than the Maraging M300 steel. It was also found that the surface roughness on the down-facing side of overhang angles had a considerably larger surface roughness the upward-facing sides. The Maraging M300 results are shown in Figure 2 below:

3. CONCLUSION

Taking the results and literature study into consideration, it can be concluded that Metal Heart Additive Manufacturing will be able to additively manufacture thin walled components of aluminium only up to a minimum of 0.2 mm at all overhang angles, while the Maraging steel M300 can be printed at all heights, widths and overhang angles using the SLM Solutions 280 machine. It can also be concluded that the surface roughness on the down-facing side of overhang components will be larger than the surface roughness on the upward-facing sides.

REFERENCES


Analysis Of Melt Pool During The Laser Powder Bed Fusion Of Tungsten

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1. INTRODUCTION

Laser powder bed fusion (LPBF) is an additive manufacturing (AM) process used by various industry sectors to lower the cost of production for high value low volume manufacturing and for complex shapes. LPBF is emerging as an alternative to conventional methods such as machining and casting. Fox et al. [1]. A high-powered laser is used to fuse metal powder into a solid component using data from a sliced 3D CAD file, one layer at a time. The layer thickness is typically in the range of 30 to 50μm. More details of LPBF have been published by Sidambe [2]. Tungsten (W) is a metal which is ideally used in ultra-high temperature and shielding applications Deprez et al. [3]. The processing of pure W using LPBF is difficult because of W has a high thermal conductivity, high melting temperature and a ductile-to-brittle transition temperature which renders W susceptible to cracking. Therefore processing of W via LPBF although technically challenging, would lead to an advantage in the high value manufacturing sectors such as medical implants, rocket nozzles and support hardware because LPBF has the ability to manufacture complicated shaped W parts with small dimensions, something which cannot be achieved using traditional metal working techniques such as milling, casting or pressing because of the hardness and strength of W Deprez et al. [3]. The high melting point of W has been reported to contribute to a high cohesive energy and high surface tension which in turn leads to high melt viscosity in LPBF Zhou et al. [4]. In this study, we carry out an analysis of the melting spreading and solidification of W in relation to LPBF parameters and explain the mechanisms in terms of surface tension around the W melt pool. By discussing the instabilities of the melt pool during the LPBF of W, we elaborate on the effect of the W properties.

2. METHODOLOGY AND RESULTS

Plasma-spheroidised W powder was subjected to laser melting. The powder particle size distribution was sub 45μm. W powder melting was carried out under an argon atmosphere with an initial residual oxygen content of less than 1800 ppm (0.18%) using a Renishaw AM125 system. The optimisation of the Gaussian laser beam (or laser spot) profile was carried out using an Ophir Photonics Spiricon SP620 beam profiler. The optimal focus offset was achieved at 1mm, yielding a laser beam diameter (the effective laser beam radius at which the maximum irradiance is decayed to 1/e2 Alda [5]) of 43μm. At the laser focus offset of 0 mm, laser beam diameter was 50μm. A commercially pure titanium (CPTi) substrate was used for the LPBF experiments. Careful considerations were given in selecting CPTi, because the high melting point of W makes it difficult to create a strong bonding with substrate. Studies consisted of single layer melt tracks using laser power range of 100, 150 and 200W and laser scan speeds ranging from 50 to 400 mm/s before and after the laser beam profile was optimised. The 2 dimensional (2D) linear input laser energy (defined as the laser power per laser scan speed per line area) was calculated by combining laser power, laser scan speed and laser beam diameter. The range of the 2D linear laser energy density that was used was from 5 to 93 J/mm². The melt track width and track overlap were analysed and quantified using the light optical microscopy (LOM) and ImageJ image processing software. It was found that when the 2D linear energy density was insufficient, this resulted in poor spreading of the melt tracks accompanied by melt break up which led to discontinuous melt tracks. With the increase of energy input which was achieved by increasing the laser power and lowering the laser scanning speed, continuous melt tracks of increased width were formed. The results confirm that when the linear energy density was increased, there was complete melting of the W followed by rapid cooling, thereby elimination of the breakup of the melt pool. This is thought to have been caused...
by the surface tension. Figure 1 shows the quantification of the melted track width for the W as a function of the 2D linear laser energy density and shows the range of the line width (100 to 470 μm). The optimised laser beam had the effect of increasing the achievable maximum laser energy density as expected and this is demonstrated in Figure 1. At the lower energy densities, the melt track width was found to be less varied when the laser beam diameter of 43 μm was used than when the laser beam diameter of 50 μm was used to melt the W. Whereas as the laser energy density increased, the melt tracks were wider at the focus offset of 1 mm than at 0 mm. Figure 1 (b) is a plot of the laser power as a function of the laser speed for the optimised laser beam, i.e laser beam diameter = 43 μm and focus offset = 1 mm. It can be confirmed from Figure 1 that the geometrical dimensions of the melt tracks were dependent on scan speed and on the linear energy density. The result indicated the presence of a well-known phenomenon where the surface tension coefficient as well as the melt viscosity decrease with increasing temperature Yadroitsev et al. [7].

3. CONCLUSION

In this study we have optimised the parameters so that the laser energy was able to melt the W and create a strong bond on a CPTi substrate. The mechanisms through which this was achieved were by overcoming of the high cohesive energy and high surface tension which reduce the melt flowability. When the conditions were inadequate, there was breaking up of the melt pool and “balling”, probably as a result of additional reduction of the surface free energy. By melting the W powder on the CPTi substrate, the melting point was lowered to that of the CPTi and the thermal conductivity was expected to be lowered by not more that 25% as reported by Lukáč Lukáč et al. [8], which also contributed to the promotion of the melt pool spreading. Furthermore, W is also susceptible to oxidation and our results suggest that the effect of oxidation was minimal and had no negative effect on melt pool spreading resulting in a clean solid–liquid interface at the atomic level Das [9]. The boiling point of W oxide is below the melting point of the metal W at 1700ºC, therefore the oxides vaporised. The processing has also been carried out in an argon atmosphere to prevent oxidation.

REFERENCES


Particle Emission From And Exposure To Metals During Powder Bed Fusion Additive Manufacturing Using Maraging Steel Powder

S. DU PREEZ1*, D.J. DE BEER2, AND J.L DU PLESSIS1

ABSTRACT
Of the seven AM process categories, powder bed fusion (PBF) is the most researched technology in terms of the feedstock materials used and technology development. However, research on emissions from PBF exposure of AM operators and potential health risks remains limited. This could be attributed to the small number of PBF machines in operation as well as the industrial size of the machines, limiting access to study emissions but also preventing studies in a controlled environment (chamber studies). Therefore, the aim of this study is firstly to establish the PSD, shape and elemental composition of maraging steel powders obtained from an AM facility in South Africa. Secondly this study’s aim is to assess particle emission from and AM operator’s personal respiratory exposure to maraging steel during PBF at an AM facility.

1. INTRODUCTION
AM processes can be categorised according to the material used, the deposition technique or by the manner in which the material is fused or solidified [1]. One of the prominent AM processes that are powder-based and commercially used for the production of metal parts is PBF [2]. All powder handling actions required for AM processes are performed manually by AM operators. Prior studies have indicated that smaller desktop material extrusion Fused Deposition Modelling (FDMTM) 3D printers are high emitters of particulate matter and volatile organic compounds (VOC’s) [3,4]. However, emission information for AM technologies other than FDMTM is limited. A study by Graff et al. [5] found that nano sized particles (< 300 nm) were present in the AM workplace environment and that AM operators are exposed to chrome, cobalt and nickel while handling Inconel 939 powder. Mellin et al. [6] found small round respirable metal particles (1-2 μm) in used Inconel 939 powder following selective laser melting and that the particles contained of carcinogenic chrome cobalt and nickel. Concerns have been raised regarding AM operators respiratory exposure to AM powders, since all powder handling actions include manual loading of powders, manual removal of finished parts and manual machine and part cleaning afterwards [5,6].

2. METHODOLOGY
Virgin and used (recycled) maraging steel feedstock powder was collected from the facility. Particle size was evaluated by means of particle shape distribution (PSD) and static image analysis (scanning electron microscopy (SEM)). Particle size and shape evaluation were conducted using the Malvern Morphologi G3 with its associated software (Malvern Instruments Ltd., United Kingdom). All samples were analysed in triplicate. Sampling was carried out at an AM facility 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 maraging steel metal powder materials. Personal sampling was conducted by means of GILAIR constant using the NIOSH 7300 method. All sample analysis was conducted by a SANAS accredited testing laboratory. Nanoparticle respiratory deposition (NPD) samplers were used to collect particles smaller than 300nm. 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).

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3. RESULTS

PSD differed between maraging steel virgin and used powder due to the recycling of powder during AM processes, which may influence the particle size (du Preez et al., 2018 a, submitted). Elemental composition analysis of virgin and used powders differed from the composition disclosed in the MSDS. The results from the direct read instruments indicated that airborne particles are emitted in the workplace atmosphere during pre-, processing and post-processing. AM operator’s personal exposure to maraging steel during each AM process phase was in accordance with area monitoring, AM operators, were exposed to eight inhalable metals namely aluminium, cobalt, chromium, copper, iron, nickel, titanium and vanadium in powder form. AM operator exposure to the individual metals was compared to their respective South African OELs, and it was found that exposure were all < 3.60% of the respective OELs. It was found that exposure to different metals smaller than 300 nm in size is also evident in some instances.

REFERENCES


4. CONCLUSION

There are many factors to be taken into consideration when determining an AM operator’s respiratory exposure. This study aimed to provide a better understanding of the PSD, shape and elemental composition of maraging steel powders and to assess AM operator’s personal respiratory exposure to maraging steel metal powders. The findings of this study serve as guidance for AM industrial facilities on what control measures to implement to eliminate or reduce AM operator/employee exposure during the use of maraging steel powders.
Surface Contamination From Use Of Metal Powders At Two Additive Manufacturing Facilities

R.L. HYSLOP1; S. DU PREEZ1; A. FRANKEN1 & S.J. LINDE1*

ABSTRACT

Little information exists regarding potential health hazards associated with the use of metal powders during additive manufacturing. The aim of this study was to assess the surface contamination caused by the use of metal powders at two additive manufacturing facilities using surface wipes. Results showed that detectable concentrations of various potentially hazardous metals were present on surfaces in printing and non-printing (canteens and offices) areas within the facilities. This could lead to the possible ingestion, inhalation and dermal absorption of these metals and possible adverse health effects for the operators. Poor housekeeping contributed substantially to the contamination.

1 INTRODUCTION

Additive manufacturing of metal powders is a relatively new technology, especially in South Africa; therefore little information exists on the potential health hazards involved. Maraging steel, stainless steel, and titanium alloy powders are used in additive manufacturing processes, including the process categories of powder bed fusion and direct energy deposition. As such, these powders may contaminate workplace surfaces and contribute to overall inhalation, dermal, and ingestion exposure. Exposure to metal powders such as nickel, chromium, and cobalt, which are steel component metals, can lead to various health effects, including dermal or respiratory sensitisation.

The aim of this study was to determine surface contamination caused by use of maraging steel, stainless steel, and titanium-6aluminium-4vanadium (Ti-6Al-4V) powders during powder bed fusion and direct energy deposition at two additive manufacturing facilities using a wipe sampling method. This was done in order to estimate the potential risk for secondary exposure to metal components.

2 METHODOLOGY AND RESULTS

2.1 Wipe methodology

Sampling took place at two additive manufacturing facilities where maraging steel, stainless steel, and/or Ti-6Al-4V powders were used in powder bed fusion and/or direct energy deposition. Surface wipe sampling was carried out in printing and non-printing areas using Ghostwipes™. Printing activities were divided into three printing phases (pre-processing, processing, and post-processing) and, where possible, samples were collected before and after activities in each of the phases. Even surfaces were wiped three times consecutively following an s-shaped pattern and using a 10 x 10 cm template. Uneven or irregular surfaces were also wiped three times consecutively and the area sampled was measured and used to adjust the results. The surface samples as well as the collected field and media blanks were subjected to inductively coupled argon plasma atomic emission spectroscopy analysis.

2.2 Results

Detectable concentrations of aluminium (below detection limit [BDL] 42.422 µg/cm²), cadmium (BDL-0.051 µg/cm²), cobalt (BDL-66.741 µg/cm²), chromium (BDL-132.727 µg/cm²), copper (BDL-3.84 µg/cm²), iron (BDL-1072.28 µg/cm²), lead (BDL-0.311 µg/cm²), manganese (BDL-3.625 µg/cm²), molybdenum (BDL-22.943 µg/cm²), nickel (BDL-77.539 µg/cm²), tin (BDL-0.217 µg/cm²), titanium (BDL-8.0 µg/cm²), vanadium (BDL-0.538 µg/cm²), and zinc (BDL-1.175 µg/cm²) were found to be present on surfaces in both printing and non-printing areas at both of the facilities. Contamination occurred prior to as well as during the different printing phases. When comparing total metal concentrations, significant differences (p ≤ 0.05) were found between the concentrations of contaminants on certain surfaces prior to specific printing phases and the concentrations of contaminants after those printing phases. Cross-contamination was found to occur between and within printing rooms where more than one type of metal powder was used. Significantly higher metal powder concentrations were found on surfaces in the printing rooms compared to that of surfaces in non-printing rooms.

1 * Occupational Hygiene and Health Research Initiative(OHHRI) North-West University, South Africa (Corresponding author)
3. CONCLUSION

Direct energy deposition with stainless steel powder, and powder bed fusion with maraging steel powder and Ti-6Al-4V powder caused detectable levels of metal powder contaminants to be present on printing room surfaces and non-printing room surfaces at both facilities. Cross-contamination as a result of airborne and/or contact transfer was found to have occurred from previous print builds with different metal powders in the same room. Contaminated surfaces presented as potential secondary sources of worker exposure through inhalation, dermal contact, and ingestion. Some of the metals that were found to be present on surfaces are capable of eliciting toxic responses in humans, including hypersensitivity reactions and cancer, and potential surface contamination-related exposure may contribute to the development of the adverse health effects associated with these metals. While surface contamination occurred as a result of the additive manufacturing activities, poor housekeeping contributed to the extent of surface contamination. The concentrations of metal powders found to be present on surfaces at the AM facilities is comparable to that found in other industries including the cemented tungsten carbide industry.

Key words: Surface sampling; maraging steel; stainless steel; Ghostwipes™; Ti-6Al-4V.
Machine Learning In Additive Manufacturing As Enabler For Smart Sustainable Manufacturing: A Review

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ABSTRACT

Machine learning is becoming an increasingly popular concept in the modern world since its main goal is to optimise systems by allowing one to make smarter and effective use of materials, products and services. In the manufacturing industry machine learning can lead to increased quality, lead time reduction, minimised cost, etc. At the same time, it enables systems to be designed for managing human behaviour. This research study used a systematic review to investigate the different machine learning algorithms within the sustainable manufacturing context. This paper focuses on additive manufacturing with optimised scheduling, process chains and quality assurance as applications.

1 INTRODUCTION

Additive manufacturing (AM) processes are processes which utilise technologies to build physical 3D objects directly from computer-aided design (CAD) data, by adding thin layers of material on top of each other to create the final product[1]. The material which can be used, include plastic, metal and concrete. Additive manufacturing produces high quality 3D products with complex geometries in minimum lead time[2].

Machine learning algorithms are becoming increasingly popular and have been applied to a variety of additive manufacturing processes to reduce building time and to increase quality (improved surface finish, minimised support structures, increased structural strength, increased stiffness, reduced warp deformation, increased dimensional accuracy, etc.).

2 METHODOLOGY AND RESULTS

2.1 Systematic review

The research methodology used for this study is the systematic review. The systematic review enables the growth of a knowledge base consisting of relevant and useful information, generates information based on research conducted in the areas of study which are of interest and identifies opportunities for further investigation[3]. A systematic review makes use of a pre-specified criteria to collect, evaluate and summarise the collected empirical evidence and research to answer a well-defined research question.

The focus of this paper is to review the different machine learning techniques which have been applied in the additive manufacturing industry, in terms of optimised scheduling, process chains and quality assurance. The literature review covers full papers from 2000 to 2017 which are selected according to the criteria provided in Table 1. The template was created by[4] and modifications were added by the author.

2.2 Machine learning techniques

A variety of machine learning techniques have been applied in the research. The most popular methods include neural networks (NNs)[1][5], genetic algorithm (GA)[6][7], fuzzy inference systems (FIS)[2][8] and regression modelling[9][10]. Less common methods include support vector machines (SVMs)[11], response surface methodology regression models (RSMs)[12], simulated annealing (SA)[13], finite element analysis (FEM)[14], etc. Hybrid or combinations of machine learning techniques have also been applied[12][15].

2.3 Machine learning applications in additive manufacturing

Machine learning algorithms have been applied to a variety of additive manufacturing process types including polymerization laser-based[7], melting laser-based[16], thermal extrusion[12], material jetting[17] and electron beam additive processes[14].
3. CONCLUSION

From the systematic review, the author learned of the different machine learning techniques which have been applied to additive manufacturing processes, the process of applying machine learning techniques in additive manufacturing processes and the machine learning trends in these manufacturing processes.

REFERENCES


The Development Of A Ti6Al4V DMLS Topology Optimised Model For Finite Strength Analysis

Evaluation Of The Validity Of Finite Element Strength Analysis On Topology Optimised DMLS Ti6Al4V

J.A VAN ROOYEN1, A, DR. JAN J. JANSE VAN RENSBURG1, B, CP KLOPPERS1, C

ABSTRACT

The objective of this research is to use solidThinking® Inspire™ 2018 for the development of a Ti6V4Al DMLS (direct metal laser sintered) topology optimised model; with the assumption of the weakest material properties as homogenous and to perform a finite strength analysis using Siemens NX12. DMLS is an additive-or layered manufacturing process used to melt metal powder by a high laser power to produce customised components. Topology optimisation is a type of structural optimisation that uses a mathematical method to optimise a defined problem within a design domain with fixed boundary conditions, and the optimisation is done for appropriate objective condition satisfying the constraints. \[1\].

1. INTRODUCTION

For the human race, it has always been an essential skill to be able to use technology to improve our lives. The development of additive manufacturing has made it possible to manufacture complex geometry and with this, the development of structural optimisation has expanded over recent years. Since 3D printing has key features to produce complex geometry and non-uniform wall thickness, having a tool to analyse the mechanics of such products or structures is of course of great interest.

The long term goal of this research is to design and develop a prosthetic arm to assist an amputee to be able to do on-and off-road cycling as well as on-and off-road motor biking. Since weight plays a major role in cycling, geometry optimisation techniques have to be deployed with the weight reduction as the main constraint. However the iterative process of geometry optimisation generates complex structures. These complex structures need to be manufactured and evaluated. The chosen manufacturing technique would be additive manufacturing because it enables the user to manufacture complex geometries. In order to evaluate these DMLS-CG (Direct Metal Laser Sintered Complex Geometries) one would need to know the behaviour of such geometries under specified load conditions.

A strength analysis of the DMLS-CG needs to be performed and evaluated in order to design and develop a lightweight prosthetic arm assisting an amputee in various cycling activities. DMLS is a layered manufacturing process and because of this, mechanical properties of the material depends on a number of factors\[2–9\].

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In order to conduct a valid strength analysis these factors need to be taken into consideration and therefore a verifiable test specimen needs to be generated. The test specimen’s geometry should mimic the prosthetic arm and therefore it must be geometry optimized with complex loads; torque, bending and axial.

2. METHODOLOGY

The methodology followed in this paper is illustrated in Figure 1.

As stated in the introduction, the material properties need to be obtained and a series of tests performed as recommended in the whitepaper by EOS [9]. The loads applied is a critical factor in ensuring a proper topology optimised test specimen, thus the loads are determined in such a manner that they play an equal role in the geometry development. This is done to eliminate the dominance of one load. The design area is determined according to the capabilities of the MTS Landmark® 100kN tensile test machine to minimise the uncertainty factor. With the determination of these factors topology optimisation can now be done as well as the finite element strength analysis.

REFERENCES


Printed RFID Tags On Paper Substrates Towards Low-Cost Connected Sensor Systems

S. SMITH1*, A. OBERHOLZER1, K. LAND1, J.G. KORVINK AND D. MAGER2

ABSTRACT

We present printed sensing radio frequency identification (RFID) tags on different paper substrates towards low-cost, automated connected sensor solutions. Combining the Internet of Things (IoT) with printed electronics and low-cost substrates, this work showcases rapid prototyping of devices for automated sensor readout and wireless transmission using a screen printed antenna and RFID sensing chip. Functionality of the tags on three low-cost, flexible substrates was demonstrated through read range measurements and wireless built-in temperature read-out to illustrate the potential of low-cost, connected sensors to be utilized for a range of applications, from cold-chain monitoring to point-of-care diagnostics.

1. INTRODUCTION

This work showcases the rapid prototyping of ultra-high frequency (UHF) RFID sensing tags screen printed on three different low-cost, flexible substrates, with the long-term goal of providing solutions for point-of-care diagnostics in resource-limited clinic settings. The approach combines IoT with the field of printed electronics to realize low-cost, automated devices with sensing and wireless communication capabilities which could be utilized for patient and sample tracking, ease of record keeping and automated read-out of a test result.

UHF RFID is an advantageous technology as it affords longer read ranges, with multiple tag readings achievable. In addition, these tag devices can function in passive mode, eliminating the need for on-board power and reducing the cost of the tag devices. In this mode, the tags are powered from the electromagnetic field supplied by the RFID reader device, which could be a permanent fixture or a handheld solution. Complementary to this is the development of printed electronics and printed antennas, where successful printing on to various flexible substrates has been achieved [1,2]. RFID antennas typically have simpler geometric designs, assisting with the printability of these devices. Sensing RFID solutions have also been explored, with this work focusing on the SL900A sensing RFID chip (AMS, Austria), which enables a number of different sensors to be directly connected and the readout from these sensors to be wirelessly communicated [3]. We showcase logging and readout of temperature as an example for tags printed on to different low-cost substrates.

