RAPDASA
Rapid Product Development Association of South Africa

THE HEART OF 4.0

19th ANNUAL CONFERENCE

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

6 - 9 NOV 2018
Protea Parktonian, Braamfontein, Johannesburg

Conference Proceedings

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FOREWORD & WELCOME

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
FOREWORD FROM THE TECHNICAL CHAIR

The theme of this 19th Annual International RAPDASA conference is Additive Manufacturing (AM) as a key driver of the 4th industrial revolution. The choice of this theme matches the transition time that the entire world is experiencing from the 3rd industrial revolution characterised by the digital emergence to the 4th industrial revolution of which AM is among the salient technologies.

This year conference intends to highlight and share progress and development through the various research projects and initiatives currently undertaken worldwide and in South Africa in particular about AM steering the 4th Industrial revolution.

Following a rigorous double-blind peer review process, twenty-nine scholarly articles meeting the criteria of innovation and scientific contribution to the field of AM were selected from fifty-two submissions. These papers contained in these conference proceedings illustrate fundamental research and applications of AM spanning numerous disciplines inter alia, medicine, engineering, art and design. The studies foster advancement and competitiveness of human activities and endeavours in the age of the 4th industrial revolution.

The collection of papers in these proceedings is also a testimony of the vibrancy of AM in South Africa. As such, the country positions itself to fully embrace the 4th industrial revolution. In addition, the papers adequately respond to the objectives of the South African AM strategy developed in 2016.

Continued success and progress are wished to the Additive Manufacturing community of researchers, academics and practitioners in South Africa.

Prof K Nyembwe  
Technical Chair  
2018 RAPDASA International Conference
A formal “Call for papers” for the 19th Annual International RAPDASA Conference was issued in April 2018 to submit an ‘Extended Abstract’ within the identified tracks/themes. Extended Abstract submissions were subjected to an internal reviewing process, whereby successful submissions were notified and invited for presentation to the conference. Authors were subsequently invited to submit an optional ‘Full Paper’, which was published as a conference proceeding. Both the Extended Abstracts and Full Papers were submitted online through the RAPDASA submission page www.rapdasa.org/conference where acknowledgement of receipt was sent to authors. Authors were informed that a double-blind review process is applied to Full Paper submissions.

The following dates were set by the technical committee:

- Call for papers: 15th April 2018
- Submission of extended abstracts (2 pages): 31st May 2018
- Notification of acceptance of abstracts: 5th June 2018
- Submission of full papers: 16th July 2018
- Feedback on paper reviews: 17th August 2018
- Revised paper submissions: 17th September 2018
- Selected papers to be submitted to SAJIE: 30th September 2018

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

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

A double-blind reviewing process was used for the Full Paper submissions. As such, both the reviewer and author identities were concealed from the reviewers, and vice versa, throughout the review process. Each Full Paper submission was sent to a minimum of two reviewers, with a third reviewer being requested in case of non-consensus between the first two reviewers. The reviews were completed by national and international academics, and experts in the respective field, listed on the Technical Committee page.

A total of 32 reviewers participated in the review process, each reviewing on average between two and three papers. Reviewers were asked to review submissions according to the following criteria and were encouraged to provide recommendations and suggestions.

- Does the title reflect the contents of the paper?
• Does the paper relate to what has already been written in the field?

• Do you deem the paper to be proof of thorough research and knowledge of the most recent literature in the field of study?

• Is the paper clearly structured, easy to read and with a logical flow of thought?

• Are the arguments employed valid and supported by the evidence presented?

• Are the conclusions clear and valid?

• Does the paper conform to accepted standards of language and style?

• Any other recommendation(s)?

• Select reviewer recommendation: ‘Accept Submission’, ‘Revision Required’, or ‘Decline Submission’.

Reviewer feedback was saved on the submission system, where acceptance emails together with review comments were sent to the authors, allowing them to revise the submission. The authors were given between 2 and 4 weeks to incorporate changes, after which the final document was submitted for approval and publication as a conference proceeding.

Full papers were accepted under the following themes:

• Additive Manufacturing business developments / New Additive Manufacturing applications.

• Impact of Additive Manufacturing on the intellectual property environment.

• Design for Additive Manufacturing.

• Reverse engineering.

• Internet of things.

• Simulation and modelling.

• Process monitoring and control.

• Material evaluation and selection.

• Post processing and qualification.

• Material / Process development.

• Product development.