2. METHODOLOGY AND RESULTS

RFID tag designs were based on the SL900A development kit, consisting of a printed dipole antenna and electronic tracks, a 39 nH surface mount inductor, SL900A chip and a 3 V coin cell battery. Tag designs were screen printed on to three different low-cost flexible substrates, namely standard printing paper, cardboard packaging and transparent adhesive vinyl, using a silver screen printable ink (AG-800, Applied Ink Solutions, USA). Screen printing was carried out using a modified ZellPrint LT300 stencil printer (LPKF Laser and Electronics, Germany) with screens manufactured by Chemosol (Pty) Ltd. (Johannesburg, South Africa) using a synthetic mesh of 71 threads/cm. Printed devices were cured in the oven at 90°C for 15 mins, after which components were assembled using a silver epoxy conductive adhesive.

Printed features were analysed using a brightfield microscope (Meiji Techno EMZ-8TR) and a laser scanning microscope (LSM 5 Pascal, Carl Zeiss, Germany), with results shown in Figure 1. LSM was used to perform surface roughness measurements for each substrate and the printed ink layers. Substrate roughness values ranged from 0.29 µm for adhesive vinyl to > 5 µm for cardboard packaging. The printed ink roughness was approximately 4.5 µm on standard printing paper and cardboard packaging, and 0.9 µm on adhesive vinyl.

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2 Institute of Microstructure Technology, Karlsruhe Institute of Technology (KIT), Germany
Maximum read ranges at which the tags could be detected and at which sensor values, e.g., temperature, could successfully be obtained were recorded using the reader development kit (AS3993-QF_DK_R Fermi reader, AMS, Austria) with monopole reader antenna (gain = 2.2 dBi). Measurements were carried out for three tags for each type of substrate, both in passive (no battery) and active (battery-assisted) modes (Figure 2a). The reader transmit power is 22 dBm and reader settings were selected to be 917 – 920 MHz, covering the standard South African frequency range for RFID, with reader sensitivity set at -68 dBm. In active mode, logging of sensor data can be implemented through the SL900A built-in EEPROM, even when the tag is not in the range of the reader (Figure 2b). Read ranges of more than 200 mm are achieved in all cases.

### 3. CONCLUSION

Rapid prototyping of low-cost, automated and wireless sensor devices on different flexible substrates has been successfully demonstrated. Low-cost, accessible substrates that can easily be integrated with other devices or diagnostics show repeatable wireless read-out of sensor values from the tags in both passive and active modes. Logging of sensor data over periods of time has also been successfully demonstrated. Future work will be built on the assumption that a reliable link to the outside world exists and will focus on the electrical readout of the diagnostic result on paper, with the potential to solve many of the challenges faced in diagnostic testing carried out at rural and resource-limited clinics.

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**Figure 1:** Assembled printed RFID sensing tags on low-cost substrates (110 mm x 30 mm) with corresponding microscope and LSM images (substrate = left, ink layer = right, scan area = 450 x 450 µm) for assessing printed features for a) standard printing paper, b) cardboard packaging and c) adhesive vinyl substrates.

**Figure 2:** a) Maximum read ranges in both active and passive mode for tag detection and temperature readout for different tags compared to read ranges obtained using the commercially available printed circuit board (PCB) development kit for the SL900A as well as a milled PCB of the tag design manufactured and assembled in-house. b) Example of temperature and battery level data logging and wireless read-out from a tag printed on adhesive vinyl substrate.

### REFERENCES


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| 15:40 Tensile And High Cycle Fatigue Properties Of | Lerata Botsane Malefane |
| Annealed Ti6Al4V (ELI) Specimens Produced By | |
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| 16:00 X-Ray and Computed Tomography as a Tool | Philip Sperling |
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| 16:20 Experimental Analyses of Heat Treated | Amukelani Sydney Sydney Ngoveni |
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| 18:30 Gala Dinner for 19:00 | 18:30 Gala Dinner for 19:00 |

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<td>Spheroidisation of Titanium Metal Powder by RF Thermal Plasma Processing</td>
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Patient Specific Dynamic Hand Splints Produced Through Selective Laser Sintering

W.A. KINNEAR*, J.G. VAN DER WALT**, F.A. KLEINHANS*** AND T. BUCHANAN****

ABSTRACT

The ability of Additive Manufacturing (AM) to produce on demand and patient specific medical devices has made it an attractive technology in the medical orthoses and prosthetic environment.

Current available dynamic hand splints are not cost effective and have extended manufacturing lead times due to the patient specific and complex nature of the devices. This paper highlights the use of AM to locally manufacture cost effective and accessible patient specific dynamic hand splints. AM design principles such as lattice structures and in process assembly of parts were utilised to produce a dynamic hand splint with improved functionality, allowing for motion in a specific direction while restricting and supporting undesired motion.

1 INTRODUCTION

A functional hand is a prerequisite for the optimal performance of all activities of daily living that make it possible to meaningfully fulfil one’s life roles and tasks. The hand is a complex structure that integrates basic abilities such as muscle strength, range of movement, sensation and proprioception in order to perform both simple and complex fine and gross motor tasks. Participation in daily tasks is still possible in the presence of impaired hand function, but requires the implementation of a suitable assistive device that facilitates function. It is essential that this device compensates for the specific impairment but does not negatively impact on other basic abilities. Static and dynamic hand splinting are widely used to stabilise, maintain, restrict and/or facilitate active use of the hand during various stages of recovery following impairment or, as an alternative to compensate for a permanent loss of one or more functional ability. Dynamic splinting is used in acute and chronic nerve and tendon injuries, acute and chronic neurological conditions, soft tissue injuries involving multiple structures, pain related conditions as well as degenerative conditions under the guidance of qualified professionals [1]. Conventionally manufactured dynamic hand splints are not cost effective or accessible due to their patient specific nature, needing a highly trained professional to manufacture the splints [2]. These splints are also bulky, have poor functionality and aesthetic appeal due to the number of parts and design elements needed to restore the complex biomechanical function of the hand (Figure 1).

Figure 1. Conventionally manufactured dynamic hand splints.

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3 FA Kleinhans orthotics & prosthetics, Bloemfontein, Free State, South Africa
4 Nurture Hillandale rehab hospital, Bloemfontein, Free State, South Africa
The patient specific and complex nature of dynamic hand splint manufacturing makes this well suited to AM. Paterson et al. investigated various AM process to directly manufacture upper extremity static splints [3]. They concluded that Selective Laser Sintering (SLS) and PolyJet material jetting displays unique advantageous characteristics when manufacturing splints, only made feasible by the manufacturing processes. Munguia et al. showed that SLS structures can be produced with varying flexural properties utilising geometric features [4]. The authors found that functionally graded stiffness can be controlled by means of parametric features of the lattice structures.

2. METHODOLOGY

Research into the feasibility of producing a dynamic hand splint through AM was performed on an EOS P385 printer with nylon PA2200 as printing material. This printing process and material were selected because of the durability of parts produced and no need for support structures during manufacturing. The following experimental procedure was followed:

• Comparison of in process assembled hinges and lattice structures to produce finger supporting structures.

• Comparison of spring wire, custom manufacture elastics and in process produced AM springs as resistive elements to replace tendon function.

• Optimisation of lattice structure parametric features to produce functional durable finger structures that allow flexible movement in a specific direction while restricting/supporting undesired motion.

• Case study, to determine functionality and durability.

• Cost and procurement process comparison.

3. RESULTS

Results on different hinge and tensioning mechanisms were attained from the experimental work and what found to give the best results were combined into a newly developed dynamic hand splint that was produced through AM (Figure 2a and b).

4. CONCLUSION

It was concluded that hinges made up of lattice structures and tensioning provided through elastic bands produced a dynamic hand splint with the intended functionality. The device was proven to be durable and can be produced at relatively low cost through AM.

REFERENCES


Evaluating The Suitability Of Alumide Tooling For Injection Moulding Of Different Polymers

J COMBRINCK*+, J.G VAN DER WALT, G.J BOOYSEN AND D.J DE BEER

ABSTRACT

This paper describes the possibility of using laser sintered Alumide® as an alternative material for producing Rapid Tooling (RT) inserts. To determine the durability of Alumide® inserts for the Injection Moulding (IM) process, a product with geometrical features was developed and Alumide® inserts were manufactured for IM trials using Polypropylene (PP), Acrylonitrile-Butadiene-Styrene (ABS), Polycarbonate (PC) and Polyamide 6 (PA 6). From these trials, it was concluded that polymer materials with process parameters similar to PP and ABS can be used with Alumide® inserts as RT inserts for the IM process.

1. INTRODUCTION

Since Additive Manufacturing (AM) was introduced in the early 90’s, it has become an important part of the product development process in many industries [1]. AM prototype parts can be quickly produced for validation, measurement and in some cases, for actual trials [2]. Parts that may be difficult or even impossible to manufacture by conventional manufacturing methods can often be manufactured through AM technologies. The demand for quicker methods to create technical prototypes, manufactured in the correct material, using the appropriate production method (such as IM), has led to RT techniques using AM technologies [3].

RT defines mould making processes that can create tools quickly and with minimum direct labour. RT includes tool manufacturing techniques that apply additive, subtractive, and pattern-based processes. RT can be applied in a variety of applications from IM to casting and sheet metal stamping operations. The potential of RT has led to tremendous interest in RT solutions for product design and manufacturing. Whether RT is used for prototyping, limited run, or production tooling, it provides an opportunity to reduce the time and cost of product development [4].

This paper investigates the possibility of using laser sintered Alumide® as an alternative material for producing RT inserts.

2. METHODOLOGY AND RESULTS

2.1. Methodology

To determine the durability of geometrical features of an Alumide® insert, a product was designed with different geometrical features which normally require secondary operations (such as electrical discharge machining) to manufacture using conventional methods. These features include engraving, sharp internal corners and ribs. Different IM polymers (PP, ABS, PC and, PA 6) were used during the IM trials to test the suitability of different polymers for use with Alumide® inserts.

1 * Department of Mechanical & Mechatronic Engineering, Central University of Technology Free State, South Africa
2 Technology Transfer and Innovation Support, North-West University, South Africa
From the results, it can be concluded that polymer materials with a processing temperature of below 230°C can be used for limited production runs with AlumideÆ if the insert features can be cooled to a temperature less than the melting temperature of AlumideÆ and that polyamide and polycarbonate materials are not suitable for use with AlumideÆ inserts.

REFERENCES


ABSTRACT

High residual stress, a martensitic microstructure and porosity pose major restriction in the qualification of Selective Laser Melting (SLM) produced Ti6Al4V parts for biomedical and aerospace applications. This study is aimed in identify ageing strategies that effectively relieve residual stress while at the same time achieve an optimal strength and ductility ratio (i.e. maintain the advantage of relatively high strength and ductility). It was found that annealing at 560 °C relieved 90% of the residual stress after ~1 hour, however resulted the formation of fine β precipitates forming heterogeneously at α/α' boundaries and twins which led to the embrittlement of the material. At higher temperatures, above 600 °C, fine β precipitates agglomerate to achieve more optimal tensile properties.

1. INTRODUCTION

SLM is a powder metallurgical Additive Manufacturing (AM) technique in which ultra-fine powder is melted in a layer-wise fashion to build parts. AM offers numerous advantages over traditional subtractive manufacturing techniques such as: lower material waste, lower lead times and the capability of achieving high part complexity. The technique has been successfully applied to build parts from pre-alloyed Ti6Al4V powder. This alloy is the most popular titanium alloy in the traditional manufacturing industry (wrought, rolling and CNC). This is due to wrought-produced Ti6Al4V’s superior mechanical properties, particularly its high strength to weight ratio [1].

The SLM-produced form (prior to post-processes) however does not achieve the same superior mechanical properties as it’s wrought-produced counterpart. Due to the extreme localised melting of powder, high thermal gradients in the part volume and high cooling rates of the scan track cause high residual stresses [2] and unfavourable meta-stable martensitic microstructure (α’ & α’’) [3]. Residual stress can cause delimitation of part layers and between the part and the build plate. Residual stress has also been shown to cause pre-mature part failure in static and fatigue loading [4]. Martensitic microstructure has been shown to cause poor part ductility, fatigue life, and toughness [4]. Various literature studies have been conducted to develop post-process heat treatments to relieve residual stress and decompose martensitic microstructure into a ductile α+β microstructure [5]. While various studies have identified temperature ranges where this is achieved, this is usually at a loss of material strength [6]. Furthermore, very little is literature exists of the microstructural changes at temperatures below 650 °C (so called ‘aging’ [1]). This study investigated the nature of low temperature stress relaxation and phase transformation to developed more tailored post-process heat treatments that achieve stress relieved parts that are still able to achieve optimal part strength.

2. METHODOLOGY AND RESULTS

Cylindrical samples of diameter 15 mm and length 90 mm were built using a Concept Laser M2 machine. Layers were built at 30 µm using uni-axial zig-zag scan strategy. Laser parameters were: power = 100 W, scan speed = 1000 mm/s, laser spot size = 100 µm and hatch spacing = 100 µm. Samples intended for stress analysis and microstructural investigation were sectioned 5 mm from the top using a slow-speed diamond-edged cutting blade. Microstructural samples were polished using Buehler metallography equipment and standard procedures for Ti-alloys. A Bruker D8 Advanced X-ray diffraction (XRD) machine was used in which a single φ angle was scanned in the centre of the sample plane at 11 ψ angles (-45° to +45°). Microstructural analysis was done using as Zeiss MERLIN scanning electron microscope (SEM) in conjunction with a backscatter detector (BSD). Micro-indentations were done using an Emcotest DuraScan automatic indentation machine with a load of 2 kgf for 10 seconds in accordance with ASTM E348-10. Samples intended for uniaxial tension tests were machined to dog-bone specimens with gauge diameter of 5 mm and gauge length of 25 mm in accordance to ASTM E8. Uni-axial quasi static tensile tests were conducted using a MTS Criterion frame at displacement rate of 0.13 mm/min. Samples were annealed at temperatures of 427, 480, 560 and 610 °C each at times ranging from 5 minutes to 30 hours in a box-furnace.

The temperature range of 427 to 480 °C showed a slow stress relief. Annealing at a temperature of 560 to 610 °C showed an exponential increase in stress relief over a shorter time. It was found that the Vickers hardness of all annealed samples increased immediately (measured after 5 minutes) from the as-built sample’s hardness of 350 HV2 followed by a slight decrease in hardness after 30 hours. Samples annealed at 427 to 560 °C all reached a maximum hardness of ~ 400 HV2 after...
approximately 1 hour followed by decrease to 390 HV2 after 30 hours. The sample annealed 610°C reached a maximum hardness of 370 HV2 after 5 min and then decreased back to 350 HV2 after 8 hours where the hardness remained unchanged after 30 hours.

Nano-sized phase precipitates at martensitic grain boundaries and twins were observed for the sample annealed at 480°C for 30 hours. These precipitates appear to agglomerate and grow in size along the α/α’ grain boundaries when annealed for 30 hours at 560°C while further growing along α/α’ grain boundaries at a temperature of 610°C. Through XRD analysis a BCC phase was observed at 560°C (30 hours). Two BCC phases of differing lattice spacing were observed at 610°C after 8 hours. After 30 hours at 610°C the BCC phases were replaced by α” (face-centred orthorhombic martensite). This transformation has been theorised by Zeng and Bieler \cite{7} and observed directly for the first time in this study. The transformation is summarised as: \[ \alpha' \rightarrow \alpha + \beta \rightarrow \alpha + \beta + \delta \alpha' \rightarrow \alpha + \beta + \delta \alpha'' \rightarrow \alpha' + \beta. \] The increase in hardness is very likely caused by a β phase nucleating at the α/α’ grains boundaries. This has theorised by Donachie \cite{1} and Gil Mur \cite{8}. Fine Ti3Al particles precipitate homogeneously in α grains and result in an increase in hardness. Similarly, as shown by Carreon et al. \cite{9} for α+β equiaxed microstructures, the hardness reached its maximum value (≈400 HV) after 100 hours of heat-treatment. It is therefore likely that the hardness is caused by phase transformation to β precipitates as observed by SEM and XRD. The increased hardness was shown to cause an increase in strength and a decrease in ductility.

### 3. CONCLUSION

It can be concluded that even though residual stress can be relieved up to 80 % at 480 °C and 90 % after an hour at 560 °C, the increase in Vickers hardness caused by the formation of β precipitates at α/α’ grain boundaries and twins, causes a decrease in ductility. The particles appear to form much faster in martensite than in stable α+β microstructures. To avoid embrittlement but retain a high material strength while relieving residual stress, it is recommended to anneal at a minimum of 610 °C for at least 8 hours.

### ACKNOWLEDGEMENTS

The authors would like to thank the Department of Science and Technology for the financial support through the Collaborative Programme in Additive Manufacturing.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Percentage stress relieved after</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 min</td>
</tr>
<tr>
<td>427</td>
<td>-</td>
</tr>
<tr>
<td>480</td>
<td>8 %</td>
</tr>
<tr>
<td>560</td>
<td>75 %</td>
</tr>
<tr>
<td>610</td>
<td>90 %</td>
</tr>
</tbody>
</table>

### REFERENCES


Characterisation Of The Anisotropic Mechanical Properties Of Carbon Fibre Reinforced Thermoplastic Composites

G.A. POTGIETER, A1 & C.P. KLOPPERS, B

ABSTRACT

Continuous Fibre Fabrication is an additive manufacturing technique prominent to MarkForged where reinforced fibres (carbon, fibreglass or kevlar) are thoroughly ironed against core materials such as nylon or onyx [1]. From this definition, it may be evident that the classical laminated theory must be used for simulation and analysis purposes on this kind of composites [2]. However, an investigation on the anisotropic effects (specifically carbon fibre with nylon) was done and the results are thought-provoking. A new database was created together with a possible mathematical model to predict the material properties with different fibre angle combinations.

1. INTRODUCTION

Fused Filament Fabrication (FFF) is an additive manufacturing (AM) process of creating solid, three-dimensional objects from a digital file. During this additive process, an object is created by successive layers of material (thermoplastic filament) being laid down until the entire object is formed. Each of these layers can be seen as a thinly sliced horizontal cross-section of the final object. However, a technology called Composite Filament Fabrication (CFF) ensures reinforcements of these objects by means of in-layer fibre AM [1].

In order to optimize any component design in AM, the interior structural properties need to be investigated together with the printed material. The machine that will be used during this study is the Markforged Mark II that will operate with the Eiger as the slicing software. All necessary internal structure patterns and orientations will be controlled by this program, while the material is limited to Nylon (core material) and Carbon Fibre (reinforced material).

The most applicable method for determining the basic material property data for component design and service performance assessment is tensile testing. This is, therefore, the selected testing method for this investigation project.

1.1. Problem statement

The development of a mathematical model for the prediction of the ultimate tensile strength of continuous fibre fabricated components under tensile load.

2. METHODOLOGY AND RESULTS

The study requires the testing and investigation of nylon with carbon fibre reinforcement specimens that are printed on the Markforged Mark II printer. All tests are done according to certain standards to obtain valuable material properties in terms of different printing layup orientation.

2.1. Research objectives

- Nylon with carbon fibre reinforcement specimens go through tensile tests to obtain all necessary material properties according to several printing layup orientation combinations;
- Data gathered from these tests is subjected to statistical deductions and compared to the usual classical laminated theory by making use of the laminated analysis program (LAP);
- Constructing a mathematical model to predict ultimate tensile strength results by using appropriate methods.

2.2. Comparing CFF vs LAP

The following table shows all four different layout combination’s experimental results compared with the theoretical values obtained by making use of LAP in percentage error. It is evident that the CFF material behaves more linear than non-linear with the Tsai-Wu and Tsai-Hill failure criteria being the most accurate methods. Note that the lowest individual result is 10.39% (single, non-linear and Tsai-Hill) while the lowest percentage for failure criteria is the Tsai-Wu under the linear conditions with a value of 25.77%. These values are however still too high and a more accurate method still needs to be implemented to predict
the ultimate tensile strength of CFF material. A mathematical model was constructed and can be seen under the next heading.

Table 1: Percentage comparison between experimental and LAP results

<table>
<thead>
<tr>
<th>Layout</th>
<th>Linear</th>
<th>Non-Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tsai-</td>
<td>Tsai-</td>
</tr>
<tr>
<td></td>
<td>Wu</td>
<td>Hill</td>
</tr>
<tr>
<td>Mean</td>
<td>22.68</td>
<td>30.78</td>
</tr>
<tr>
<td>Single</td>
<td>29.2</td>
<td>11.16</td>
</tr>
<tr>
<td>90°</td>
<td>22.9</td>
<td>27.03</td>
</tr>
<tr>
<td>45°</td>
<td>36.0</td>
<td>52.72</td>
</tr>
<tr>
<td>30°</td>
<td>14.8</td>
<td>43.56</td>
</tr>
<tr>
<td>Mean</td>
<td>25.7</td>
<td>33.62</td>
</tr>
</tbody>
</table>

2.3 Mathematical Model

The following mathematical equation was constructed for the prediction of the ultimate tensile strength after the conclusion was made that CFF material does not follow the classical laminated theory with all possible layout combinations. It is a purely analytical approach (Fig. 1a) and the results show that the average percentage difference is only 9.04%.

\[
UTS = \frac{(\theta_{CM} \cdot UTS_{CM}) + (\theta_{comp.} \cdot UTS_{hcm})}{(\theta_{CM} + \theta_{comp.})}
\]

Where:
- \(\theta_{CM}\): Number of core material (nylon in this case)
- \(UTS_{CM}\): UTS of core material
- \(\theta_{comp}^*\): Number of complete sets of carbon fiber before it repeats
- \(UTS_{hcm}\): Theoretical UTS calculated as follows:

\[
UTS_{hcm} = (UTS_{SP} \cdot \lambda)(\cos \alpha + \cos \alpha + \cos \alpha + \ldots) + (UTS_{SP} \cdot \beta)(\cos \beta + \cos \beta + \cos \beta + \ldots)
\]

Where:
- \(\alpha + \beta = 90°\)
- \(A + B = 1\)
- All values of \(A\) can be obtained from the \(\frac{UTS_{All\ Single\ Combinations}}{UTS_{SP}}\) graph

(Fig. 1b)

x coordinates on this graph can be calculated as follows:

\[
\text{coordinate} = \frac{\text{Combination Layout}}{2} - \frac{\text{Ratio Degree}}{2}
\]

Values of Ratio Degree can be obtained from 3D constructed graph (Fig. 1c)

3. CONCLUSION

Taking everything into consideration, the results obtained from LAP shows that CFF material tends to be more linear than non-linear - especially when the angles between a layer and its successive layers increase. This is true when one considers the fact that the CFF material behaves both linear and non-linear within the single combination category but after that, it tends more to be linear. Therefore, the verification process of this article shows that the lack of material property data of the CFF material (validation of the article) is, in fact, a problem that could not just be solved by assuming that the material complies with the CLT. Thus, the characterisation of the anisotropic mechanical properties of carbon fibre reinforced thermoplastic composites that were required and constructed. This analytical approach showed promising results and further investigation can be made to optimise such a mathematical model.

REFERENCES


Variation Of Impact Toughness With Temperature Of As-Built DMLS Ti6Al4V (ELI) Specimens

A M MUIRURI1*, M MARINGA2, W B DU PREEZ3 & LM MASU4

ABSTRACT

The response of DMLS produced Ti6Al4V (ELI) to impact was investigated using Charpy impact testing. Impact testing was conducted over the temperature range of -130°C to 250°C. The effect of the orientation of the v-notch with reference to the base plate was investigated. The results obtained showed better values of impact toughness for samples produced with the v-notch facing the base plate in comparison to those that had the v-notch facing away from the base plate over most of the test temperatures. The study further established that the alloy retains appreciable notch toughness even at the low temperature of -130°C.

1. INTRODUCTION

Toughness is a measure of the energy that is absorbed by a material upon application of load on it until fracture. Toughness is often estimated by calculating the area beneath the stress-strain curve. Low temperatures can adversely affect the toughness of many commonly-used engineering materials. This study is motivated partly by the fact that literature on the variation of impact energy with temperature using standard Charpy test specimens for additive manufactured Ti6Al4V is very limited. The available literature focuses on the impact energy of various microstructures of the alloy at specific temperatures such as room temperature [1, 2]. This paper discusses the response of DMLS produced, Ti6Al4V (ELI) to Charpy impact loading at temperatures varying between -130°C and 250°C. The effects of residual stress are discussed based on the results of testing specimens printed with a v-notch facing the base plate (LO) on the one hand and facing away from the base plate (UP) on the other hand. The transition curves and ductile to brittle transition temperatures (DBTTs) are presented and the resulting fracture surfaces at various temperatures presented, studied and analysed.

2. METHODOLOGY AND RESULTS

2.1 Methodology

Standard v-notch Charpy specimen were built in a DMLS EOSINT M280 system with the specifications outlined in the ASTM E23 standard illustrated in Figure 1. A total of 36 specimens were printed. Half of them were printed with the notch facing the base plate (LO) of the DMLS machine and the rest with the notch facing away from the base plate (UP). The Charpy impact test was used to determine material toughness at various temperatures by hitting each test specimen with a hammer mounted at the end of a pendulum in an arrangement such as is shown in Figure 2. The lateral expansion (LE) or increase in thickness of the specimen due to plastic deformation around the zone of fracture was measured on the broken samples using a digital caliper as outlined in the ASTM E23 standard. The resulting fracture surfaces of the tested specimens were studied using a Scanning Electron Microscope (SEM).
### 2.2 Experimental Results

The charpy v-notch toughness and lateral expansion of the tested specimens, the latter resulting from Poisson’s ratio expansion, are presented. The results obtained showed an increase in the notch toughness of the tested specimens with the test temperatures and so also the lateral expansion in both cases of UP and LO specimens. There was a shift in DBTT to the left (low temperatures) for the LO specimens in relation to the UP specimens. This increases the range of service temperatures at which the alloy can be used without catastrophic failure due to sudden loading, as the advent of brittle fracture moves to a lower temperature. It was also noted that the DBTT toughness of the LO specimens at their transition temperature is higher than that of the UP specimens at their transition temperature. The resulting fracture surfaces of the tested samples exhibited four distinct regions; crack initiation, shear lips, flat fracture area and final fracture. Each of these zones represent distinct failure mechanisms. The flat fracture area was observed to gradually diminish in size with increasing temperature.

### 3. CONCLUSIONS

The variation of the impact toughness of the as-built DMLS Ti6Al4V with temperature was studied. The alloy did not show drastic changes in toughness with increase in temperature. Appreciable notch toughness was recorded even at the low temperature of -130°C. The presence of residual stress in the samples is thought to have given rise to lower values of the DBTT for the LO than for the UP specimens.

### REFERENCES


Utilisation Of Additive And Subtractive Digital Fabrication Processes In The Manufacture Of Moulds For Ceramic Slip-Casting

A.M. BULLOCK1* & M. BOLTON2

ABSTRACT

This paper intends to illustrate and discuss two alternative approaches in the forming of plaster moulds for ceramic slip casting. The first process being the utilisation of 3D printing for the creating of mould-making patterns from CAD generated files, and the second being the direct CNC cutting of the ceramic slip-casting cavities straight out of pre-cast Plaster of Paris blocks. The generation of CAD files was done with SolidWorks, 3D printing undertaken with a low-end FDM 3D printer, and toolpath generation for CAM processing done with Rhino & RhinoCam, and CNC Cutting undertaken on a small-bed HIGH-Z milling machine.

1. INTRODUCTION TO CERAMIC SLIP CASTING

Slip casting is a ceramic manufacture process used to create hollow vessels or products with an even wall thickness. Slip casting is a filtration process, in which a thin slurry or ‘liquid slip’ (a mixture of dry clay, water and deflocculants) is poured into a mould made from a hydroscopic plaster most commonly Plaster of Paris. The porosity of the Plaster of Paris causes a capillary action and the mould withdraws the liquid (filtrate) from the slip. As the liquid is ‘sucked’ into the mould, the suspended clay particles are forced towards the mould walls leaving behind a stiff layer of clay particles on the wall of the mould creating the even wall thickness of the final product/vessel. After a length of time, determined by the desired wall thickness on the part/vessel, the remaining liquid slip is poured out of the mould. As the clay dries, it shrinks and pulls away from the sides of the mould and can be released for further drying and firing [1].

2. THE DIGITAL-HANDMADE

Ceramic production technology has not advanced significantly over the past centuries. However, the recent advancements and accessibility of digital fabrication software and machinery has lead to the growth of a digital revolution in ceramics of “digital crafting” whereby designers explore new relationships between the hand, traditional skill and digital technology, combining cutting edge fabrication with craft traditions through the use of digital design, tooling and manufacture [2].

3. PATTERN AND MOULD MAKING – PROBLEM AND OPPORTUNITY

The first step in mould making process for slip casting is the modelling of a master model of the desired shape known as the original, pattern or positive. Modelling involves the art of manipulating a malleable material, such as clay, plasticine, modelling clays, wax, papier-mâché, synthetic foams and wood [3]. The process of modelling is heavily time intensive and requires a great amount of skill and craftsmanship. From a design point of view, this is a limiting factor as the form giving and level of detail or complexity that can be achieved is limited to the skill of the maker. Incorporating CAD & CAM software and machinery into the process of mould making offers great opportunity for increased design complexity and detail as well as increased production efficiency. The following consists of two approaches to transforming the mould making process though the incorporation of 3D printing in the pattern-making process, and CNC Cutting in the mould-making process.

4. METHOD 1: 3D PRINTING MASTER PATTERN

The incorporation of 3D printing in this sequence allows for a mould pattern to be created directly from a CAD model using 3D printing. The sequence illustrated below illustrates and example of this in the creation of a small geometric planter to be cast from black ceramic slip. The initial CAD form was created in SolidWorks which was a solid geometric faceted form modelled with solid modelling feature steps. This SolidWorks file was imported into the UP! Mini 3D Printing software and printed using ABS plastic filament. This was then used to create a ceramic 3 part mould which would allow for the entire faceted form to be slip-cast, dried then fired. Figure 2 shows the 3D Printed master form, the 3 part mould, and final geometric planter.

1 * Department of Industrial Design, University of Johannesburg, South Africa (Corresponding author)
2 Department of Industrial Design, University of Johannesburg, South Africa
5. METHOD 2: CNC CUT PLASTER MOULD (NO PATTERN NEEDED)

The second method attempts to eliminate the pattern making step/process altogether and subtractive milling the mould cavity from a pre-cast block of Plaster of Paris. In the example below a SolidWorks Part file of a small dish was imported into Rhino, and a Boolean subtract command subtracting the dish from a solid rectangular block creating the mould form. This was then prepared for cutting using RhinoCam. The cutting sequence used was 4 layers of horizontal roughing, followed by a spiral cut starting at the lowest centre spot of the mould. The cutting bit utilised was a 6mm Tungsten Carbide end-mill. The CNC cutting was undertaken using a prepared cast block of Plaster of Paris mounted within a small desktop router (High-Z CNC Router). The mould was then used to slip-cast black ceramic dishes with a final wall thickness of approximately 2mm. These were then fired once dried. This sequence is visible in Figure 2.

6. BENEFITS OF USING CAD CAM WORKFLOW FOR THE MANUFACTURE OF SLIP-CAST MOULDS:

- Calculating and compensating for ceramic shrinkages for tolerance specific parts:

  For instance, if a ceramic is tested and is known to have a 8.5% shrinkage once fired, the file can be scaled up by the exact factor to take this into consideration.

- Dependence on CAD accuracy for form reproduction:

  The mark of the craftsman is often desired, however, if the dependence on extreme accuracy and surface finishes is required, then the inaccuracies and human error are undesirable. This allows for the accuracy of the 3D Printer or CNC machine to be the limiting variable.

- Multiple component assemblies:

  With the reliance on CAD Components for the production of the moulds, these components do not have to be singular components, but could be multiple components forming complex assemblies.

7. CONCLUSION

Although the ceramic slip-casting process has been utilised for hundreds of years, there are many opportunities for new approaches within the mould making process. This paper illustrates just two examples, but the aim is to pursue more complex products and different processes not only in the mould making, but also in the product compositions and usages of various materials.

REFERENCES


3D Printing In The Missile Industry

AHMED FARUK LAHER

ABSTRACT

The presentation encompasses case studies in the Aerospace industry, specifically the missile industry with the advent of 3D printing. Denel currently prints with ABS plastics and composites such as Carbon fibre, Kevlar and Fibreglass. The presentation deals with the question of where does 3D printing fit in the development cycle, the value added by 3D printing in the industry, what is Denel doing in the 3D printing space, can 3D printed parts be used on missiles and where does 3D printing fit into Denel’s technology roadmap.

1. INTRODUCTION

The missile industry is slowly starting to adopt 3D printed parts in their products after a lot of apprehension and mistrust of this technology. Issues around material properties specifically that of the density of printed parts and whether they will survive under fatigue loading, were always a major concern. In the past, printed parts were only destined to be prototypes and in certain cases, jigs and fixtures. However, with all the research and development funding being poured into this field, the industry has taken note and is slowly adopting these materials in end-use products. The case studies below will highlight some of the amazing results afforded to us by using 3D printing.

2. PLASTIC PRINTING - ABS P430 PLASTIC – FORTUS 250MC

2.1. Plastic printing

Denel has had a Fortus 250mc for several years now, since 2011, and the primary purpose of this machine was to print parts that show the form and fit of a part. This sped up the development phase substantially but these parts, at the end of the day, still had to be machined in metal, thus not fully utilising the value added by 3D printing. Conventional design techniques were used as if the part was to be machined. This is slowly changing, and I believe the adoption will be much greater once we purchase a metal 3D printer.

2.1.1. Case study 1

Actuator Assembly

One of the key issues in electro-mechanical systems are the looms. We are currently unable to model flexible looms on CAD software so 3D printing the actual part allows the technician to build the looms accurately with the final dimensions. Assembling the loom onto the hardware allows the technician to check the connector positions, shrink-sleeving positions, integrated loom guides and channel effectiveness, bend radii as well as get a feel for how the assembly process works and make the necessary adjustments. One can also see how the physical mechanism interacts with the part and check the tolerance build-up.

3. COMPOSITE PRINTING - ONYX/NYLON/CARBON FIBRE/KEVLAR/FIBREGLASS - MARKFORGED MARK 2

3.1. Composite printing

Denel acquired a Markforged Mark 2 printer in 2017 which gave us a few headaches at the start, but the results are amazing. The material properties of this tiny printer are impressive with regard to the surface finish, flexibility, toughness and heat resistance.

3.1.1. Case study 2

Kevlar Data Logger

The first day that the Markforged arrived, one of our chief engineers got really excited about the prospect of printing carbon fibre and kevlar and took it upon himself to model a part he wanted to use in an upcoming flight test. The part was a housing for a data logger which sat behind the warhead, at the rear of the missile. In an effort to help the part survive, it was designed with crumple zones, the mass was cut in half to decrease its momentum and copious amounts of kevlar was used, the most we could add to the part. The missile was fired into a container, with a 20kg warhead, sending the panels flying metres away. Figure 1 shows the result of the experiment.
4. METAL PRINTING

4.1. Titanium, Tool Steel and Aluminium 3D printing

Denel has been working with industry and the CSIR to develop 3D printed metal parts for one of our flagship Air-to-Air missiles. The parts are redesigned for 3D printing. Fatigue testing will be done on these parts to determine their suitability for flight. The idea is to encourage the missile programs to allocate budgets for 3D printing and consider this technology for all missile designs. Savings are substantial as can be seen in Table 1.

5. DESIGN FOR 3D PRINTING

Every year Denel gets a group of interns that are tasked with executing projects such as hexacopters, guided munitions etc. The project this year was a surveillance projectile system. Usually 3D printing is not allowed, this year they were encouraged to use it. The reason was because we have noticed that all engineers design with conventional manufacturing methods in mind and they have to shift their thinking in order for us to be competitive in this brave new world. Figure 2 is an example of what they came up with.

Table 1: Saving due to 3D printing

<table>
<thead>
<tr>
<th>Part</th>
<th>Conventional Machining Cost</th>
<th>3D Printing Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boat tail</td>
<td>R45800</td>
<td>R35000</td>
</tr>
<tr>
<td>Gimbal base structure</td>
<td>R35360</td>
<td>R24000</td>
</tr>
</tbody>
</table>

6. CONCLUSION

Denel’s view on 3D printing is slowly changing from hopeful scepticism to cautious embrace. Our role in the rapid prototyping department is to make the transition smooth and lately, the 3D printing community has supported us in making this possible. The Aeroswift and Metal Heart team has really helped us to move along the industry mind-set from conventional machining to 3D printing and if all goes to plan, we will be 3D printing missiles in the not so distant future.

Denel, South Africa

Figure 1: Before and after pictures of the Onyx and Kevlar data logger

Figure 2: ABS and Onyx working together
Production Of Spherical Titanium Based Powders From Powder Metallurgy Bars

C.N MACHIO1*, R. MACHAKA2, T, M MOTSAI3 AND S.CHIKOSHA4

ABSTRACT

This article describes the results of investigations in the production of spherical titanium-based powders from powder metallurgy feedstock. The investigations seek to localise the manufacture of high quality, low cost, spherical powders. Feedstock for atomisation was prepared using low capital intensive equipment and atomised using either vacuum induction melting (VIM) or electrode induction gas atomisation (EIGA) systems. The atomised powders were characterised for properties and application using a LENS AM system. All the investigated feedstock production routes were found to be feasible. The powders produced were spherical and deposited well on the LENS system.

1. INTRODUCTION

The Republic of South Africa has a strategy to beneficiate and add value to its bodies of ores [1]. One such body of ores is for titanium consisting of ilmenite and rutile, of which South Africa has the world’s fourth largest deposits (behind Australia, China and India). Research efforts led by the Council for Scientific and Industrial Research (CSIR), are currently underway to convert the titanium ore to titanium metal granules/powder, at low cost, and to further convert the metal powder to intermediate and finished products. Alongside the beneficiation strategy, the additive manufacturing (AM) strategy was recently commissioned [2]. These two strategies are complementary in that the titanium from the beneficiation strategy is to be used as a raw material in the AM strategy.

AM produces products via layer by layer material deposition from either powder feedstock or wire. It is a disruptive technology with the potential to massively improve competitiveness. The manufacture of Ti-based components by AM is currently well established [3]. However, uptake of the technology has been slow, caused by among others, expensive feedstock powder [4, 5]. In the case of South Africa, cost of feedstock is exacerbated by the fact that users import their powder.

Ti-based AM feedstock powder can be produced by a number of atomisation techniques, among them electrode inert gas atomization (EIGA), plasma rotating electrode process (PREP), plasma atomisation (PA) [5] and lately vacuum induction melting (VIM) [6]. The current, most used methods of making AM Ti-based feedstock powder start with Ti-based feedstock powder start with Ti-based feedstock bars or wires made by the ingot metallurgy technique of vacuum arc re-melting (VAR) [7] adding enormously on the cost of the powders. The cost of the feedstock bars can be reduced if they can be manufactured using powder metallurgy (PM). In this study, Ti6Al4V bars have been produced by powder metallurgy techniques and atomised using either EIGA or VIM. Subsequently, the atomised powders have been characterised and deposited into components using a LENS 850R system.

2. METHODOLOGY AND RESULTS

2.1. Methodology

The materials used in this study were Ti HDH and 60Al40V master alloy. They were weighed in the right proportion to make Ti6Al4V alloys by weight percent. The oxygen content of the powders was determined by an Eltra ONH 2000 gas analyser to be up to 0.32 wt.% for the Ti HDH and 0.03 wt.% for the 60Al40V master alloy. The powders were blended in a cone mixer for 30 minutes. Two sets of bars, differentiated by length, were made for atomisation using EIGA and VIM-gas atomisation. The flowability of the atomised powders was determined using a Hall Flowmeter, while the oxygen content was as for the starting powder, by using an Eltra ONH 2000 gas analyser. The morphology was determined using a JEOL JSM-6510 Scanning Electron Microscope (SEM). The microstructures of the powders were determined from polished sections using the JEOL JSM-6510 SEM. The suitability of the powders for additive manufacturing applications was tested on a directed energy deposition (DED) technique Laser Engineered Net Shaping (LENS) 850-R system.

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2,3,4 CSIR-MSM, Light Metals, Republic of South Africa
2.2. Results

Figure 2 shows the typical morphology and microstructure of the powders atomised by EIGA and VIM. The powders were spherical, with only limited satellites on the EIGA powders. The microstructures showed the occurrence of martensitic laths, typical of fast cooled Ti6Al4V alloy. Table 1 shows the oxygen contents of the billets and atomised powders, and the flowabilities of the powders. The oxygen content of some of the powders was higher than ASTM standard specifications, while some powders did not flow. In general, even though some powders did not flow well, they all grew components relatively easily (Figure 3).

3. CONCLUSION

The production of spherical Ti-based powders from powder metallurgy produced bars was demonstrated. Atomisation by EIGA and VIM produced powders that differed slightly in flowability, but the powders could still be processed by AM - LENS. Work is continuing to improve the quality of the PM processes employed in order to produce powders that meet the specifications of international standards.

REFERENCES


ACKNOWLEDGMENTS

Khodani Ramabulana is acknowledged for assisting in the VIM bars preparation.
X-Ray Micro-CT Supporting The South African Additive Manufacturing Community

A. DU PLESSIS1*, S.G. LE ROUX2

ABSTRACT

This paper presents the latest developments in microCT, both globally and locally, for supporting the additive manufacturing industry. There are a number of recently developed capabilities which are especially relevant to the quality inspection of additive manufactured parts. These new capabilities are all locally available but not yet utilized to its full potential, most likely due to a lack of knowledge of these capabilities. The aim of this paper is therefore to fill this gap and provide an overview of these latest capabilities, showcasing numerous local examples. The paper also tracks the local use of microCT for additive manufacturing projects from 2012 up to 2018. This acts as a review of the use of microCT in additive manufacturing in South Africa, focusing on demonstrating what has been done, what works, and what does not work.

1. INTRODUCTION

Micro computed tomography (microCT) is now widely accepted as a powerful nondestructive testing method especially valuable for additively manufactured parts. It is widely known for visualization of internal features, and for porosity detection. Many other features are still underutilized and are still being developed with improvements in system hardware and especially with customized image analysis procedures.

These include measurements of surface roughness, localised mean porosity calculations (to quantify porosity clustering), structural mechanics simulations to identify regions of high stress in real parts, and other image-based simulations based on data of the real part, amongst others. These latest advances will be discussed in the context of specific examples demonstrating their utility to the additive manufacturing community.

2. METHODOLOGY AND RESULTS

Technical details about the X-ray microCT facility and optimization of parameters are found in [1,2]. A number of recent developments will be discussed in this paper. The first is the ability to obtain a sub-voxel precise surface (by interpolation of grey values) which allows precise dimensional measurements better than the voxel resolution, this is demonstrated in Figure 1, for a 10 mm cube coupon sample. Also shown is a porosity analysis which is done using a semi-automated methodology, removing almost all human bias from the image analysis procedure.

Figure 1: A 10 mm coupon sample, shown in a photo (left); the corner of this sample in microCT slice image at 15 μm voxel size (middle) - including sub-voxel precise surface in white line; and semi-automated porosity analysis of the same coupon sample, showing contouring error (right)

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The sub-voxel precision of the surface allows more detailed analysis such as surface roughness analysis, on the same sample. Since voxel size is 15 µm, it can be considered useful for typical "as-built" additive parts which have surfaces rougher than this value. Besides the advantage of area mapping for improved statistics, and the possibility to detect undercuts and hidden irregularities, non-flat surfaces can also be assessed as shown in Figure 2.

![Figure 2: Surface roughness measurement, also on curved surfaces.](image)

The production of complex geometries bring with it challenges, such as residual stress which causes warping and possible cracks, and unexpected porosity or internal build defects. A complex bracket is shown in Figure 3, with its CAD variance analysis showing warping of up to 0.5 mm compared to the CAD design. These parts showed no internal defects.