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

Prof Kasongo Didier Nyembwe (Technical Chair, Track Director - Simulation and Modelling)

Prof Thorsten Becker (Chairman of Rapdasa, Track Director - Material Evaluation and Selection and Material/Process Development)

Prof Andre Francois van der Merwe (Track Director - Additive Manufacturing Business Development / New Additive Manufacturing Application and Impact of Additive Manufacturing on the Intellectual Property)

Dr Kobus van der Walt (Track Director - Design for Additive Manufacturing and Internet of Things)

Dr Malan van Tonder (Track Director - Process Monitoring and Control and Post Processing and Qualification)

Ms Dalmari Mc Queen (Track Director - Product Development)

Reviewers:
Dr Chris Aggenbacht
Prof Ian Campbell
Mr Jacques Combrinck
Prof Lesley Cornish
Prof Oliver Damm
Prof Deon Johan De Beer
Prof Olaf Diegel
Mr Francois du Rand
Mr Johan Els
Dr Mutiu Erinosho
Mr Devon Hagedorn-Hansen
Mr Sarel Havenga
Prof Masengo Ilunga
Mr Cornelius Petrus Koppers
Prof Robert Knutsen
Prof Eric MacDonald

Dr Daniel Madyira
Mr David Mauchline
Dr Ntokozo Mthembu
Prof Antoine Mulaba
Prof Kasono Didier Nyembwe
Mr Filipe Peirera
Mr Marinus Potgieter
Mr Ruaan Schoeman
Mr Gerrit Matthys Ter Haar
Dr Kobus van der Walt
Dr Malan van Tonder
Mr Kim Vanmeensel
Mr Marius Vermeulen
Prof George Vicatos
Dr Ina Yadroitseva
Prof Igor Yadroitsev
# Pre-Conference Seminar on Additive Manufacturing of Titanium Parts

**Tuesday 6 November 2018**

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<td>Welcoming Address: Dr Kobus van der Walt CRPM, CUT</td>
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**Theme: ADDITIVE MANUFACTURING OF TITANIUM PARTS**

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<td>10:40</td>
<td>Investigation of microstructural characteristics of heat treated high speed selective laser melting fabricated Ti6Al4V components</td>
<td>P Lekosi, N Malele, M Tloulieng, BN Masina</td>
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<td>Evaluation of hatch distance and powder feed rate effects in Ti6Al4V alloy developed by LMD technique</td>
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<td>11:45</td>
<td>Laser powder bed fusion of SSNi-Ti shape memory alloy for biomedical applications</td>
<td>T Mphafudi, TC Dzogbewu, HK Chikwanda, I Yadroitsev</td>
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Hosted by Central University of Technology, Free State. Supported by the Department of Science and Technology.
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<td>Electro Optical Systems - Regional Director: Export North EOS GmbH - Dr. Jose Cresset</td>
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<td>Venue: Meridians room</td>
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<tr>
<td>11:00</td>
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<td>Eric MacDonald</td>
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<td>13:00</td>
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MACHINE LEARNING IN ADDITIVE MANUFACTURING AS ENabler FOR SMART SUSTAINABLE MANUFACTURING: A REVIEW

A. du Preez and G.A. Oosthuizen

ABSTRACT

Machine learning (ML) is becoming an increasingly popular concept since its main goal is to optimize 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, minimized cost, etc. It simultaneously enables systems to be designed for managing human behaviour. This study used a systematic review to investigate the different ML algorithms applied to additive manufacturing within the sustainable manufacturing context. The findings include different ML techniques which have been applied to additive manufacturing processes and ML trends in these processes.

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1. **INTRODUCTION**

Additive manufacturing (AM) processes are processes which utilize 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], without tooling or human intervention [2]. The material which can be used, include plastic, metal and concrete. The material is used in various forms, including liquid, power, sheet or wire [3]. Additive manufacturing produces high quality 3D products with complex geometries in minimum lead time [4]. Additive manufacturing is also known as rapid prototyping [5].

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. Quality within the AM industry include improved surface finish, minimized support structures, increased structural strength, increased stiffness, reduced warp deformation, increased dimensional accuracy, etc. The paper focuses on machine learning applications in additive manufacturing. Firstly, the methodology is discussed followed by machine learning techniques and their applications in the industry.

2. **METHODOLOGY**

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 [6]. A systematic review makes use of a pre-specified criteria to collect, evaluate and summarize the collected empirical evidence and research to answer a well-defined research question.

The research question for this study is: what are the different ML algorithms which have been applied to AM and what are the trends in these applications.