![Figure 3: MicroCT analysis of complex parts for geometrical accuracy - using a CAD variance analysis. The yellow wireframe shows the CAD design.](image)

### 3. CONCLUSIONS

- New methods have been developed and refined for different analysis types for AM parts
- Automation is possible to some extent and discussed
- MicroCT will continue to support the quality inspection and improvement of AM part integrity
- A chronological account of the use of X-ray microCT supporting South African additive manufacturing efforts is provided

### REFERENCES


ABSTRACT

The tensile and high cycle fatigue (HCF) properties of high temperature annealed (HTA) Direct Metal Laser Sintered (DMLS) Ti6Al4V Extra Low Interstitial (ELI) machined and polished specimens were investigated. The HTA of the specimens resulted in the nucleation and growth of the alpha and beta grains from the acicular α’ martensite grains thereby improving their elongation to failure. The specimens were micro CT scanned to identify the distribution and geometry of pores inherent in them. The influence of internal pores on the tensile strength and fatigue properties was determined and is discussed here.

1. INTRODUCTION

Additive manufacturing (AM) uses the principle of slicing a solid 3D computer aided design (CAD) model into multiple layers and thereafter uses this data to drive a DMLS machine with a laser as heat source to build up the part, layer upon layer [1]. The technology has gained use in the medical industry because of its ability to manufacture precise and complex custom, hard tissue prosthesis with little to no waste as compared to conventional subtractive manufacturing methods. The mechanical properties of Ti6Al4V (ELI) specimens depend on their grain morphology which is amenable to heat treatment. The acicular α’ martensitic grains of the DMLS Ti6Al4V (ELI) specimens, which arise from the rapid cooling of the alloy from its melt temperature during AM, result in their high yield stress and low ductility [3]. This acicular α’ martensitic microstructure also has a poor crack initiation and micro crack propagation resistance because the grain boundaries act as effective slip planes. These specimens may have porosity due to the unmelted or semi-melted powder or incomplete fusion of layers [4]. The pores reduce the fatigue strength of the alloy because they act as micro stress concentration sites during loading, whose levels of intensity depend on their distribution and orientation with relation to the loading axis.

Improved mechanical properties of DMLS Ti6Al4V (ELI) specimens are achieved by high temperature anneal, which results in the acicular martensitic α’ grain structure transforming into an α + β grain structure [2].

2. METHODOLOGY AND RESULTS

2.1. Methodology

A total of 36 square cross-section bars of width and depth = 12mm and length = 60mm were built by an EOSINT M 280 DMLS machine; 12 in the X-, 12 in the Y-, and 12 in the Z-build direction. Of these square bars 6 were machined and polished down to dog bone tensile specimens in compliance with ASTM E8/E8M – 13a and the remaining 30 were machined and polished down to dog bone fatigue test specimens in compliance with ASTM E466-15 and ISO 1099: 2006. After the machining and polishing processes, the specimens were micro-CT scanned to detect porosity. Tensile tests were conducted on them with an Instron 1342 servo-hydraulic testing machine with a clip-on extensometer of 12.5 mm and under a constant strain rate of 0.5 mm/min. The tension-tension fatigue tests were conducted with the same machine at a frequency of 10 Hz and a stress ratio R = 0.1, with varying maximum stresses, at room temperature. The graphs of stress against strain and semi-log maximum stress against life were plotted from the data collected from the tensile and fatigue tests, respectively. The fracture surfaces of the specimens were analysed using optical and scanning electron microscopy.
2.2. Results

<table>
<thead>
<tr>
<th>Specimen designation</th>
<th>Tensile stress at Yield (offset 0.2%) (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>UTS (MPa)</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-1</td>
<td>846</td>
<td>116</td>
<td>933</td>
<td>15.7</td>
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<tr>
<td>X-2</td>
<td>849</td>
<td>120</td>
<td>928</td>
<td>13.9</td>
</tr>
<tr>
<td>Y-1</td>
<td>851</td>
<td>120</td>
<td>936</td>
<td>18.8</td>
</tr>
<tr>
<td>Y-2</td>
<td>848</td>
<td>120</td>
<td>931</td>
<td>17.6</td>
</tr>
<tr>
<td>Z-1</td>
<td>765</td>
<td>108</td>
<td>908</td>
<td>14.9</td>
</tr>
<tr>
<td>Z-2</td>
<td>765</td>
<td>108</td>
<td>911</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Table 1: Tensile properties of high temperature annealed DMLS Ti6Al4V (ELI) built in the X-, Y- and Z- build directions.

![Distance vs Projected Area](image)

Figure 1: Largest pore areas projected in the xy cross-sectional plane of the fatigue test specimens and their distances from the centres of their respective specimens on the x and y-axes of the cross-sectional plane.

3. CONCLUSION

The elongation of high temperature annealed DMLS Ti6Al4V (ELI) specimens conforms to ASTM F136-13 and ASTM F1108-14. The magnitude of the change in stress intensity factor ($\Delta K$) from a pore is influenced by the size of its projected area in the $xy$ cross-sectional plane and its location (surface or internal). The $S-N$ graphs and the $\Delta K$ values from the crack initiation pores will be presented and discussed in the full paper.

REFERENCES


X-Ray And Computed Tomography As A Tool For Quality Assurance, Process Optimisation And Metrology In The Field Of Additive Manufacturing

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Keywords: Additive manufacturing, Computed tomography, Non-destructive testing

ABSTRACT

At the moment computed tomography is the only available technology to give an insight on quality, geometrical features and process quality of highly complex additive manufactured parts. With different application examples I will show the challenges for the quality of AM parts and influences by design and production process.

1. INTRODUCTION

Computed tomography goes light years beyond regular 2-D X-ray technology to deliver accurate three-dimensional images of scanned objects, including their voids and areas of differing density. It has become one of the most important and powerful non-destructive testing (NDT) methods - an achievement resulting from the continuous improvement of CT scanning and reconstruction methods.

Today, CT is used for research and development, failure analysis, process and quality control, small series inspection, combined DR-CT inspection, defect and material analysis, assembly checks and, becoming more and more important, metrology, i.e. dimensional measurements. It’s use in Additive Manufacturing was recently reviewed in detail.

2. EXPERIMENTAL METHOD

2.1 Experimental Method

The experiments were performed either with a standard laboratory dual-source micro-CT or with a customized high-power industrial CT. Depending on the material, geometry and wall thickness of the additive manufactured part we chose the most suitable solution to achieve the best results.

2.2 Challenges for Additive Manufacturing

Different application examples from different industries will be presented during the presentation to show challenges, problems and typical defects for this production method.

Figure 1: Flow measurement nozzle and air probe with internal defects.
2.3 **CT as a tool for powder characterization**

During the presentation we will show details on metal powder characterization via industrial CT.

![Figure 3: Powder characterization via industrial CT.](image)

2.4 **CT as a tool for process optimization**

During the presentation different examples how to use an industrial CT scanner as a tool for process optimization for the additive manufacturing production process will be shown.

2.5 **CT Metrology**

With the right system configuration CT is a technology to do highly precise and repeatable measurements for geometrical features. Especially for additive manufactured parts with their complex internal features like cooling channels, bionic and lattice structures it is crucial to measure internally. An example, a bionic optimized helicopter bell crank, will be presented to show the different types of measurements and analysis.

**3. CONCLUSION**

With the results of representative applications from additive manufacturing it was demonstrated how the performance of today’s x-ray and CT devices, can support the analysis and inspection tasks for quality assurance, metrology and process optimization for different industries.

![Figure 4: CT is not only a tool for quality assurance and metrology but also to optimize your design and printing process.](image)
ABSTRACT

This paper emphasises on the different temperatures of heat treatments used to reduce the residual stresses that arises during additive manufacturing by Laser Engineered Net Shaping system. Additive manufactured parts currently employ heat treatment for the reduction of internal stresses, but then additional advantages are also possible from heat treatment. The LENSTM parts out of Ti6Al4V ELI will illustrate the mechanical property possibilities resulting from the selected heat treatments in this study. The main aim of heat treatment in this case of Ti6Al4V ELI is the reduction of internal stresses. Due to the mechanical behaviour of Ti6Al4V ELI as built additive manufactured parts, the heat treatment also seems to be necessary to increase the mechanical behaviour such as the fatigue performance and the breaking elongation. X-ray Diffractometric (XRD) and Optical Microscope will be employed to carry out detailed study of the resulting microstructures and phases. The targeted properties are the developed residual stresses.

1. INTRODUCTION

The additive manufacturing technique is currently receiving exceptional attention, it is a group of emerging technologies. Since additive manufacturing is a process which involves heating, melting and solidification of an alloy by moving the heat source such as a laser or an electron beam in a layered manner, there is a significant thermal gradient which originate around the melt pool as the temperatures required to melt the metal are extremely high. Therefore, as the material on top cools down and shrinks, residual stresses develop because the thermal strains exceed the yield point of the material, mainly controlled by the magnitude of the thermal gradients in the solidified metal as also addressed by Aggarangsi & Beuth[1] & Van Zyl, Yadroitseva & Yadroitsev[2]. It is advisable that the process parameters for additive manufacturing be closely monitored and controlled to reduce and produce samples with minimal residual stresses. Also, the Post Heat treatment of samples manufactured by additive manufacturing methods have been studied by several authors such as Vrancken et al.[3] & Greitemeier et al.[4] to reduce the residual stresses produced from laser additive manufacturing (LAM).

Ti6Al4V is the most commonly used titanium alloy due to its outstanding engineering properties. During the past decades, titanium alloys have developed as an increasingly important structural material for high quality and weight sensitive components according to Banerjee & Williams[5]. The relatively high cost of titanium, however, predetermines this material for applications with specific requirements, especially in the aerospace industry.

This study is aimed at improving the performance of 3D printed titanium aerospace component fabricated by LENSTM technology using Heat treatment. This study makes use of different temperatures to investigate the residual stresses that build up during additive manufacturing. The material used in this study is titanium alloy grade 23 (Ti6Al4V ELI) and the targeted properties are the developed residual stresses.

2. METHODOLOGY

2.1 Experimental Analyses

A grade 23 titanium alloy (Ti6Al4V ELI), which is a two-phase ($\alpha + \beta$) commercial titanium alloy, was used for fabrication of the samples by the (LENSTM) system in this work. Five (5) block samples are manufactured for heat treatment following the process parameters in table 1 below. The five (5) built samples have been sectioned. The characterisation using the Optical microscope (OPM) has been conducted for the as-built Ti6Al4V ELI samples.

The as-built sample in each of the 5 built block samples will be compared with the resultant microstructures of the different heat treatment conditions followed by the residual stress measurements.
### Table 1: LENS processing parameters

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Laser Power (W)</th>
<th>Laser Scan Speed (mm/s)</th>
<th>Powder Feed Rate (rpm)</th>
<th>Hatch Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>6.8</td>
<td>2</td>
<td>0.3375</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>10.2</td>
<td>2.5</td>
<td>0.3375</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>16.9</td>
<td>3.5</td>
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<tr>
<td>4</td>
<td>400</td>
<td>16.9</td>
<td>3</td>
<td>0.3375</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>20.3</td>
<td>3.5</td>
<td>0.3375</td>
</tr>
</tbody>
</table>

### 3. RESULTS

The following figures are the micrographs of the as-built LENS TM samples. The micrographs of the 2 samples listed in table 1 above.

#### Figure 1: 200W, 6.8mm/s and 2rpm.

Figure 1 shows low levels of porosity in the as-built part. However, the resulting micrographs of the heat treatments will show further enhancement of the microstructural behaviour followed by the residual measurements.

#### Figure 2: 300W 16.9mm/s and 2rpm.

Figure 2 shows high levels of porosity in the as-built part.

### 4. CONCLUSION

All the micrographs of the as-built part show a smooth surface. The levels of porosity and cracks in figure 2 are too visible. These can further be improved by the proper heat treatments.

### REFERENCES


Problems Of The Use Of Copper Powders In 3D Printing

K. SKRZEK

ABSTRACT
The paper describes problems related to use of copper in 3D Printing and ways to solve these problems based on literature. Copper powder used in 3D Printing must have strictly defined parameters. Mastering 3D Printing from copper will allow direct transfer of this knowledge to other technical fields.

1. INTRODUCTION
Poland is the second largest producer of copper in the world, so it attaches great importance to the wide use of copper. Currently, using copper as a material in 3D Printing is not popular. Today, a plethora of 3D Printing can shape objects from an ever growing list of materials. Metal additive processes such as metal powder bed fusion and directed energy deposition are potentially capable of producing high-quality, functional and load bearing parts from a variety of metallic powder materials. Additive technology is the technology of the future.

2. METHODOLOGY AND RESULTS
3D Printing using metals powders as a material is the fastest-growing segment of additive technology. The growth of 3D Printing is tied to business opportunities and, directly, the materials available and their cost. Low-cost copper powders are the key enablers for 3D Printing, to realize its potential and transform industrial production. Available metallic powders for additive manufacturing are mostly those being used in a range of applications. Actually produced copper powders can vary widely in size, but also in shape (spherical to irregular) [1].
Copper powders used in 3D Printing should have:

- spherical shape to ensure good flow/coating ability and a high packing density,
- particle size usually below 50 μm or 150 μm,
- particle size distribution tailored to the application and properties,
- controlled chemical composition and gas content.

The particle size distribution of metallic powder particles impacts the density. From a mechanical standpoint, porosity jeopardizes fracture toughness and fatigue properties [2].

For the production of copper machine parts, attempts were made to apply the 3D Printing method - a method of selectively melting the laser layer powder. The 3D Printing method, which allows printing with the use of copper powders, is a method of melting the powder layer using an electron beam.

3. CONCLUSION

The use of copper powders with specific parameters in the melting the powder layer using an electron beam method will allow to produce of copper responsible machines parts. Therefore, work on the production of copper powders with given properties should be taken.

REFERENCES


Figure 1: Molecules of copper powders: spherical and irregular.
**ABSTRACT**

Growing interest in additive manufacturing in the construction industry has promoted research in 3D printing of concrete. This paper presents test results of early age and hardened behaviour of cement-based materials suitable for 3D printing.

**1. INTRODUCTION**

A research program on 3D printing of concrete (3DPC) is executed by the Centre for Development of Sustainable Infrastructure at Stellenbosch University. An industrial-grade gantry type 3D printer of roughly 1 m cube build volume, was designed and manufactured in 2017-2018. The point of departure was to develop a robust, versatile laboratory printer that enables research on a range of concrete material classes, printing speeds and geometrical complexity. Knowledge and experience in concrete pumping, spraying and extrusion \(^{[1,2,3]}\) (van Zijl 2005; van Zijl et al. 2016; Paul et al. 2018) informed the selection of an appropriate concrete pumping pressure range for standard to high performance (HPC) grades concrete and fibre reinforced concrete (FRC). The printer is shown in Figure 1, located in a climate-controlled laboratory room at 23±2°C and 65±5% relative humidity.

![Stellenbosch University’s 3D concrete printer together with a 90-degree twisting HPC column print of total height 800 mm printed in 26 minutes.](image)

**2. RHEOLOGICAL CHARACTERISATION FOR PRINTABILITY AND BUILDABILITY**

A benefit of concrete as a construction material is its formability in the fluid fresh state, which typically lasts for several hours before setting into a stiff, strong mass. At the same time, careful control of rheology is required to prevent blockage and segregation of fresh concrete constituents during the high-pressure pumping action. Thixotropic behaviour is required, demonstrated in Figure 2. High static shear stress is required, followed by sufficiently low dynamic shear stress for pumpability, but subsequent fast re-building through a process of re-flocculation for shape retention and stability of the printed layer after cessation of the pumping pressure. Thereby, an appropriate, cost-effective construction rate is enabled, in absence of expensive formwork required for standard concrete construction.
3. DIMENSIONAL STABILITY AND MECHANICAL BEHAVIOUR

3D printed concrete lacks the protective formwork, which may cause significant shrinkage in the plastic state due to arid local conditions. Figure 3a demonstrates plastic shrinkage reduction under extremely warm (40 °C), windy (20 km/h) and dry (RH = 20%) conditions, by addition of small dosages up to 0.3% by volume (Vf) of short polymeric micro-fibre. Figure 3b shows the mechanical properties of the 3D printable mortar with and without polymeric fibres in the hardened state. It is known that strength and stiffness stabilise at roughly 28 days but shown here are strengths and stiffness already at the age of 1 day that are sufficient for most concrete construction processes, reaching values suggesting high-performance concrete at roughly 77 MPa and 32 GPa compressive strength and stiffness respectively.

4. CONCLUSION

The thixotropic nature of a 3D printable cement-based material has been demonstrated in terms of a large difference in static and dynamic yield shear stress, and fast rebuilding of static shear stress after pumping agitation. Improved dimensional stability is achieved by inclusion of a low volume of polymeric fibre, whilst high performance mechanical properties are retained in the hardened state.

REFERENCES


Strength Modelling of Composite Filament Fabricated Materials Using Classical Laminate Theory

M. DELPORT1,a AND C.P. KLOPPERS1b

ABSTRACT

The Markforged developed a technique dubbed Continuous Fibre Fabrication (CFF) it is a subset of additive manufacturing, where a matrix material such as nylon or onyx is reinforced using fibres (carbon, fibreglass or kevlar). According to Markforged, their fibres are a continuation of nature and thus, taking this into account - the specimens must abide to the classical laminate theory when laminate failure is to be examined. It should be noted that the fibre orientations used for this study did not include blends as this changes the nature of the laminate. A new database was created using micromechanics and a mathematical model based on the classical laminate theory is developed.

1. INTRODUCTION

CFF uses thermoplastic (polymer that changes to a liquid upon the application of heat and solidifies when cooled) material injected through indexing nozzles onto a platform and is then reinforced by continuous strands of fibre embedded into the thermoplastic matrix. Fibre composites differ from normal engineering materials in that the properties are highly directional. This directionality affects the way in which the materials are used.

The machine used for this study is the Markforged Mark I in combination with the Eiger slicing software developed by Markforged. This software will be used to control the pre-defined input parameters such as internal structure patterns and orientations. The materials used are limited to Nylon (matrix) and Fibreglass (reinforcement). Tensile testing is chosen as the testing technique used for determining the mechanical properties of the composite.

1.1. Problem statement

Development of a mathematical model for prediction of tensile material properties of continuous fibre fabricated components as well as use the predicted material properties for simulation under tensile load to assist designers run finite element analysis.

2. METHODOLOGY AND RESULTS

The study comprises of the testing and investigation of nylon with fibreglass reinforcement specimens manufactured by 3D printing, using the Markforged Mark I printer. All tests were conducted using the appropriate testing standards set out by the ASTM International organisation. Material properties are calculated using micromechanics in collaboration with volume fractions.

2.1. Research objectives

- Nylon specimens reinforced with fibreglass is subjected to tensile test to obtain the necessary load vs. deflection data sets;
- Data gathered from these tests is used to determine the material properties of the individual materials present in the specimen, using micromechanics;
- Construction of a mathematical model to predict tensile properties of the specimens using laminate failure theories.

2.2. Micromechanics

The determined material properties, using micromechanics, is within 4.2% of the material properties claimed by Markforged. This falls within the allowed measurement range and the results are used to develop a mathematical model using laminate failure theories. With CFF, each layer consists of either fibre or matrix and thus micromechanics, with regards to volume fractions, can be used to determine the material properties.

When the specimen is subjected to a tensile load, each component of the composite’s layer experiences a different portion of the load, and thus the material properties can be determined. The formula below shows the typical volume formula used within the micromechanics calculations.
\[ V_{\text{fiber}} = (W - W_{\text{shell}} \cdot 2) \cdot H \cdot T_{\text{layer}} \cdot N_{\text{fiber}} \]

Where:
- \( V_{\text{fiber}} \): Volume of the component in question (the fibre in this case)
- \( W \): Width of the specimen (as per ASTM standard)
- \( W_{\text{shell}} \): Width of the specimen’s matrix shell (pre-defined within the parameters)
- \( H \): Height of the specimen (as per ASTM standard)
- \( T_{\text{layer}} \): Thickness of layers (pre-defined within the parameters)
- \( N_{\text{fiber}} \): Amount of fibre layers within specimen (pre-defined within the parameters)

2.3. Mathematical Model

Classical Laminate Theory (CLT) is an extension of the classical plate theory using Kirchhoff’s kinematic assumptions to predict the linear response of thin laminated composite plates composed of specifically orthotropic plies [2]. A laminate is designed by using a special nomenclature which includes fibre orientation of all layers stacked in the laminate. In addition to the stacking sequence of the laminate, the material properties of the composite material must be defined with regards to mechanical elasticity \( \{E_{11}, E_{22}, G_{12} \text{ and } v_{12}\} \). A mathematical model is created using Matlab® and results are all within 2.4% when compared to experimental values. These predicted values are validated using laminate software, LAP (Laminate Analysis Program), to validate the prediction model and as seen from Table 1.

3. CONCLUSION

Taking everything into consideration, the results obtained from both the developed mathematical model and LAP is within sufficient criteria and can be considered a successful prediction model for two-dimensional strength modelling. With the results imported into Siemens NX and FEM analysis being performed, the results (Table 2) indicates that using the determined material properties, three-dimensional analysis of additive manufactured composites can be done within a 2% accuracy range. Therefore, further investigation into the mechanical properties of these materials with regards to bending forces could ultimately increase the degrees of simulation possible.

Table 1: Expected strength: LAP vs Experimental

<table>
<thead>
<tr>
<th>Fibre orientation</th>
<th>Fibre/Nylon layers</th>
<th>Width/thickness</th>
<th>LAP (GPa)</th>
<th>Experimental (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pm )</td>
<td>10/2</td>
<td>12.7/1.2</td>
<td>317.583</td>
<td>320.426</td>
</tr>
<tr>
<td>( \pm )</td>
<td>10/2</td>
<td>12.7/1.2</td>
<td>221.113</td>
<td>214.57</td>
</tr>
<tr>
<td>( \pm )</td>
<td>10/2</td>
<td>12.7/1.2</td>
<td>44.236</td>
<td>46.506</td>
</tr>
</tbody>
</table>

The material properties are used to create new material data bases using a simulation package, Siemens NX was chosen for this thesis and the results when the specimen is subjected to a tensile load and the process followed can be seen in Figure 1. Table 2 shows the results obtained from the FEM analysis when compared to the verified LAP results for ultimate tensile strength (UTS).

Table 2: UTS: LAP vs. Siemens NX

<table>
<thead>
<tr>
<th>Fibre orientation</th>
<th>Fibre/Nylon layers</th>
<th>Width/thickness</th>
<th>LAP UTS (MN)</th>
<th>NX UTS (MN)</th>
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</thead>
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<tr>
<td>( \pm )</td>
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<td>10/2</td>
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<td>508.3416</td>
<td>504.20</td>
</tr>
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</table>

REFERENCES


Low Cost Custom Food Moulds Manufactured From 3D Printed Patterns

MARTIN BOLTON

ABSTRACT

With the ever growing hunger for artisanal and custom goods, there is a need to develop low cost avenues for attaining custom food moulds. In the food sector, 3D printing is an accessible and viable technology where the materials that can be printed are not of a food-grade quality. The utilisation of additive manufacturing as a step in developing affordable food moulds and customisable aspects of the technology required to produce food grade plastics and silicones is possible. This paper intends to illustrate an example of the development of low-cost food (chocolate) moulds which can be generated using various rapid prototyping processes. This will be done with a set of custom chocolate moulds (and dessert moulds currently being tested) which have been developed from a CAD component modelling software, the topographic land date is available online and is prototyped with appropriate small-scale batch manufactured moulds.

1. INTRODUCTION

3D printing of food has been an emergent technology over the past couple of years. However due to the high cost of buying a 3D printer for the sole purpose of printing edibles, and the limit of food materials that can be printed by one machine, the outreach of the technology is limited and not accessible to most. The complexity of the printing process also inhibits its acceptance by most [1]. In order to 3D print food, several conditions need to be considered and optimised for success; proper use of mechanical force, careful selection of materials, and the recipe [2]. 3D printing allows for the creation of complex shapes and allows for the designer to have complete reign on the customised designs of the food [3]. A more accessible and lower cost solution is that of printing a master form using a low-cost 3D printer, and then using this form to create a mould into which food can be moulded.

The practice of moulding food has been undertaken for centuries in the forming of gelatine-based foods [4], [5]. The process outlined below utilises existing 3D printing and plastic vacuum forming technologies with far lower initialisation costs and health risks than the conventional 3D printing of food. This makes the additive manufacturing process more accessible and appropriate.

2. DEVELOPMENT AND MANUFACTURE

The overall sequence followed was the utilisation of 3D CAD Data (either generated by the author, or obtained online) in the preparation of files for 3D printing. These were then printed using ABS plastic filament with a hollow in-fill and a fine surface finish. These 3D printed master chocolate forms were then placed in a vacuum forming machine and a thin sheet of clear PET-G plastic heated and vacuumed over the 3D print forms. Once cool, the prints can be removed from the plastic and the mould prepared for food moulding.

2.1 CAD 3D File Preparation:

Several custom chocolate forms were generated in Solidworks using feature modelling. Some simple geometric forms, and some with fine intricate details (Figure 1).

Figure 1: Chocolate master patterns modelled in SolidWorks and ready for printing.
There are various forms of free CAD files available for public download online. These are available for people to print on their home 3D Printers, for example Grabcad, Turbosquid just to name a few. A list of the 10 most popular websites is presented on the 3D Natives site. For example, a chocolate mould can be made from an STL of Table Mountain that was taken from the Terrain2STL website - which generates 3D Data directly from an interactive map.

2.2 Using vacuum forming / silicone casting and plastic to vacuum form low-cost moulds over 3D printed patterns.

The vacuum forming machine supports the master patterns below a supported sheet of plastic, above which there are heating elements which heat up the plastic until it is soft enough to drape over the forms. In a fast sequence, the patterns are lifted up whilst at the same time the air is vacuumed out, forcing the plastic over the patterns. The forms of the patterns have draft tapers similar to other casting processes in order to allow the patterns to fall out of the formed plastic sheet. This plastic sheet is then cleaned and prepared for moulding. Clear PET-G plastic was used for the moulds it is available locally, affordable, and food grade - meaning it can be in contact with foodstuffs.

2.3 Casting / Moulding the food.

The casting process below was done with both fudge and chocolate but it can be assumed that liquid or semi-liquid foods that can set to some degree of solid form can also be moulded using the same process. A suitable release agent is however required as the experiment with fudge proved to be practically impossible to remove from the mould. Chocolate however released from the mould without any difficulty. Below, the Mountain Chocolate as well as Geometric formed chocolates are visible.

3. CONCLUSION

As illustrated above, the ability to use 3D printing to make customised food is possible in ways that don’t require the food to be physically printed into forms. The method explained above allows for a mould to be generated, which allows for many custom replicas to be made from the initial 3D printed master pattern. Overviews of costing, material usage and more accurate product sequences can be provided on request and will form part of the paper presentation (as well as edible samples).

REFERENCES


Laser Engineered Net Shaping Technology For WC-Based Materials

E. MOLOBI12*, B. DAVOREN12, N. SACKS12 & M. THERON3

ABSTRACT

The application of laser enabled net shaping (LENS\textsuperscript{®}) technology in the fabrication of cemented tungsten carbide materials, or hardmetals as they are known, has not been extensively explored, and does not appear to have been commercialised as yet. While the usage of LENS\textsuperscript{®} processing to produce hardmetals may be beneficial to advancing the manufacturing industry, there remains many scientific challenges which first need to be addressed. In this study a critical review has been done of published scientific research centred on LENS processing of hardmetals in order to identify the scientific gaps which still need to be addressed.

1. INTRODUCTION

Additive manufacturing (AM) has become a revolutionary technology which has changed the way products are designed and manufactured. The move from conventional manufacturing processes to AM has been fuelled by the advantages posed by AM which include the production of net-shaped components which require no additional machining or cutting, reduced tooling and fixtures, shorter manufacturing turnaround, and the ability to manufacture intricate shapes \cite{1}. Laser Engineered Net Shaping (LENS\textsuperscript{®}) technology is a Powder Directed Energy Deposition AM process which was developed at Sandia National Laboratories in the United States in the 1990 \cite{2}. While the initial development of LENS\textsuperscript{®} technology occurred in 1990, the process was licensed to Optomec, Inc., Albuquerque N.Mex in 1997 \cite{3}. Some of the well-known features of LENS\textsuperscript{®} technology are high cooling rates, rapid processing, and proper shape control \cite{2}. The LENS\textsuperscript{®} technology has successfully been applied to a range of materials such as stainless steel, tool steels, nickel alloys, cobalt alloys and titanium alloys \cite{4}. Although some patents have been filed on the application of the technology to ceramic- based materials, its application to cemented tungsten carbides does not appear to have been adopted on a commercial level yet. There is still a considerable amount of research required in order to provide a fundamental scientific understanding of the relationships between processing parameters, powder properties and the resultant LENS\textsuperscript{®} manufactured materials. In the current paper a review is provided of the known research done using LENS\textsuperscript{®} to produce tungsten carbide based materials. The outcome of the review was used to identify scientific gaps for further research and to assist in constructing a design of experiments matrix for the critical laser processing parameters to be used in LENS\textsuperscript{®} processing of hardmetals.

2. LENS OF WC-BASED MATERIALS

Majority of LENS\textsuperscript{®} research on cemented tungsten carbides has been focussed on alloys comprising of tungsten carbide (WC) cemented by a cobalt (Co) binder, which represents the most widely used cemented tungsten carbide material. Studies have been done on the influence of laser processing parameters such as laser power, powder feed rate, scan rate and working distance on sample profiles and microstructure \cite{2, 5-8}. These four factors have been found to have a significant effect on the structural integrity of the built walls. An increase in laser power and powder feed rate as well as a decrease in traverse speed has been found to lead to an increase in the sample height as seen in Figure 1.

Figure 1: Influence of: (a) laser power, (b) powder feed rate, and (c) traverse speed, on sample height \cite{5}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Influence of: (a) laser power, (b) powder feed rate, and (c) traverse speed, on sample height \cite{5}.}
\end{figure}

\footnotesize
\begin{itemize}
\item[1*] School of Chemical & Metallurgical Engineering, University of the Witwatersrand, South Africa
\item[2] DST-NRF Centre of Excellence in Strong Materials, South Africa
\item[3] National Laser Centre, CSIR, South Africa
\end{itemize}
Shorter working distances have led to improvements in the density and microstructure. By keeping the working distance fixed and varying the other parameters, the amount of heat per unit powder mass can be controlled to a certain extent to create the required molten pool. This also influences the uniformity of the microstructure which is achieved. The influence of feed stock powder particle size was studied by Xiong et al [5], and it was observed that decomposition of the WC phase was dependent on the feedstock particle size, with nanostructured powders leading to decomposition while sub-micron sized powders did not. This was attributed to the high cooling rate, short heating time and low oxygen concentration during laser processing. The authors developed a preferred range of deposition parameters which are listed in Table 1.

In a study on the thermal aspects of LENS processing of WC-Co alloys, WC grain coarsening was observed in alternating layers, thereby creating an overall inhomogeneous microstructure [2]. It was found that the initial layer comprised of fine WC particles embedded in a Co matrix. When the next layer was deposited, the first layer experienced re-melting to the extent that the temperature which was achieved resulted in coarsening of the WC grains. This inhomogeneity causes anisotropic mechanical properties.

3. CONCLUSIONS

The application of LENS® technology in the manufacture of WC-materials has not been commercialised and its applicability is still on a research level. Currently the inconsistency in the cooling rate during the LENS® deposition of WC-materials has led to inhomogeneity in the microstructure and diverse mechanical properties. The successful application of this process appears to be in the optimisation of process parameters such as scan speed, laser power, powder feed rate and working distance. In addition a fundamental understanding of how these process parameters influence material properties is critical in order to take LENS of cemented tungsten carbides into the commercial manufacturing sector.

Table 1: Preferred LENS® deposition parameters for WC-Co alloys [5].

<table>
<thead>
<tr>
<th>Experimental Parameter</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>Laser power</td>
<td>180 – 200 W</td>
</tr>
<tr>
<td>Powder feed rate</td>
<td>7 – 10 g/min</td>
</tr>
<tr>
<td>Transverse speed</td>
<td>2 - 4 mm/s</td>
</tr>
<tr>
<td>Working plane</td>
<td>Focal plane ± 2-4 mm</td>
</tr>
</tbody>
</table>

REFERENCES


Selective Laser Melting Of Cemented Tungsten Carbide Cutting Tools: A Review

D. HAGEDORN-HANSEN1*, D.M. DIMITROV1, S. MATOPE1 & N. SACKS2,3

ABSTRACT

The use of selective laser melting for research, development and production of cemented tungsten carbide cutting tools has not been extensively reported, and commercialisation does not seem apparent as yet. While the usage of selective laser melting to produce cutting tools may be beneficial to advancing cutting tool technology, the selective laser melting process is met with many inherent drawbacks - which need to be addressed. This study presents a critical review of such selective laser melting drawbacks found in literature. These integrity issues are further discussed in detail.

1. INTRODUCTION

Cemented tungsten carbide (WC) cutting tools are used for subtractive manufacturing because of their ability to resist the damaging effects of several wear mechanisms while cutting. The tooling market is competitive and the companies with the best Research and Development (R&D) departments have the competitive edge when it comes to cutting technology. The development process for a new cutting tool is a time consuming and costly venture. Conventional production of special tools with intricate geometries and cooling channels is met with difficulties and financial implications.

In order to make the R&D and special tool production processes resource efficient, the application of the Selective Laser Melting (SLM) process is investigated. SLM is a powder bed additive layer manufacturing (ALM) process whereby fine metallic powder is melted by means of a laser energy source, in order to create a 3-dimensional (3D) object. Traditionally, cutting tools are produced with press and sinter operations, which require costly dies and punches, and a post sintering process. It is proposed that the press and sinter processes be substituted with the SLM process for the small batch production of cutting tools for R&D purposes as well as for specialised applications. However, SLM does present its own problems such as porosity, microcracking, tolerance issues, and poor surface finish [1]–[3]. Some of the factors affecting these properties as defined in literature are presented in the following sections.

2. CUTTING TOOL CHARACTERISTICS

Although there are many different types of materials for cutting tools that are being used in industry, there are certain fundamental characteristics of a cutting tool that have to exist for it to be classed as a good tool. These characteristics are hardness, toughness, and wear resistance. A desired cutting tool is one which demonstrates a balanced combination of these characteristics.

3. SLM INTEGRITY ISSUES

In order to avoid certain undesired properties or defects in SLM, the powder and exposure parameters must be optimised, taking into account their mutual interactions. Defects that are inherently associated with SLM are pores, cracks, delamination of layers, warping or curling, and changes in local material properties [4]. Properties or defects that need to be controlled during the SLM of WC-Co are toughness, porosity, microcracking, delamination, and surface finish [5][6]. Some of the factors affecting these properties as defined in literature are presented in the following sections.

3.1. Toughness

The toughness of a cutting tool is reliant on the binder and alloy content. When WC-Co is exposed to a high energy input and the molten pool temperature is above 2900 °C, the alloying elements and binder evaporate, thus leaving mostly tungsten carbide behind. This results in a brittle cutting tool with a low toughness and high porosity. However, if the WC-Co is exposed with a low energy input, typically only liquid phase sintering (LPS) takes place. This results in a high toughness and subsequently a high porosity [2]. A high porosity also inhibits the tool to cyclic loading applications, as crack initiation and formation from inherent pores is a problem.
3.2. Porosity

The AiF-Forschungsvereinigung report [5] showed how the porosity is dependent on the laser parameters as well as the Cobalt content of the powder. This phenomena was uncontested amongst various researchers [1], [2]. Reuber and Schwanekamp [6] found chemical composition, particle size distribution, and porosity of the powder to be influencing factors on the bulk density of the final product. However, the powder particle distribution was not taken into consideration by Uhlmann et al [3] when determining the factor interaction. The porosity of WC-Co samples produced using SLM and Praxair powder can be observed in Figure 1.

![Figure 1: Qualitative comparison of treatment results with WC-Co 83/17 and WC-Co 88/12 with a laser power of 140 W, scan speed of 25 mm/s, spot size of 0.2 mm with their corresponding densities [5]](image1)

3.3. Microcracking

Uhlmann, Bergmann, and Grindin [2] found that all samples produced using SLM showed a pronounced tendency to crack regardless of the varying process parameters. However, Khmyrov et al [3] was able to produce crack free layers by having a high percentage of cobalt (25wt%). The cracks and porosity of WC-Co samples produced with different parameter sets can be observed in Figure 2.

![Figure 2: Porosity and cracks of the test samples characterised by their different factor levels [2]](image2)

3.4. Delamination and Curling

Delamination occurs due to weak local bonds between layers and/or the base plate. Delamination generally occurs when sub-optimal melting parameters are used and the heat distribution is not high enough to sufficiently bond the layers together [1]. High energy input and crack tendency were found by Ott [7] to result in part delamination of cemented carbide components.

4. CONCLUSION

This research presents a critical review of integrity issues with selective laser melting of tungsten carbide cobalt for production of cutting tools, as found in literature. Knowledge gained from this review will allow for an improved WC-Co cutting tool to be manufactured using the SLM process. The current literature in main stream journals and dissertations analyse only the SLM process and the effects on the quality of tungsten carbide tools. There is very little focus on the initial powder parameters as well as the effects of certain factors (such as laser power, scan speed) on the wear of the tool produced with SLM.

REFERENCES

Spheroidisation Of Titanium Metal Powder By RF Thermal Plasma Processing

H. BISSETT*1

ABSTRACT

Spherical powders of narrow particles size distribution and high density are required for the manufacturing of high quality components using Additive Manufacturing such as direct laser sintering. Rapid in-flight heating of titanium powders were examined in an inductively coupled radio-frequency thermal plasma. The plasma power and sheath gas composition were altered in order to optimise the spheroidisation (%) and reduce the fraction of evaporation (wt %) for titanium powder in the size range 250 – 300 µm. An increased fraction of evaporation (%) was observed at high plasma power, whilst a larger fraction of evaporation was observed in the presence of hydrogen/argon compared to helium/argon as sheath gas.

1. INTRODUCTION

Titanium and titanium alloys are widely used in industries such as aerospace, medical, sports and automotive. The metal and its alloys have high specific strength as well as good corrosion resistance combined with low density making it suitable for the manufacturing of strong, lightweight components. Cost effective additive manufacturing (AM) techniques have made the use of this high cost and “hard-to-machine” material an attractive possibility [1]. Manufacturing technologies such as 3D printing require free-flowing spherical powders to ensure a dense defect free part. Spherical particles also have a minimum surface area to volume ratio, effectively reducing surface contamination e.g. oxygen adsorption. Surface oxidation should be prevented as this increases the surface tension, hindering material from flowing during sintering [2].

Recently, high melting point metal powder processing has been possible by the re-melting of irregularly shaped particles at high temperature by means of a thermal plasma processes and solidifying the resulting droplets by rapid quenching [3]. Thermal plasmas are characterised by their high temperatures (3 000 - 10 000 K) and rapid heating rates (~ 106 K/s) under oxidizing, reducing or inert conditions. This makes them particularly suitable for spheroidisation of almost any powders [4]. The Tek-15 inductively coupled radio-frequency (RF) thermal plasma system from Tekna Plasma Systems Inc. has been designed for the spheroidisation of metal, alloy and ceramic powders on research and development scale.

In this study, the spheroidisation of irregularly shaped pure titanium metal powder was investigated. The processing characteristics for the spherical particle formation were investigated at various plasma power inputs making use of either hydrogen or helium in the sheath gas composition. The particles obtained were characterised in terms of morphology. Spheroidisation of powders should result in an optimum spheroidisation (%), whilst minimising the fraction of material evaporated.

2. METHODOLOGY AND RESULTS

The 15 kW RF thermal plasma was obtained recently and therefore the intended purpose of the study was to perform experiments to investigate the influence of various parameters on the spheroidisation of titanium powder as well as to determine the limitations of the equipment relating to maximum size in obtaining spheroidised powders. Pure titanium powder in the size range 250 – 300 µm was used in these experiments.

2.1. Experimental method

The spheroidisation efficiency, spheroidisation (%) and the fraction of material evaporated is influenced by various plasma parameters. A schematic of the RF inductively coupled plasma torch and Tek-15 spheroidisation system is shown in Figure 1 (a) and (b) respectively. The powder was fed through the feeding probe with the assistance of a carrier gas. The particles were rapidly melted in the plasma “tail flame”, followed by rapid quenching to form spherical particles. A quartz tube separated the sheath (Ar/H2 or Ar/He) and central gas (Ar), both of which could be adjusted to alter the parameters for spheroidisation. In a set of six experiments all parameters remained constant, whilst only adjusting the energy input of the plasma (Table 1) and the plasma sheath gas composition. The powder was fed into the plasma at 0.35 kg/h. 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 (%). Scanning electron microscope (SEM) images of the untreated and treated spherical powders were also obtained.

1* Department of Applied Chemistry, The South African Nuclear Energy Corporation (Necsa), South Africa (Corresponding author)
2.2. Results

In Table 1 the results are shown. An increase in the energy input resulted in an increased fraction of evaporation, similarly to what was observed in literature [3]. Comparing hydrogen or helium sheath gas, it can be seen that the use of hydrogen resulted in overall higher spheroidisation efficiencies and higher fraction of evaporations compared to helium as sheath gas. This phenomenon is due to the higher plasma temperatures obtained using hydrogen compared to helium at equivalent gas enthalpy inputs.

\[ \text{slpm} = \text{standard litres per minute} \]

In order to indicate that spheroidisation occurred, SEM images of the feed powder and only spheroidised particles were obtained. The feed powder is shown in Image 1 and the spheroidised plasma treated particles in Image 2. Comparing Image 1 with Image 2, it can be seen that a high degree of sphericoidicity was obtained by plasma spheroidisation, producing powder with a smooth surface and no satellite particles observed.

3. CONCLUSION

Titanium powder was plasma treated by means of a 15 kW RF inductively coupled thermal plasma system from Tekna Plasma Systems Inc. The spheroidisation (%) and fraction evaporated increased with an increase in plasma power due to the plasma temperature increase. This study indicated that large titanium particles can be spheroidised by thermal plasma technology.