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 quality assurance, optimized processes, etc. The literature review covers full papers from 2000 to 2018 which are selected according to the criteria provided in Table 1. The template was created by [7] and modifications were added by the author.

<table>
<thead>
<tr>
<th>Criteria</th>
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<td>Specific process</td>
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<td>Purpose of the study</td>
<td>Scheduling, process chains, quality assurance</td>
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<td>Keywords</td>
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</tr>
<tr>
<td>Date of publication</td>
<td>January 2000 - April 2018</td>
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Every paper was further analyzed and the following data about each was extracted: title of the paper, year published, the specific additive manufacturing process (ex. fused deposition modelling), the purpose of the study (scheduling, process chains, quality assurance), the machine learning algorithm(s) used, input variables and output variables. This data is used to fulfil the objectives of the study.

In the following section the results and findings of the literature review is presented.

3. **FINDINGS**

3.1 **Machine learning techniques**

A variety of machine learning techniques have been applied in the research. The most popular methods include neural networks (NNs), genetic algorithm (GA), regression modelling, response surface methodology (RSM), and fuzzy inference systems (FIS). Less common methods include support vector machines (SVMs), simulated annealing (SA), finite element analysis (FEM) [8], etc. Hybrid or combinations of machine learning techniques have also been applied.

3.1.1 **Neural networks**

A neural network (NN) or artificial neural network (ANN) is an arrangement of statistical algorithms which structure is based on the biological brain patterns found in human brains. NNs are used to identify and create the non-linear mathematical relationships between input variables and the output variable(s). NNs are applied to classification, estimation, simulation and prediction problems [1].

A NN is an interconnected parallel network consisting of 3 or more parallel layers: input layer, hidden layer(s) and output layer. Each layer consists of parallel neurons, which uses weights, biases and transfer or activation...
functions to create a model which best describe the non-linear relationship between the input and output variables. The input layer has a number of neurons equal to the number of input variables and the same holds for the output layer and output variables. The transfer functions (also called neuron functions) are mathematical functions and examples include sigmoid-logistic [9], linear [10], tangent-sigmoidal [11] [12], hyperbolic trigonometry, exponential [1] and Gaussian [13] activation functions. Figure 1 shows the structure of a basic NN. Network parameters include the number of training and testing data, learning rate, number of hidden layers and neuron function used and they have an effect on the accuracy, reliability, effectiveness and computational load of the neural network [1]. A variety of NNS are available, including back propagation NN (BPNN), feed-forward NN (FFNN) or multi-layer perceptrons, general regression NN (GRNN) [13], recurrent NN (RNN) and radial basis function NN (RBFNN). The self-organization feature map (SOP) [14] is a variant of a NN. With some NNS, including back-propagation NN (BPNN) and recurrent NN (LRNN), the output or part of the output of the hidden layer is fed into to hidden layer as input, thus creating a feedback loop.

Figure 1. A basic feed-forward neural network.

To develop and apply a neural network, three sequential processes occur: training, validation and testing. The neural network must be trained to determine the most applicable weights and biases to model the non-linear input-output relationships. The training includes multiple simulations of the NN consisting of different combinations of the number of neurons in the hidden layer and the number of delays in the feedback. Various training algorithms exist including the Bayesian regulation [11], Levenberg-Marquardt algorithm [12], resilient gradient descent [10], Conjugate Gradient Descent (CGD), and Bayesian Inference (BI). Next, the neural network is validated using validation data to determine whether it models the non-linear relationship between the variables accurately or within acceptable limits. Usually minimized error is used to validate the NN. Different statistical measures are used to determine the error of the net, for example Mean Absolute Percentage Error (MAPE), mean square error (MSE), root mean square error (RMSE), Regression value or coefficient of determination (R or R²), multi-objective error function (MO) [9] and maximum/average relative error. Lastly the neural network is applied to the test data to determine the answer to the research question for which it was developed. The test data also measures the final performance of the NN.

Various algorithms are available to assist during the development of the NN. The Kennard-and-stone algorithm can be applied to assist in selecting proper training and validation datasets [13]. The Back-propagation through time (BPTT) enables the RNN to increase its convergence speed. The Nguyen- Widrow algorithm helps decrease training time by providing a method for determining the initial weights of the NN [1]. Bayesian regularization [11] can be used during the training stage to skip the validation stage[15].