Table 1: Plasma parameters for treatment of typically 10 g of powder. Performed at 2 slpm argon carrier gas flow rate, with the feeding probe at the center coil using argon as central gas

<table>
<thead>
<tr>
<th>Sheath gas</th>
<th>Plasma powder</th>
<th>Fraction evaporated (wt %)</th>
<th>Spheroidisation efficiency (%)</th>
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<tbody>
<tr>
<td>(Ar/-)</td>
<td>(g)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂</td>
<td>11</td>
<td>13.10</td>
<td>20</td>
</tr>
<tr>
<td>H₂</td>
<td>13</td>
<td>14.89</td>
<td>30</td>
</tr>
<tr>
<td>H₂</td>
<td>15</td>
<td>20.23</td>
<td>35</td>
</tr>
<tr>
<td>Helium</td>
<td>11</td>
<td>2.18</td>
<td>20</td>
</tr>
<tr>
<td>Helium</td>
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<td>2.18</td>
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<tr>
<td>Helium</td>
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<td>8.45</td>
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<th>TIME</th>
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<tbody>
<tr>
<td>08:00</td>
<td>Opening and Welcome: Management Committee - Prof Didier Nyembwe</td>
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**PLENARY SESSIONS: PROTEA ROOM**

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<tr>
<td>08:15</td>
<td>Coordinator of 3D Research Group, CTI Renato Archer - Dr Jorge Vicente Lopes da Silva</td>
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<tr>
<td>09:00</td>
<td>Centre for Rapid Prototyping and Manufacturing - Gerrie Boosen</td>
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<td>09:45</td>
<td>TEA BREAK</td>
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<td>10:15</td>
<td>INDUSTRY SESSION</td>
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<tr>
<td>10:15</td>
<td>Rapid 3D</td>
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<td>TECHNICAL PRESENTATIONS (3 BREAKAWAY SESSIONS)</td>
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<tr>
<td>11:00</td>
<td>A Conceptual Framework For The Identification, Storage And Implementation Of Standards And Regulations Applicable To Additive Manufacturing</td>
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<td>Presenter: Barend Jacobus Lodewicus Duvenage</td>
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<tr>
<td>11:20</td>
<td>Transforming Academic Research into a Business Model: an i-Corps Case Study for AM Part Verification in the Aerospace and Medical Industries</td>
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<td></td>
<td>Presenter: Godfrey Mills</td>
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<td>11:40</td>
<td>Empirical Verification Of Pricing Algorithm For Laser Sintering Additive Manufacturing</td>
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<td>Presenter: Heinrich van der Merwe</td>
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<tr>
<td>12:00</td>
<td>Design Cycle Of AM Prismatic and Biomimetic Aerospace Components</td>
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<td></td>
<td>Presenter: Neil Britz</td>
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<tr>
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<td>Effect Of Annealing Temperature Microstructure And Mechanical Properties Of Direct Metal Laser Sintering Ti-6Al-4V Alloy For Biomedical Application</td>
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<td>11:20</td>
<td>Review Of An Active Re-Coater Monitoring System For Powder Bed Fusion Systems</td>
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<td>Presenter: Francois du Rand</td>
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<tr>
<td>11:40</td>
<td>Validation Of Microphone Placement For Acoustic Emission For Online Detection Of Porosity Forming Phenomena During Metal Laser Powder Bed Fusion</td>
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<tr>
<td>12:20</td>
<td>Effect Of Annealing Temperature Microstructure And Mechanical Properties Of Direct Metal Laser Sintering Ti-6Al-4V Alloy For Biomedical Application</td>
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**VENUE: MERIDIANS ROOM**

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<td>Presenter: Heinrich van der Merwe</td>
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<td>Presenter: Godfrey Mills</td>
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<td>12:00</td>
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<td>Presenter: Neil Britz</td>
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<tr>
<td>12:20</td>
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**CLOSING SESSION: PROF. THORSTEN BECKER (MANAGEMENT COMMITTEE)**

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<tr>
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<tr>
<td>13:00</td>
<td>COLLECT VIP LUNCH PACKS</td>
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FRIDAY 9 NOVEMBER 2018

08:00 Opening and Welcome: Management Committee - Prof Didier Nyembwe

PLENARY SESSIONS: PROTEA ROOM

08:15 Coordinator of 3D Research Group, CTI Renato Archer - Dr Jorge Vicente Lopes da Silva

09:00 Centre for Rapid Prototyping and Manufacturing - Gerrie Booysen

09:45 TEA BREAK

10:15 INDUSTRY SESSION

VENUE: PROTEA ROOM VENUE: OAK ROOM

10:15 Rapid 3D New Foundry Generation Forum (NFGF) - Altair Engineering SA Pty Ltd

11:00 TECHNICAL PRESENTATIONS (3 BREAKAWAY SESSIONS)

VENUE: PROTEA ROOM VENUE: OAK ROOM VENUE: MERIDIANS ROOM

Session Chair: Marius Vermeulen
Session Chair: Malan van Tonder
Session Chair: Gideon Potgieter

Theme: Additive Manufacturing Business Development
Theme: Process Monitoring
Theme: Material Process - Sand Moulds

Title
A Conceptual Framework For The Identification, Storage And Implementation Of Standards And Regulations Applicable To Additive Manufacturing
Detecting Defects During Powder Deposition In Additive Manufacturing
Fatigue crack growth rate threshold of selective laser melted Ti6Al4V titanium alloy
Transforming Academic Research into a Business Model: an i-Corps Case Study for AM Part Verification in the Aerospace and Medical Industries
Review Of An Active Re-Coater Monitoring System For Powder Bed Fusion Systems
Minimum Mould Thickness Design Specifications For Printed Sand Moulds

Title
Empirical Verification Of Pricing Algorithm For Laser Sintering Additive Manufacturing
Validation Of Microphone Placement For Acoustic Emission For Online Detection Of Porosity Forming Phenomena During Metal Laser Powder Bed Fusion
Determining The Effect Of Three-Dimensional Printing Orientation On The Bending Strength Of Sand Moulds And Cores When Using A Voxeljet Additive Manufacturing Machine
Design Cycle Of AM Prismatic and Biomimetic Aerospace Components
Automatic Focus Control System For High-Power Laser Additive Manufacturing
Sulfonic Acid Coating Of Refractory Sand For Three-Dimensional Printing Applications

Title
Effect Of Annealing Temperature On Microstructure And Mechanical Properties Of Direct Metal Laser Sintering Ti6Al4V Alloy For Biomedical Application
Wireless Sensor Detection of Casting Core Shift within 3D Printed Sand Molds

Title
CLOSING SESSION: PROF. THORSTEN BECKER (MANAGEMENT COMMITTEE)

13:00 COLLECT VIP LUNCH PACKS
ABSTRACT

Additive manufacturing standards are being developed to attend to problem areas. However, major companies often prefer to develop their own set of guidelines. The paper aims to address this convention of redeveloping the wheel. A study is done into the state of additive manufacturing standards to validate the claim that the problem is no longer a lack of standards, but rather difficulty in finding those applicable. From this, a framework is proposed to aid in the identification, storage and implementation of standards and regulations.

1 INTRODUCTION

While it is widely accepted that additive manufacturing is set to replace conventional manufacturing methods in many applications, most experts agree that additive manufacturing standards are a key obstacle to adoption of the technology\cite{1}. Potential adopters have a need for repeatability and consistency of manufactured parts\cite{2}. The difficulty experienced whilst trying to find standards applicable to a specific process results in many major additive manufacturing companies creating their own set of materials- and processing guidelines\cite{3}. Industry leaders have often discussed the problems and opportunities related to additive manufacturing during conferences and workshops, and repeatedly found a lack of standards to be a key issue\cite{2,4}. Owing to this, the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM International) crafted a standards development structure to ensure the joint development of standards in prioritized areas\cite{5}. Another such initiative is that of America Makes and the American National Standards Institute (ANSI) joining forces to establish the Additive Manufacturing Standardization Collaborative (AMSC), aimed at creating a roadmap-assessment of the state of standards in additive manufacturing to address problem areas\cite{6}.

Standards are becoming more readily available, yet the field remains largely unstandardized and unregulated. As such, the problem is no longer a lack of available standards, but rather difficulty in identifying those related to a specific product. The article will investigate this claim and discuss the development of a framework to aid in the identification, storage and implementation of standards and regulations relevant to a certain product. The framework was developed through expert interviews and case studies of medical and aerospace applications of Ti6Al4V. The value of this research lies in the ability for additive manufacturing companies to now adhere to standards and regulations as required, increasing customer confidence and international commercial viability. The framework also facilitates newcomers in the field, thereby increasing adoption of the technology and simultaneously advancing the field.

2 METHODOLOGY AND RESULTS

The research done is predominantly qualitative, based on expert interviews, and follows a systems engineering approach. The first step was that of defining the problem through a literature review and analysis of standards and standardization in additive manufacturing to determine the gaps and opportunities. The state of additive manufacturing standards was investigated by determining the number of available standards applicable to a case study of an established medical additive manufacturing application of Ti6Al4V. Figure 1 shows the results of this investigation divided into the initial standards already identified by the company, those added after doing a blind search and those identified whilst evaluating the framework. Another study aimed at identifying the number of additive manufacturing related standards available is currently in progress. The expected conclusion from these studies is that there are many standards available, yet they are not used as extensively as is the case with conventional manufacturing methods.
Following these studies, expert interviews were conducted to determine best practices in identifying standards and regulations. These were used to develop a conceptual framework for identifying, storing and implementing standards and regulations. From these interviews it was also concluded that a database containing all additive manufacturing standards would be beneficial to adoption and advancement of the technology.

The developed framework is based on the Plan-Do-Check-Act (PDCA) framework. As shown in Figure 2, the framework consists of five stages and requires continual improvement. The first two stages entail preparing for the identification stage. During stage three, standards and regulations applicable to the considered process are identified using the methodologies developed. Due to the confidential nature of information in the field, it is suggested that each company develop their own relational database during stage four, based on the guidelines provided. Stage five entails the implementation of standards and regulations to the process through the development of standard operating procedures (SOP).

This paper will further describe the outcome of an evaluation of the framework by means of two more case studies and additional expert interviews, which are currently in progress.

3. CONCLUSION

The current study investigates the state of additive manufacturing standards to determine reasons for the lack of use of standards in the field. A framework is proposed to aid users in identifying, storing and implementing standards into their process. The framework is currently limited to regulated applications of Ti6Al4V, such as medical and aerospace. The study will also highlight opportunities, one of which is to produce a scaled-up model of the relational database by a body such as RAPDASA to increase adoption of the technology in South Africa.

Figure 1: Case study analysis results.

The developed framework is based on the Plan-Do-Check-Act (PDCA) framework. As shown in Figure 2, the framework consists of five stages and requires continual improvement. The first two stages entail preparing for the identification stage. During stage three, standards and regulations applicable to the considered process are identified using the methodologies developed. Due to the confidential nature of information in the field, it is suggested that each company develop their own relational database during stage four, based on the guidelines provided. Stage five entails the implementation of standards and regulations to the process through the development of standard operating procedures (SOP).

This paper will further describe the outcome of an evaluation of the framework by means of two more case studies and additional expert interviews, which are currently in progress.

REFERENCES


Transforming Academic Research Into A Business Model: An I-Corps Case Study For AM Part Verification In The Aerospace And Medical Industries

GODFREY MILLS, LESLIE G. BUTLER, AND WARREN R. HULL

ABSTRACT

Images of flaws and fatigue in Additive Manufacturing objects with advanced X-ray and neutron techniques show the potential for a business opportunity in material characterisation. A $50,000 National Science Foundation Innovation Corps grant was awarded to a three-person team to undertake a customer discovery journey and create a business model. The team consists of an entrepreneurial lead, a technical expert, and a business mentor. A Go/No-Go decision on commercialization is supported by data from multiple real-world customer interviews, and not by the biased opinion of the inventor.

1 INTRODUCTION

Recent results from our lab-images of flaws and fatigue in AM metal objects [1-4] (Figure 1) with advanced X-ray [5] and neutron techniques (Figure 2) show the potential for a business opportunity. In the US, academic entrepreneurial activities are encouraged with grants called small business innovation research (SBIR). Unfortunately, historical evidence shows only modest successes with SBIR-funded lab-to-commercial success. Hence, the US funding agencies have recently invented a new program, I-Corps, to address the most critical question: Is there a market for the academic invention? Herein, we describe our experience with the I-Corps crash business course as applied to an AM flaw detection idea.
2. METHODOLOGY AND RESULTS

An I-Corps grant provides $50,000 in travel funding to a three-person team. The team consists of an entrepreneurial lead, a technical expert, and a business mentor. An I-Corps class has twenty teams taught over seven weeks by faculty from business schools and private industry. The coursework is a fast overview of small business development and the language of venture capitalists: value proposition, customer segment, and the current communication tool of the day, the business model canvas. The single most important lesson is the customer interview; the team must complete more than 100 customer interviews in the seven weeks. A successful customer interview is open-ended, is not biased by leading questions, and is performed to test hypotheses about the commercialisation of the academic research. The quality of the academic research is NOT the subject of the I-Corps training; the "widget" is assumed to be perfect. The I-Corps customer interviews determine if anyone needs the widget, why they need it, and how much is the widget worth to them, regardless of the production cost of the widget.

In week 1, we thought customers wanted in-situ imaging of AM metal printing based on our questions of “would you like?” Unfortunately, that is a biased question and provides no useful business information. By week 3, open-ended questions of “how do you ensure quality AM parts” led to answers covering a blend of process validation and post-print part verification. In demanding applications such as turbine fuel injectors, part verification shows a 10% failure rate of a $20,000 part as determined by a $2,000 imaging method. Now we see that commercial success depends on finding enough product lines and reducing the implementation cost of our academic idea. The first customer interviews were intimidating, but now we see their value and the 100 interviews target is highly satisfying. The twenty teams provide peer instruction via weekly video conference. The I-Corps website has a leader board showing which team has conducted the most customer interviews for the past week.

3. CONCLUSION

The I-Corps faculty has many case histories of start-ups skipping the customer interview and then cratering spectacularly. A Go/No-Go decision on commercialisation is supported by data from multiple real-world customer interviews, not by the biased opinion of the inventor.

3. REFERENCES


Empirical Verification Of Pricing Algorithm For Laser Sintering Additive Manufacturing


ABSTRACT

“Industry 4.0”, is internationally in the development programme of companies operating within the advanced manufacturing ambit. Unfortunately, many South African captains of industry have still not come to terms with the challenges and opportunities of digital transformation or with the conceptual leap it represents. The South African Science and Technology community is only now emphasising the importance of implementing the technology governing the trends in automation and data exchange. The challenge in the advanced manufacturing ambit is to offer the customer the freedom of enquiry, to receiving a reliable quotation and to place an order for products and services in the digital realm. In the Additive Manufacturing world, the technological opportunities are not in question; the need to understand the underlying cost drivers needs investigation. A fundamental understanding of the economics that underpin the application of this technology, which is a fundamental precursor to converting the interface for this application to utilise the advantages of the digital aspects incapsulated in all facets of “Industry 4.0”. This paper presents the findings of an empirical research project aiming to develop a holistic understanding of the underlying economics of additive manufacturing. The result could be an algorithm that assists to capture all the cost drivers, enabling the end-user to present a full-cost model for Laser Sintering Additive Manufacturing technology.

1. STUDY OVERVIEW

3D printing has grown beyond expectations in the past couple of years. This has led to new challenges in the management of the technology in a sustainable way. Additive manufacturing (AM) commonly referred to as 3D printing, has evolved into an accepted manufacturing technology. The current understanding in consultation with AM Specialists is that this advanced manufacturing process is principally considered as having two distinct advantages over conventional manufacturing techniques. Firstly, it avoids many of the tooling-related constraints on the geometries that can be achieved through conventional manufacturing processes. Secondly, AM allows the efficient creation of products in very small quantities, down to a single unit, enabling the manufacture of customised or highly differentiated products. This is a typical conventional consideration, and the design flexibility needs further consideration.[6]

The new understanding is that AM must not be seen as a manufacturing process in isolation, but rather as part of the advanced manufacturing and mass manufacturing processes. The major driver for this research was to create the tools to link industrial AM to the “Industrie 4.0” principles, and then encourage them to review, redesign, and optimise existing designs in order to take full advantage of the benefits that AM can offer. The economics of AM are fundamentally linked to the distinct advantages it offers when it comes to design freedom.[6]
The cost of a model is thus just one aspect to be considered. This new way of thinking brings several economic factors into play; the structural design and geometry optimisation aspects, the full advantage of topology optimisation, which negates the non-stressed areas within specific geometry. This is all possible by collecting pre-defined information and design criteria from the end-user. The past analysis of the economics of AM in principle focussed on the capital investment and material cost, the Model: EOS Formiga P 100 is the platform that will be used in all the calculations see table 1.

Table 1: P100 information

<table>
<thead>
<tr>
<th>Model: EOS Formiga P 100</th>
<th>Notes:</th>
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| Selective Laser Sintering machine | 1) Machine build size: W240 x D190 x H300 mm  
2) 3d print model shrinks.  
3) Tolerance is 0.1-0.2mm.  
4) Min thickness 0.6 (x-y), 0.1 (z).  
5) Printing on X-Y plane makes for higher strength output. |

System manufacturer | EOS GmbH |
Process type | Laser Sintering |
Energy deposition | CO2 laser, 30W |
Usable build volume size (X / Y / Z) | W240 x D190 x H300 mm |
Process atmosphere | N2 |
N2 source | N2 generator, internal power supply |
Heater type | IR and resistance |
Melting temperature | ~173 °C |
Build material | PA2200, Polyamide 12-type thermoplastic |
Used layer thickness | 100 μm |
Support structures | Not required |

The approach to link the AM technology to a conventional ERP (enterprise resource planning) system requires a more traditional approach. The principle that will be followed is to analyse the body of knowledge at the VUT when it comes to the Laser sintering of products.

For an ERP system to work properly, a series of builds to determine the actual cost were identified \[2,3,4\] this data will form part of the full paper. Three of the builds are at maximum build height, around a 282 mm useful capacity. The Materialise Magics software was used to prepare the builds.

The Costing Model’s objective is to analyse the entire process, starting with the receipt of the customer’s specification (3D Model or EBOM (engineering bill of materials), including the AM sintering process on the EOS platform EOSINT P100 (table 1), and ending with the delivery to the customer (despatch). This ultimately led to the identification and understanding of the complete list of cost drivers. Information captured in financial system and the quoting and technical departments will be used to determine the influence of each cost driver on the product cost. Based on this an adaptive costing model is developed. Costs are grouped into: material, electricity, machine and labour cost.\[1,6\] The analysis of these groups will be interrogated in the rest of the paper.

The aim is to use the body of knowledge in the AM department at the VUT to develop a holistic all-encompassing predictive cost model for the AM processes. The control will be to empirically test the costing algorithm with a series of results.

REFERENCES

[2] EOS. 2010. EOS FORMIGA P100 Datasheet
Design Cycle Of AM Prismatic And Biomimetic Aerospace Components

N.BRITZ

ABSTRACT

The hypothesis of the study is the design cycle process for prismatic and biomimetic aircraft components that will be manufactured with the focus on Additive Manufacturing. There will also be advocating for traditional methods of manufacturing when using the design cycle. Many factors have to be taken into account, thus the design cycle will be split into various phases. Each phase will be looked at individually before the design cycle as a whole. This is purely done to refine each phase of the cycle to make sure the component is fully optimized for the desired outcome.

1. INTRODUCTION

The popularity of topology optimisation methods in structural design has increased since the rapid development of Additive Manufacturing (AM) technology. AM is making it possible to manufacture more biomimetic shapes generated by topology optimisation, as opposed to a more prismatic perspective where specific parameters had to be set in place for Traditional Manufacturing (TM) techniques. Biomimetic refers to the organic or natural shapes that are generated when topology optimisation is applied. Prismatic shapes are also generated using topology optimisation, but it is necessary to set certain parameters. For example, the draw direction and symmetry planes. In 2004, Zuo et al said that topology optimisation was rapidly developing and with the maturation of topology theory and the increased number of tools, it had become a strong method in the design of components. As the study progressed a range of problems like porosity, a design with checkerboards, mesh dependency, local minimum results, etc. came up. This lead to non-manufacturable topology - like machining that could not be accepted in the traditional manufacturing processes. As mentioned previously, with the recent development of AM, the possibility to manufacture more biomimetic shapes generated by topology optimisation has increased tremendously.

However, Zhang et al stated that although AM significantly opens the design space up, it is not completely a free-form manufacturing technique. For example, to be able to evacuate the solid powder that did not melt, enclosed voids in structures should be avoided in powder-based processes such as selective laser melting (SLM). Other important factors that have an effect on the manufacturing quality are the building accuracy, interlayer mechanical properties and surface finish. Additional support structures should also be taken to into account because it has added advantages, for example: it keeps AM components from collapsing if the overhang angle becomes too great, it will also dissipate heat into the build platform to avoid local distortion of the component. However it is clear that it also has an effect on the cost of the component with additional material being added. There is an effect on the quality of the surface finish if the post-processing isn’t done carefully. So it is clear that there are many factors and parameters that still need to be taken into account when optimising a component even if it is manufactured using AM.

2. METHODOLOGY AND RESULTS

2.1. Methodology

In this study, the design cycle for AM and TM components will be investigated. The design cycle consists of 6 phases: CAD, optimisation, internal features and surfaces, manufacturability, qualification and certification, and model as a solid (back to CAD). The design cycle can be seen in figure 1. The main focus is to implement a process where a designer designs for AM or TM and then follows the design cycle to get a certified component or 3D CAD model. The number of iterations of the design cycle will mainly be influenced by the qualification and certification phase of the cycle to see if it was over designed or if it meets the design criteria. Each part of the cycle will be looked at individually and a process manual for each phase will be generated. At the end of the study, a complete document of the design cycle as a whole will be created. These process manuals will equip any designer/engineer with the basic skills needed to operate the software to optimise parts and eventually achieving the desired client specifications.
2.2. Results

The expected results of the study will include a component that is manufactured using Additive Manufacturing technologies and has gone through the design cycle process. The part will be optimised to the extent where it can be effectively manufactured and meets the design requirements.

3. CONCLUSION

The hypothesis of the study is the design cycle process for prismatic and biomimetic aircraft components which is still under investigation.

REFERENCES


Detecting Defects During Powder Deposition In Additive Manufacturing

A.J. HENDRIKS1, R. RAMOKOLO1, C. NGOBENI1, M. MOROKO1 AND D. NAIDOO1

ABSTRACT

Additive manufacturing applications, in areas such as aerospace and medicine, are limited due to the lack of process stability and quality management [1]. In particular, geometrical inaccuracies and the presence of mechanical defects hinder repeatability of the process. To break into industries with very high quality standards, an important issue to be addressed is in-situ quality control during a built. The work which will be presented here is focused on image based process monitoring of the powder bed after the deposition of a new powder layer. We will also discuss the effects these might have on powder-metal consolidation. Preliminary results will be shown of defects identified and processes after a new powder layer has been deposited.

1. INTRODUCTION

In additive manufacturing (AM) parts are fabricated by consolidating material layer-by-layer from a three-dimensional computer aided design (CAD). This technology has the advantage over current industrial subtractive manufacturing (milling and turning) as it allows building of high geometrical complex parts. Due to the methods being drastically different the adoption of standards and certification of quality from subtractive manufacturing is not possible. New standards and part certification is required for AM as it is a new technology completely different from subtractive manufacturing. Verifying the quality of a part is mainly done after part fabrication which does not allow the operator to act upon defects like scraper damage etc. created during the process of powder deposition. T. Craeghs [2] showed it is possible for in-line process monitoring to scraper related defects during powder deposition. This method is based on the principle that shadow regions will form on uneven surfaces if a light source is placed at an angle relative to the surface normal.

This work will present an image based system to collect information of powder layer deposition. The main defects during a scrape will be identified and analysed to establish the influence of the defect. For this a software package was developed to auto-detect defects and give it a score according to its severity. This is aimed towards developing a system which in the future will contribute to quality assurance.

2. METHODOLOGY AND RESULTS

2.1. Image capturing

Visual detection of a powder bed was achieved with a high resolution CCD cameras leading to an image resolution of roughly 15 μm/pixel and a cropped field-of-view 20.8 x 20.8 mm. The technique used to detect defects is dependent on the formation of shadows on the powder bed due to a light source illuminating the powder bed from the side. Basic issues with regards to imaging and light source locations were addressed with the aid of a set of experiments to establish the ideal setup. An example of the power bed after powder deposition is shown in fig.1. showing several defects. This includes recoater damage (1), super elevation of the part (2), powder deficit (3) as well as power blade hopping (4) each creating its own type of error [3,4]. Recoater damage and powder blade hopping lead to high surface roughness. Super elevation of the part leads to more powder deposited at the super elevation region which in turn allows the super elevated part to grow in size. Powder deficit leads to the solid part to be re-melted causing souring temperatures and the creation of high stress levels. These defects can lead to a poor quality part or and even part failure.
2.2. Data analysis

In fig.1 several powder deposition defects after recoating is highlighted. In the past these were identified through visual inspection which implies an operator need to be present at all times. In the future this will be circumvented using software to identify the defects which might lead to build errors. In this work software was developed to automatically identify the defects shown in fig. 1. To provide a few examples fig. 2. shows a horizontal cross-sectional cut of the data in fig. 1 (blue line) which is perpendicular to the scraper movement direction. Vertical lines can be seen in fig. 1. which is a result of the scraper blade. If however these lines extends beyond 2 standard deviations from the norm (fig 2 left. red dashed lines) it is considered as scraper damage which in turn will lead to high surface roughness. The second example (fig. 2. right) shows super elevation of the part which extends beyond the new powder layer deposited. These types of defects are localized and more difficult to identify. However, by sampling over the horizontal axis and searching for local centre of mass locations within the image it was possible to pinpoint the location of the defect.

REFERENCES


3. CONCLUSION

Certifying AM parts plays a big role in the success of AM parts in industry. We have performed preliminary experiments and developed software which can detect powder bed defects which at a later stage will be unified with software identifying defects after powder-metal consolidation. This will provide fundamental information regarding consolidation defects related to powder layer deposition towards part qualification by process monitoring.
Review Of An Active Re-Coater Monitoring System For Powder Bed Fusion Systems

F. DU RAND¹, P.J.M VAN TONDER², H.C. VZ PIENAAR³ AND D.J. DE BEER⁴

ABSTRACT

When manufacturing parts using powder bed fusion additive manufacturing technologies, failed prints due to re-coating errors have been identified as an aspect that could reduce the reliability of the technology. An active re-coater monitoring system has been developed to provide re-coating quality feedback after each layer. This research paper will review the capability of an active re-coater monitoring system to detect re-coating errors during the build process. Some of the parameters of the various image processing functions will also be verified using the data recorded during the case study.

1. INTRODUCTION

In the field of additive manufacturing, specifically when using powder bed fusion technologies, failed prints can become very costly due to the high cost of the raw material. Parts with printing defects, as displayed in Figure 1, must be reprinted to ensure clients receive good quality parts. Re-coating errors can be identified as a key factor that may cause failed prints and, in so doing, reducing the reliability of the technology [1].

Re-coating errors, identified in the following research study, could directly be linked to re-coater short feeding or blockages and debris that may fall onto the surface of the powder bed.

Currently, powder bed fusion technologies have no method of determining the quality of the re-coating process [1]. This indicated the need to develop an active re-coater monitoring system. The design ideology of the active re-coater monitoring system was to detect defects and re-coating errors on the surface of the powder bed during the printing process.

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The active re-coater monitoring system was installed on a voxeljet VX500 powder bed fusion machine. The developed system uses computer vision to monitor the surface quality of the powder bed. The system consists of a camera module, Raspberry Pi 3 microcomputer and lighting fixtures. The block diagram in Figure 2 displays the layout of the system.

A build, consisting of 1946 layers, was selected to benchmark the system. The build contained several small and large parts stacked throughout the volume of the build volume. Once the build had been completed, the data was analysed to determine whether defects occurred during the building process. The recorded data is then plotted graphically using a line graph, which will indicate any re-coating errors.

The design of the system allows for the mounting of the camera in such a way that it captures the entire surface of the powder bed in a single image. The system will capture an image after each re-coating cycle. The standard machine light luminaire was used to illuminate the powder at a 45 degrees angle, in relation to the powder bed.

A software program was developed to process the captured images, using OpenCV library. OpenCV library is an open source computer vision and machine learning software library that contains 2500+ optimised algorithms [2]. The image processing algorithm used to identify surface defects include histogram equalisation, Gaussian blur and Canny edge detection. The program was developed to process images in near real-time so that the analysis on the image would be complete before the successive re-coating cycle.

Re-coating errors have been identified as a key factor that may cause failed prints in powder bed fusion technologies and could reduce the reliability of the technology. Thus, an active re-coater monitoring system was developed using computer vision to provide real-time re-coating feedback of the surface quality of the powder bed. The following study will focus on benchmarking the selected parameters for the various image processing functions. A single build will be monitored as a case study to verify the capability of the proposed system to detect defects and re-coating errors on the powder bed surface.

REFERENCES


Validation Of Microphone Placement For Acoustic Emission For Online Detection Of Porosity Forming Phenomena During Metal Laser Powder Bed Fusion

D. KOUPRIANOFF 1*, N. LUWES2, I. YADROITSAVA1 AND I. YADROITSEV1

ABSTRACT

One of the main drawbacks of laser based powder bed fusion is lack of fusion between tracks following non-optimal input process parameters, scanning and building strategies and/or inhomogeneity in delivered powder layer. Unstable geometrical characteristics of single tracks and high roughness of the powder layer can cause porosity in 3D parts. In this study an online non-destructive monitoring technique such as acoustic emission was used to determine lack of fusion and balling effect of single tracks. These phenomena were simulated by increased powder layer thickness. Analysis of the acoustic behaviour of the system and comparison of acoustic emission during processing of single tracks and visual data obtained from track morphology were carried out.

1. INTRODUCTION

In-process sensing and control is one of the main steps for ensuring repeatability and consistency of LPBF manufacturing [1]. Key process parameters in LPBF are: laser and scanning parameters, powder material properties, powder bed properties and re-coat parameters and build environment parameters. Process signatures emanating from the melt pools in LPBF are molten/solidified pool, plasma emission/absorption, radiation, reflected/scattered light, etc. These phenomena are the basis to control stability and repeatability of the LPBF process. Available commercial LPBF monitoring systems based mainly on photodiode melt pool monitoring, CMOS camera for powder bed imaging system, IR and UV photosensors and pyrometers; build atmosphere monitoring [1].

For quality control of the ever growing laser technology implemented in industrial applications Mao et al. [2] suggested using AE as it has high signal to noise ratio, fast response, and non-contact. During laser welding, various phenomena such as thermal stresses, vaporisation, cracking and the interaction of gasses between phases are all related to acoustic phenomena. It was shown that acoustic spectrum of conduction welding was different from that of a keyhole welding and strong correlation between AE energy signal and laser power, welding speed, focusing distance (laser spot size) was found. Another study by Lawrence Livermore National Laboratory (LLNL) showed that a notable difference could be obtained from the acoustic signatures of varying laser powers during LPBF [3]. They found that the results showed a clear shift and missing peaks in spectral analysis between the two different laser powers [3].

2. METHODOLOGY AND RESULTS

Maraging steel with chemical composition Fe-18Ni-Co-5Mo-1Ti being Ni 17.6%, Co 8.88%, Mo 4.85, Ti 1.06% was used. Samples were produced on the substrate with similar chemical composition. The building chamber was filled with nitrogen atmosphere. The single tracks were 200 mm in length and were scanned at a laser power of 305 W with a scanning speed of 1.01 m/s with an EOSINT M280 system. To determine if AE can be used to detect luck of fusion and balling phenomena, scanning on an increased layer thickness was compared to scanning on normal layer thickness of 50 µm. AE was measured using two ICP microphones; first having a frequency range of 3.75-20 000 Hz(±2dB). And second 4-70 000 Hz(±2dB). The microphones were placed inside the building chamber (Fig. 1). Data recordings were initialised before laser scanning started to obtain ambient sound data. Post processing of data was carried out with LabVIEW using signal processing algorithms.
Increase energy intensity is seen in higher frequencies when balling occurs as seen in Fig. 2. This increase can be seen more prominently with the high frequency microphone results.

3. CONCLUSION

A clear distinction was made between the tracks where balling occurred (greater powder thickness). A difference in the energy content at different frequency bands is seen between the two layers.

REFERENCES


Automatic Focus Control System For High-Power Laser Additive Manufacturing

C. JACOBS1, D.P. PREUSSLER1*, F.S. ROUX1,2, Y. ZHANG1,3, L. BURGER1,2 AND R. RAMOKOLO1

ABSTRACT

Thermal lensing presents a significant obstacle in the advancement of next generation additive manufacturing systems based on kilowatt-class lasers. We present a new, patent pending active thermal lensing compensation technique; an online, real-time automatic beam focus control system which can stabilise and control laser beam size and divergence in an active feedback loop. For the initial low-power experimental setup, artificial (de-)focussing was introduced by manually adjusting an additional inline telescope. The control system could maintain beam size accuracy within ±3% of the reference value and keep beam divergence below 60 μrad, all within a response time of under a second.

1 INTRODUCTION

Recent years have seen considerable advancements in additive manufacturing (AM) processes. In the case of selective laser sintering or melting of metals, laser output powers have increased from several 100 watts to multiple kilowatts in an effort to decrease material contact time and increase build speeds and part volumes. One such high power system, AeroSwift has been under active development at the CSIR in collaboration with industrial partner Aerosud, supported by the South African Department of Science and Technology. At these high laser powers thermal lensing in optical components have been observed and reported (as part of project AeroSwift [1], and by others [2]). Thermal lensing occurs as a result of a thermally induced refractive index gradient (thermo-optic) as well as thermally induced mechanical stresses (with associated photo-elastic refractive index changes and physical end-face bulging).

For AM, it is important that the power density on the powder bed of an AM system remains constant to ensure high-quality and consistent part building. It has been observed that even high-quality optics (such as low-absorption Infrasil, Suprasil and Sapphire) used in AM machines experience significant thermal lensing when irradiated at laser power levels above 500 W. To make matters worse, an advanced multi-component AM machine may contain such optics over an extended optical path, resulting in a much stronger compound thermal lens effect. Thermal lensing changes the focusing properties of the optical system and as a result both the spot size and the focus location changes as a function of the laser power and laser duty cycle (which changes according to the part being built).

It is thus essential that any changes in spot size induced by thermal lensing are compensated for or minimised by some mechanism. Current techniques mainly involve minimising thermal lensing through design (e.g. minimum optics, short path lengths, better cooling, large beams and multiple lasers) but severely limit design freedom and improvements. Passive compensation optics [3, 4] based on negative coefficient of refractive index materials is an alternative, but only where fixed laser power is required (e.g. for cutting and welding applications). In this paper we present a new active compensation technique; an online, real-time automatic beam focus control system which uses a beam sensor (or set of beam sensors) and one or more motorised zoom telescopes (MZT) to sense and automatically adjust laser beam size and divergence in an active feedback loop.

2 METHODOLOGY AND RESULTS

As a first step towards developing an active compensation technique, selected optical windows were irradiated at a constant continuous wave power levels of up to 5 kW and the influence of thermal lensing on beam diameter (at the focus of a lens) measured over time (see figure 1a). Reverse ray tracing was then used to determine thermal focal length strengths of 20 to 30 m depending on the substrate. However, the low absorption coefficient substrates alone simply cannot absorb enough laser energy to result in thermal lensing of this magnitude, as confirmed through analytical calculations. This led to the formulation of a new hypothesis that the bulk of the absorption occurs rather in the optical coatings. With thermal lens strength magnitudes confirmed, additional ZEMAX modelling was done to evaluate the viability of active compensation using a number of fixed-focal length lenses at adjustable positions (see figure 1b). The ZEMAX-based modelling indicated that at least six optical elements are required (of which four is position adjustable) to compensate for a specific thermal lens strength (for each of the roughly 10 thermally affected optics in an AM machine).
Figure 1: (a) Measured beam size as a function of time for various optical materials. (b) Compensating lens positions for four movable lenses as a function of the thermal lens strength to negate.

Figure 2a illustrates conceptually how such a compensation scheme would operate. The thermal lensing manifests itself as a change in the collimation of the high powered beam, which when focussed onto a beam waist analyser or similar camera just before the scanner, would result in a measurable change in beam waist size and position. This data is then used by a controlling computer to determine corrective MZT lens positions (i.e. 1x three lens beam reducing telescope (BRT) and 1x three lens beam expanding telescope (BET)) which would counteract the thermally-induced change in collimation (based on a custom trajectory search algorithm). These actions repeat continuously in a feedback loop to ensure the required beam (in size and divergence) enters the scanner. Figure 2a also illustrates how a secondary powder bed beam sensor could be added to control the beam directly at the work surface.

The initial proof of concept experiment was done at low power using a single motorised BET as shown in figure 2b. A manually adjustable 1:1 imaging telescope had one of its lenses mounted on a translational stage. A single compound thermal lens effect could then be simulated by moving this lens in and out of focus. Beam size and divergence was measured with a beam camera illuminated with two beams, one near and one far (~1 m longer beam path). The compensation program was able to correct for total changes in beam divergence of ±1 mrad and beam size changes of 50% provided this change was gradual. The program was able to maintain the beam size within ±3% of its target value and the divergence below 60 µrad, all under a second.

3. CONCLUSION

We have successfully demonstrated the fundamental principles of an active thermal lens compensation scheme using a low power laser and a single three lens MZT. The system could correct artificially induced focussing and defocussing. For the specific case of thermal lens control in a High-Power Additive Manufacturing Machine, the system could be used to ensure the laser spot size on the working surface remains constant or simply that the high-powered beam entering the scanner remains collimated at all laser powers and operating duty cycles. The compensation algorithm must still be further optimised and tested with two MZT as actuators and the BWA-CAM in the feedback loop. The final system needs to be demonstrated on a high-power laser system with realistic thermal lensing, including dynamic changes due to variable output powers and duty cycles.

REFERENCES


Effect Of Annealing Temperature On Microstructure And Mechanical Properties Of Direct Metal Laser Sintering Ti6Al4V Alloy For Biomedical Application

S.T. CHINGOWO*, P. MENDONIDIS 2 AND I.D ADEBIYI 3

ABSTRACT

Direct Metal Laser Sintering (DMLS) is a fabrication process that enables the manufacturing of intricate and complex geometries. Quality of Additive manufactured parts is more dependent on unpredictable porosity, deformations and accuracy. Heat treatment is applied to improve ductility and microstructure to comply with ISO standards for implants. In this study, Ti6Al4V samples fabricated by DMLS were annealed at 650 ºC, 950 ºC and 1100 ºC in a vacuum for 2 hours and then characterised. There was the transformation of alpha martensite to alpha and beta phase, a decrease in hardness and improved elongation with increased annealing temperature. Therefore, in future quality processing treatments, raising the annealing temperature should be considered to enhance mechanical properties.

1. INTRODUCTION

DMLS is an additive fabrication process that uses a laser to melt or fuse the powder from a 3D design. It has been reported parts produced DMLS have residual stresses similar to a conventional, traditional fabrication process such as welding [1]. Comparing DMLS to soldering, it is argumentative that DMLS has better structural integrity due to the absence of joints as found in welding. However, one major drawback of DMLS process is multiple modes of heat and chemical reactions that make the process very complicated leading to temperature gradients [2]. This results in thermal tensile and compressive residual stresses. The tensile stresses, when they exceed the yield strength of the material, result in premature fracture and failure. The rapid cooling of the DMLS parts during fabrication also results in an alpha martensitic microstructure which is undesirable as it is very brittle and hard. Furthermore, another major factor that affects the quality of the end products produced by DMLS is porosity, which is undesirable since it can lead to premature failure [3]. DMLS under optimal process parameters produce little porosity or at least to the point where little integration with biological tissue will be promoted by surface breaking pores. Several studies have been performed on post treatments’ effectiveness on additive manufactured parts to combat mechanical problems of the as-built products. However, the influence of annealing temperature on the material behaviour of the Ti6Al4V alloy is not entirely understood. Methodical research on the impact of annealing temperature during heat treatment to get better in-depth knowledge is viable.

2. METHODOLOGY AND RESULTS

2.1. Methods

The as-received tensile samples built by DMLS at Central University of Technology using EOS machine with the chemical composition (wt.%) of 6.15Al, 4.1V, 0.01N, 0.02C, 0.12O, 0.002H and 89.7Ti were used. The samples were cut from the substrate after in-situ stress relieve. The samples were annealed in an argon furnace at 650 ºC, 950 ºC and 1100 ºC temperatures. The microstructure of the heat-treated samples was studied using Olympus optical microscope after sample preparation. Phase identification, tensile and hardness properties were measured by Shimadzu X-ray diffractometer, Instron Tensile tester and Vickers Hardness Tester respectively.

2.2. Results

Figure 1 shows the optical micrographs of the as received and heat treated Ti6Al4V alloy. As shown in Figure 1(a) an α’ martensitic structure was observed. The microstructure was identified by the needle in the figure. Murr, Gaytan [4] suggests that the α’ martensitic structure results from rapid cooling during sintering.
Figure 1(b) shows the micrograph obtained from samples heat treated at 650 ºC. It was observed that in the samples heat treated at 650 oC; the microstructure remains unchanged as α’ martensitic Figure 1(b). This is probably because 650 ºC is not sufficient to induce phase transformation[5]. Figure 1(c) shows the alloy after heat treatment at 950 oC. The microstructure is characterised by laths of alpha (white) and beta phase (grey) Figure 1(c). Figure 2-1d shows the presence of a widmanstatten alpha in the beta matrix at 1110 oC with large grains.

3. CONCLUSION

Increasing the annealing temperature in Ti6Al4V alloy results in a decrease in hardness and yield strength.

Graph 1: XRD diffraetogram of Ti6Al4V sample heat treated at 650 ºC , 950ºC and 1100ºC in an argon atmosphere

XRD patterns of the samples heat treated at 650 ºC, 950 ºC and 1100 ºC showed the characteristics peaks for the primary alpha phase (Ti) at 2θ angles of 42o and 77o. The peaks in the as-built samples are quite broad but are sharper in the annealed samples. The broadening could be an indication of small grains (nanocrystalline) in as-built samples. At the high annealing temperature of 1100 ºC the peaks become sharper which is indicative of large crystallite grain size. The average hardness of the as-received specimens at 6 indentations using 1000kgf were 408 ± 10 HV, 399 ± 9 HV,320 ± 6 HV and 301 ± 5 HV for samples heat treated at 650 ºC, 950 ºC and 1100 ºC respectively. The yield strength of the as received, heat treated at 650 ºC, 950 ºC and 1100 ºC were 1083 ± 34 Mpa,1111 ± 25 Mpa,948 ± 16 MPa and 910 ±20 MPa using a load of 12KN respectively.

REFERENCES


Fatigue Crack Growth Rate Threshold Of Selective Laser Melted Ti6Al4V Titanium Alloy

N.M. DHANSAY1* & K. VANMEENSEL2 AND T.H. BECKER1

ABSTRACT
High residual stress, a martensitic microstructure and porosity pose major restriction in the qualification of Selective Laser Melting (SLM) produced Ti6Al4V parts for biomedical and aerospace applications. This study aims to study the fatigue crack growth threshold of as-built SLM produced Ti6Al4V Compact Tensions (CT) specimens in two crack orientations, namely the YXZ and ZXY according to ASTM F2921. Results show that a similar threshold value exists for both orientations. However, the data shows a difference in threshold behaviour between the two orientations that may be attributed to differences in crack closure effects.

1. INTRODUCTION
SLM is an Additive Manufacturing (AM) technique which produces parts from powdered material via the consolidation of a laser beam in a layer wise fashion. AM offers numerous advantages over traditional subtractive manufacturing techniques such as: lower material waste, lower lead times and the capability of achieving high part complexity. Ti6Al4V alloy is the most popular titanium alloy in the traditional manufacturing industry (wrought, rolling and CNC). This is mainly due to wrought-produced Ti6Al4V’s superior mechanical properties, particularly its high strength to weight ratio [1].

Typically, parts used for the aerospace and biomedical industries are subjected to high cycle fatigue loading conditions [1]. Thus, of importance are fatigue properties. One such property is the fatigue crack growth rate threshold value, which is the measure of the materials ability to resist fatigue crack propagation. To date, little literature has been published on the fatigue crack growth threshold of SLM produced Ti6Al4V. This study serves as one of the ongoing investigations into the fatigue crack growth threshold of SLM produced Ti6Al4V in an as-built condition. Considered are two build orientations to investigate the effect of the inherent inhomogeneity of the layer wise SLM process. Furthermore, various load ratios are considered, as these have been shown to affect fatigue crack growth threshold values in wrought Ti6Al4V.

2. METHODOLOGY AND RESULTS
This study conformed to the ASTM E647 standard for the measurement of fatigue crack growth rates [2]. CT specimens were built with a nominal width $W = 50\,\text{mm}$ and thickness $B = 6.5\,\text{mm}$ using an EOSINT M280 (EOS GmbH) machine. A layer thickness of $30\,\mu\text{m}$, a $200\,\text{W Yb-fibre laser}$ and a multidirectional scanning strategy along with standard process parameters were implemented. The CT specimens were orientated in the ZXY and YXZ orientation according to ASTM F2921, where ZXY designates a crack growth perpendicular to the build layers and parallel build orientation, and YXZ parallel to the build layers and perpendicular to the build orientation. Testing was conducted on an Instron Electropuls E3000 dynamic tester at frequencies of up to $75\,\text{Hz}$. Crack length measurements were captured using the compliance technique and periodically confirmed via optical measurement. All specimens were kept in an as-built condition. Two test approaches were utilised to obtain crack growth rate threshold values, namely a constant R-ratio and a Kmax approach. A fatigue threshold value $\Delta K_{\text{th}}$ was considered as the cyclic stress intensity for a crack growth rate of less than $10^{-10}\,\text{m/cycle}$. The R-ratio was calculated as the min/max load applied to the specimen. Uncertainty of the results are based on errors of the load cell, tuning of fatigue machine and measuring equipment. The combination of these equate to $\pm 0.05\,\text{MPa.m}^{0.5}$ due to the Electropuls load cell having an accuracy within $\pm 0.5\%$ of load reading [3]. For this reason, uncertainty in R-ratios and Kmax are too small to display in Figure 1.

Figure 1a) shows the results obtained for the two orientations for various R-ratios. Noticeable is the asymptotic behaviour whereby a convergence value of $\Delta K_{\text{th}} = 1.5\,\text{MPa.m}^{0.5}$ was achieved towards a theoretical maximum R-ratio of 1. Figure 1b) shows the results obtained for various Kmax values. Similarly, an asymptotic behaviour with a convergence value of $\Delta K_{\text{th}} = 1.5\,\text{MPa.m}^{0.5}$ was noticed for higher Kmax values. This suggest a true fatigue crack growth threshold value exists for SLM produced Ti6Al4V in the as-built condition.

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However, a noticeable difference in behaviour between the two orientations is observed: The ZXY orientation shows significantly lower threshold values for both lower R-ratios and Kmax values compared to the YXZ orientation. Variations in ΔKth have been attributed to roughness and residual stresses induced crack closure effects [5], [6]: i.e. when the applied load and the effective crack load are not equal. This is either due to opposing fracture surfaces making early contact due to an inherent irregular surface roughness, or due to high residual stresses resulting in localised plasticity (which can also result in an irregular surface roughness). At high R-ratios or Kmax values these effects are overcome, thus resulting in a convergence in fatigue crack growth rate threshold behaviour. The data suggests that the ZXY orientation, i.e. a crack propagating perpendicular to the build layers, suffers from crack closure effects. Visual observations of the fatigue crack surface confirm a more tortuous crack path suggesting a surface roughness effect that may have been induced by the high residual stresses. Further investigations are required to confirm this.

3. CONCLUSION

Investigated were the fatigue crack growth threshold of SLM produced Ti6Al4V in two build orientations at various load ratios. It can be concluded that a true material threshold value of ΔKth = 1.5 MPa.m0.5 exists. However, a dependency of the load ratio is observed between the two orientations, which suggests that the ZXY orientation suffers from crack closure effects that may more negatively influence its fatigue behaviour.

ACKNOWLEDGEMENTS

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REFERENCES

Minimum Mould Thickness Design Specifications For Printed Sand Moulds

C. BEUKES1*, P.J.M VAN TONDER2 AND D.J. DE BEER3

ABSTRACT

While sand printed moulds and cores have been used in the foundry industry for large complex parts, no minimum design specifications for sand moulds with regards to the casting process exist. This may influence the design of complex geometrical parts since modern parts are testing the boundaries of traditional manufacturing methods like sand casting15. This research paper will determine the minimum mould thickness specifications for designing 3D printed sand moulds with regards to the external factors introduced during the metal casting process.

1. INTRODUCTION

With the geometrical complexity of modern parts designed using topology optimisation and other computer assisted design methods, traditional sand casting is becoming obsolete due to the limitations of the process. The high cost and size limitations of direct metal additive manufacturing technologies limit the mass production of most modern parts. This creates a need for a less expensive manufacturing method to mass produce complex metal parts. A study analysing 3D printed moulds did revise the design parameters for parts with regards to the capabilities of printers, however no specifications for the casting process were made22. Parameters such as the minimum wall thickness for load bearing walls can be calculated using the theoretical tensile strength of the 3D printed sand moulds, however there is currently no information available on the forces inflicted on the mould during the casting process.

This study aims to quantify the forces experienced during the casting process to determine a minimum wall thickness parameter set for 3D printed moulds and cores.

2. METHODOLOGY

The study has been divided into three sections. Firstly, test samples were printed on a Voxeljet 1000 and exposed to two different curing conditions followed tensile tests. Initially the samples would have been exposed to three curing conditions and various characterisation tests however due to unexpected failures during printing, the samples size have been reduced and only the most important conditions could be tested. The first set of samples were baked at 100̊ C for 1 hour while the second set of samples were baked at 100̊ C for 16 hours. Tensile strength test performed on the test bars reviled a mean tensile strength of 69 N/cm² for the baked samples and 47 N/cm² for the extended baked samples. These values are validated by previous studies34.

Secondly the forces experienced by the mould during the casting process were established theoretically. The pressure exerted on the mould by the metal during the casting process and the initial impulse of the metal entering the mould are estimated to be the critical forces to be considered. It can be assumed that all internal thin walls will be surrounded by metal once fully submerged in metal. This limits the forces experienced by the mould to only compression force. The resulting pressure applied by the metal will be distributed evenly at any given height resulting in no bending moments from pressure applied to the mould5.

Regarding the initial impulse exerted by the metal during pouring, Mould design guidelines prohibits un-even filing of a casting to reduce surface defects on the final product6. Any initial impels experienced by internal thin walls will therefore be

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replaced by an even pressure exerted on both sides quickly to achieve an even filling. Method design guidelines for castings aims to reduce the velocity in the ingate to 0.5 m/s regardless of the total velocity gained by the acceleration due to the pouring height experienced by the metal. Therefore, the following values have been assumed: Exposure time 0.5-1 second and a maximum impact velocity of 0.5 m/s

Lastly these results and values have been validated using Magmasoft v5.3. Various moulds have been simulated to ensure the correct forces were applied to the design criteria. The Magma simulations verified the 0.5 m/s flow after the ingate, however due to the large increase in cross-sectional area after the ingate the velocity decreases to an average of 0.2 m/s while flowing though the casting. This results in the forces experienced by the mould due to the casting process is negligibly small compared to the conditions the mould experiences during cleaning[3].

3. CONCLUSIONS

If a casting’s method has been designed correctly then the forces experienced by the mould during the casting process is negligible when compared to the forces inflicted during preparation and handling of the mould. The values for minimum strength requirements is therefore seen as the critical values for minimum wall thickness. Further investigation is needed to determine if sudden changes in cross sectional areas in the casting geometry can cause enough of an acceleration to consider the velocity of the metal a critical value. However due to the large range of variables involved in a casting, it could be beneficial to develop a design guideline for castings rather than define minimum ranges for mould thickness from the perspective of the casting process.

REFERENCES


Determining The Effect Of Three-Dimensional Printing Orientation On The Bending Strength Of Sand Moulds And Cores When Using A Voxeljet Additive Manufacturing Machine

JJ LA GRANGE2, K. NYEMBWE1, PJ M VAN TONDER2, DJ DE BEER3 AND T VAN WYK2

ABSTRACT

Ideally, the mechanical properties of sand moulds and cores produced by three-dimensional printing have to be uniform throughout the part. This will ensure that the casting produced from the sand moulds or cores have uniform properties. The study investigated the effect which the printing orientation has on the bending strength of printed parts. The three printing orientations, x, y and z, were considered in the investigation. Descriptive and inferential statistics was used to assess and interpret the consistency of the bending strength in additive manufactured parts.

1. INTRODUCTION

Additive manufacturing (AM) processes like three dimensional sand printing offers an alternative to the conventional manufacturing of moulds and cores. AM processes can be applied as a substitution or in combination with conventional processes. Literature showed that foundry men do have concerns with printed moulds and cores due to the low forming efficiency, weak metallurgical connection between layers and inferior mechanical properties. In addition to the above mentioned concerns, the cost of printing sand moulds and cores was also identified as a possible technology uptake inhibitor due to high printing costs. Decision makers in foundries do not necessarily have discrete criteria to evaluate the economic feasibility of using printed sand moulds and cores, especially with complex geometry castings.

Previous research showed that the mechanical properties of sand samples printed in the same build on a Voxeljet VX1000 three dimensional sand printer were not consistent when analysed. In addition it was found that the building orientation of parts has an influence on the printed part’s bending strength. Mould strength needs to be constant as it could cause casting failures. This study therefore aims to determine the variation of bending strength that exist within the building envelope.

The results of this study will lead to the determination of the best strategy to place a part in the building envelope to ensure that the bending strength has the highest probability of being consistent.

2. METHODOLOGY

A Voxeljet VX1000 was used in this study, with a printing layer thickness of 300µm. The study was limited to silica sand received from the OEM. The sand was pre-coated with a sulphonic acid activator by the OEM.

The build envelope of the Voxeljet VX1000 is 1080mm (X) X 600mm (Y) X 500mm (z). The full build envelope of the Voxeljet VX1000 was considered to investigate the possible variation of bending strength of parts printed within a single build process. Test specimens were placed at different orientation and angles throughout the building envelope. The specimens conformed to the recommendations of the American Foundry Society (AFS).

The specimens were cured at 110oC for 2 hours to ensure maximum part strength to determine the bending strength.

The test results was analysed using statistical analysis software and included determination of central tendency, and measures of variability of the different print orientations and angles. The results were shown in the form of box plots and histograms.
3. CONCLUSION

The study investigated the variance of the bend strength of printed components at different print orientations and angles. This may lead to further studies and or recommendations on the placement and orientation of parts within the building envelope.

The obtained data could also be used to compare bend strength of printed sand moulds to sand moulds manufactured using traditional methods and could be used to compile a quality assurance framework.

REFERENCES


Sulfonic Acid Coating Of Refractory Sand For Three-Dimensional Printing Applications

O. DADY1, K. NYEMBWE2 AND M. VAN TONER3

ABSTRACT

Applications of three-dimensional printing to metal casting include the fabrication of sand moulds and cores. Commercial additive manufacturing systems are based on the furan process. In this case, a specially manufactured material consisting of sulphonic acid coated sand is used during additive manufacturing. The present paper investigated the sulphonic acid coating process of selected refractory sands under various experimental conditions including catalyst addition and time. Sand testing specimens are three-dimensionally printed and the resulting properties assessed for mechanical properties.

1. INTRODUCTION

Three dimensional technology in foundry industry compared to the conventional method of manufacturing parts comprises printing of moulds and cores using various siliceous and non-siliceous refractory materials such silica sand, chromite sand, olivine sand, synthetic sand, etc. Particle size, clay content, pH level, acid demand, acid demand value, refractoriness, surface morphology, angularity are key properties required in the traditional manufacturing as it also applies for the sand for additive manufacturing to have these essential characteristics [1]. Property as flowability has crucially influence in the material selection in the additive manufacturing which determines the manner by which sand particles are deposited during three dimensional. This research focuses on material preparation consisting of coating different foundry sand with sulfonic acid. In the idea of material preparation aiming to coat the sand a pre-assessment of flowability analysis from an optimization process was conducted using local silica sand and a chromite. Different batch sands were prepared while varying the sulfonic acid content in each mix respectively 0.2 to 0.7%. The Flowability was measured by calculating the angle of repose formed by the free flow of sand on a cylindrical support and multiple images were taken by the use a camera focusing on the position of the interface sand/air.

The higher the angle of repose; the poorer the flowability of the granular material. Based on the experimental data silica sand with 0.2% sulfonic acid addition yielded the lowest angle of repose with 35° compared to chromite sand with 36° with relatively same sulfonic acid content. Lumay et al suggested that a powder material with an angle of repose between 25-30° is regarded as a material with an excellent flowability [2].

2. METHODOLOGY AND RESULTS

2.1. Experimental procedure

The raw materials used in the experimental work were local sands and a sulfonic acid. Two types of sands were used during the coating process, silica sand and chromite sand. The following steps were conducted in the methodology.

- Samples of silica sand and chromite sand from local supplier.
- Sand characterisation for size distribution, relative density, grain shape and pH.
- Angle of repose

2.2. Grain Morphology

![Figure 1: Shows the grain shape of the different type of sands obtained by stereo microscope.](image-url)
2.3. Particle size distribution

![Particle size distribution chart]

Figure 2 shows the sands grain size distributions obtained with a particle size distribution analyser (Fritta).

2.4. Sand classification

<table>
<thead>
<tr>
<th>Properties</th>
<th>New silica sand</th>
<th>New chromite sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.91</td>
<td>7.13</td>
</tr>
<tr>
<td>Size distribution</td>
<td>57.0</td>
<td>44.0</td>
</tr>
<tr>
<td>Relative density</td>
<td>2.62g/cc</td>
<td>4.63g/cc</td>
</tr>
<tr>
<td>Bulk density</td>
<td>1.52g/cm³</td>
<td>2.75g/cm³</td>
</tr>
<tr>
<td>Average grain size</td>
<td>150μm</td>
<td>300μm</td>
</tr>
</tbody>
</table>

2.5. Angle of repose

<table>
<thead>
<tr>
<th>% Mix</th>
<th>Silica Sand</th>
<th>Chromite sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>35</td>
<td>36</td>
</tr>
<tr>
<td>0.3</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td>0.5</td>
<td>38</td>
<td>44</td>
</tr>
</tbody>
</table>

3. CONCLUSION

The initial test results of the flowability properties indicates that increase in sand flowability with decreased in the amount of sulfonic acid in the sand assembly due to the fact the presence of humidity caused by the acid negatively affecting the sand particles mobility. The particle size also has a direct influence on the granular mobility. Silica sand being fine with smaller particles stick to each other and are able to form some cohesive bridges between them as result the angle of repose decrease. On the other hand, chromite being coarser yields an opposite behaviour. In addition, grain shape and the density of the material have direct relationship also. Rounded particles are less dense and will have a high mobility, preventing the piling up of material particles. Therefore silica sand has demonstrated a better flowability than chromite sand.

REFERENCES


**Wireless Sensor Detection of Casting Core Shift within 3D Printed Sand Molds**

ERIC MACDONALD², JASON WALKER, KIRK ROGERS³ AND BRETT CONNER²

**ABSTRACT**

Additive manufacturing is revolutionising sand casting with the use of binder jetting technology to create sand moulds with complex geometries. However, an increase in complexity leads to challenges in terms of understanding both the thermodynamics of the casting process. In situ sensor data is required for process monitoring with sensors (Internet of Things) within moulds to enable collecting data at difficult to access locations. Core shifts within moulds, high pressures affecting surface finish of castings and even magnetic fields can be monitored - all to improve quality. Core floating was detected in the presented experiment.

**1. INTRODUCTION**

Additive manufacturing (AM) or 3D printing emerged as a new manufacturing method since the 1980s, but has generally been limited to production of prototypes. However, the benefits of 3D printing for the casting industry were identified early [1]. The capability to fabricate complex part geometries using layer-by-layer deposition as opposed to traditional subtractive manufacturing now enables production of moulds, cores, and patterns that would be otherwise impossible to create without 3D printing. One important use of AM in the casting industry is 3D printed sand moulds which provide complex cavities, good dimensional accuracies, the ability to insert components within the casting and/or mould, and an increased freedom in the design of the metal delivery system (gating, sprue, risers, etc.). While the inherent benefit of AM-enabled casting is the freedom of geometry, the accompanying challenge is the increased complexity of the casting process and potential reduction in part manufacturability. To overcome the challenges, casting simulations are required to predict the flow of metal potentially causing entrapment of gases or erosion of sand from interior surfaces. In the context of 3D printed moulds, simulations are required with the nearly unlimited design freedom enabled by 3D printed moulds. Furthermore, the resulting complex surfaces of the cavity within the mould can lead to difficult-to-predict heat dissipation which directly affects solidification.

The presented effort included leveraging an “Internet of Things” strategy for non-traditional sensing of AM-enabled castings (a) in moulds and (b) in a core in order to collect data to fuel the analytics necessary to advance in situ evaluation, model validation, and casting qualification. In addition to modelling, comprehensive collection process data has been shown to validate simulation [2-3], in situ quality control can provide immediate feedback and possibly support the qualification of casting designs and mould printing processes (rather than Edisonian methodologies). IoT Sensor systems were used in this study that included an ARM processor, a low power Bluetooth radio which can allow for the collection of data in difficult-to-reach positions within a sand mould or core and include sensing for:

1. Three axes of magnetic field,
2. An inertial measurement unit providing three axes each of rotation and acceleration, and
3. An environmental sensor with relative humidity, pressure, and temperature.

**2. METHODOLOGY AND RESULTS**

The sensor used in this experiment included an inertial measurement unit which captured three axes of acceleration and was capped and glued into a suspended core of a cast bell. The data of the accelerometer is presented in Figure 1 and the vertical dashed line shows the time at which the pour began. Several seconds after the start of the pour, the metal filled the cavity and resulted in the core floating. The resulting motion of the core was registered with the accelerometer. Near the end of the time plotted, additional accelerations are manifest indicating movement; however, as these measurements are taken as the temperature of the sensor begins to exceed the operating temperature, these final motions are suspect and could be a result of the inertial measurement unit beginning to fail due to the harsh conditions. Understanding the behaviour as seen in the last minute will be the focus of future work.

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REFERENCES


Figure 1: Accelerometer data indicating core float in bell casting

Figure 2 shows the top of the mould at the start and finish of the casting. In the left picture, the cap covering a sensor buried within is shown and the right picture shows the resulting core shift (floating) that caused unintentional thickening of the bell and consequently a defective casting.

3. CONCLUSION

The age-old process of sand casting stands to benefit from both additive manufacturing as well as the Industrial Internet of Things. With today's wireless sensor systems, data from deep within moulds and cores are now available, particularly when paired with the design and manufacturing freedom afforded by 3D printing. This study has demonstrated the utility of leveraging 3D printing to enable the process monitoring of internal cores providing negative features in castings like the interior of a bell. In the demonstration, core shift was manifest externally with video as the core floated during the metal filling of the internal cavity. Simultaneously, the shift was also detected by internal disposable sensors as data was collected for as much as three minutes after the beginning of the pour. The collected data corroborated the video data and demonstrated immediately that the casting had failed.

REFERENCES


Boosting AM Performance In Powder Bed Fusion Processes With Simulation-Guided Optimisation

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ABSTRACT

Powder bed fusion processes are increasingly used to produce both metal and polymeric functional products. However, the most challenging designs still require several iterations before finding the best printing conditions and need to be repeated with different build setups until the designs can be printed successfully. In this context, simulation plays an increasingly important role for those looking for assistance to reduce residual scrap rate and accelerate the manufacturing process. In this work, the benefits of using pre-build simulation-driven approaches are demonstrated on several case studies for both Laser Sintering of PA12 and Selective Laser Melting of Ti6Al4V. The insights derived from the simulations are validated via X-ray Computed Tomography.

1. INTRODUCTION

Manufacturing highly complex structures combined with geometric freedom is a unique capability of Additive Manufacturing (AM) technologies. Among them, the powder based applications such as Laser Sintering (LS) and Selective Laser Melting (SLM) have reached the highest technological readiness levels and are increasingly used to produce both metal and plastic functional parts. Often the manufactured products are used in high-end industries like automotive, biomedical and aerospace, which have very demanding requirements in terms of material properties such as porosity, stiffness and strength, but also in terms of dimensional accuracy, lead times and costs. Depending on the complexity of the part, the development efforts necessary to meet the quality and functional requirements can be very different, with the most challenging designs often requiring several tests and printing iterations. Within an industrial environment, a delayed process optimisation translates into economic losses due both to the high costs of the prolonged testing phase and the missed sales opportunities. Moreover, in certain cases, even when the manufacturing procedure is defined, a high number of parts is still scrapped due to the difficulties in keeping the various steps of the production workflow under control and consistently meeting the quality requirements. By analysing data from different steps in the AM process, it is possible to find manufacturing settings that allow users to print parts within the requirements, but at the lowest cost possible. This, however, requires specific skills mastered only by highly skilled AM engineers. User-friendly AM process simulations can significantly help to reduce the skillset required to optimise the printing process, reducing at the same time the number of prototypes required in the development phase. In fact such simulations offer an opportunity to carry out ‘virtual tests’, minimizing the trial and error approach which is a common pitfall in AM. In this work, the benefits of using pre-build simulation-driven approaches to optimise the printing process and reduce the scrap rate are demonstrated on several case studies for both LS of PA12 (e.g. insole and grippers) and SLM of Ti6Al4V (e.g. bike crank). For the Laser Sintering of PA12 the approach followed is the one described in [2-3], where the energy distributed on the build platform while building the part is assessed prior to print and adjusted accordingly in order to maximise the quality output. For the Selective Laser Melting of Ti6Al4V, the new Magics metal simulation [4] will be used, which is based on Simufact technology [5]. The quality insights provided by the different pre-build simulation approaches are compared with X-ray Computed Tomography data of the actual printed part to validate the prediction made.

2. METHODOLOGY & RESULTS

2.1. Methodology

2.1.1. Sample production

All the builds have been prepared using Magics v22 [4] and sliced using the StandardSLx Build Processor v2.3 [6]. All LS-PA12 samples investigated in this study are produced in a state-of-the-art LS machine equipped with the Materialise Control Platform (MCP) [2] using a PA2200 PA12 powder.
(EOS GmbH) with a mixing ratio of 50/50 between virgin and recycled powder, and a layer thickness of 120 µm. All SLM-Ti6Al4V samples investigated in this study are produced in a state-of-the-art SLM machine equipped with the Materialise Control Platform (MCP) \(^7\) using a Ti6Al4V powder using a layer thickness of 30 µm.

### 2.1.2. Simulation

For the assessment of the processing conditions while building a part, the Build Processor framework incorporates technology which allows to visualise the distribution of the energy on the platform of the 3D printer while building a part. This method, which is described in \(^2\)\(^{-3}\) will be used to assess the LS-PA12 parts. Such method will soon be incorporated in several Materialise software programs. For the assessment of the SLM-Ti6Al4V the new Magics metal simulation \(^4\) will be used, which is based on the Simufact technology \(^5\).

### 2.1.3. X-ray Computed Tomography

X-ray CT was used to investigate both the internal and external structure of the printed parts. The CT scans were performed using a 225 kV CT machine from Nikon Metrology. The datasets were reconstructed using CT Pro 3D (Nikon Metrology NV) and analysed using VGstudio max v3.0 (Volume Graphics GmbH).

### 2.2. Results

Figures 1 and 2 show the comparison between the simulated and the CT scan of the parts produced respectively via LS (PA12 - insole) and SLM (Ti6Al4V - bike crank).

### 3. CONCLUSION

The results shown highlight how a pre-build process simulation approach can foresee the result of the manufacturing process. This offers the opportunity to optimise the process without actually printing the part, reducing the scrap rate and the costs associated with the development phase.

### REFERENCES


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