3.1.2 Genetic algorithm

The genetic algorithm (GA) is an evolutionary algorithm based on Darwin’s theory of natural selection and evolution [13]. At the start an initial population consisting of chromosomes (feasible solutions) is randomly generated. Each individual or solution is evaluated according to the fitness function. The fitness or objective function is a user specified criteria which determines the output variable value of a solution given its input variable characteristics (its genes) [16]. Three primary genetic operations occur to create the next generation or population in order to explore the solution space: reproduction, crossover and mutation.

During reproduction parent chromosomes are randomly selected or selected according to their fitness value, to create offspring and they are duplicated [13]. Crossover is the process where genetic material is exchanged between the two duplicated parents by randomly selecting a crossover point and swapping their ‘genes’ to create two offspring which are different from the parents. Single-point or multi-point crossover can occur. During mutation a random chromosome and random mutation point on the chromosome is selected. The value of the
selected ‘gene’ is then altered or in the case of binary ‘genes’ a 1 becomes a 0 and vice versa. Figure 2 shows the genetic algorithm and the processes of crossover and mutation. The elitist members of the current population, the non-dominated chromosomes, are selected and added, together with the offspring (some are mutated), to create the next population. GA parameters include mutation probabilities, mutation rate, crossover point probabilities, crossover rate, reproduction probabilities, reproduction rate, elitism number (number of good solutions in current population which are transferred to next population), population size number of generations, etc.

Variations on the GA are available, including genetic programming (GP), gene expression programming (GEP) [17], multi-gene GP (MGGP) [18], non-dominated sorting genetic algorithm (NSGA) and particle swarm optimization (PSO) [19]. The key difference between GA and PG are the following: GA evolves fixed length binary or real valued strings while GP evolves tree structures called models which can vary in length throughout the evolution [2]. GA works with chromosomes while GP works with computer programs (mathematical formulas, computer programs, logical expressions, etc.). GP also incorporates genetic operators like gene/tree duplication and deletion [13]. GEP is developed from GP and the only modification is that models are represented in Expression Trees (linear structure) which simplifies the diversity of the tree population [17]. MGGP is a variant of GP where each evolved model is a combination of trees/genes whereas in GP, each evolved model is a single tree/gene.

The NSGA is a variation of the GA, developed for multi-objective optimization problems, where groups or fronts of non-dominated optimal solutions are determined by using the rank of the group, the crowding distance and the fitness value. All the solutions are evaluated, and the first front is the group of non-dominated optimal solutions (solutions which are equally good compared to other solutions from the same front). This process is called the first sorting and the non-dominated solutions are given a rank of 1. During the second sorting the remaining solutions are evaluated with the same process and this process repeats until all the solutions have been given a rank [20].

The PSO was developed to solve continuous optimization problems. The algorithm is based on the foraging behavior of a swarm of birds or fish. It enables the competition model using GA and ensures cooperative behavior among individuals (birds or fish) [19]. The population is called the swarm and it is composed of volume-less particles (feasible solutions) with stochastic velocities (a vector of independent variables). For each generation the global best solution and the best solution so far of every particle is recorded to determine the new velocities of each particle in the next generation. The new velocities also depend on the previous velocity of the particle, the cognitive learning parameter (the confidence the particle has in itself), the social learning parameter (the confidence the particle has in the swarm) and the inertia weight (controls the search skills of the swarm). The velocity updating formula is available in [21] and the algorithm steps in [22]. The algorithm finds the optimal solution by letting the particles ‘fly’ through the solution space. PSO parameters include swarm size, generation limit, maximum global velocity, maximum particle velocities, inertia weight, social and cognitive parameters.

### Other machine learning algorithms

Other evolutionary and swarm intelligence-based algorithms include bidirectional evolutionary structural optimization (BESO) [23], bacteria foraging optimization algorithm (BFOA) [24] [25], mutable smart bee algorithm (MSBA) [26], quantum-behaved particle swarm optimization (QPSO) [27] and differential evolution (DE) [14]. Additional classification approaches include decision tree (DT), k-nearest neighbor (KNN), support vector machine (SVM) [28], Linear Discriminant Analysis (LDA), and Quadratic Discriminant Analysis (QDA) [29].

Further learning methods include grey relational analysis [5], random order heuristic [30], cross-coupled path pre-compensation (CCPP) algorithm [31], Graph theory [32], gradient descend algorithm [33], geometric algorithm [34], simulated annealing (SA) [30], adaptations of the solid isotropic material with penalization
algorithm (SIMP) [35], fuzzy logic [36] [37], finite element analysis (FEA) or finite element method (FEM) [38],
regression modelling [39] and response surface methodology (RSM) [40].
Hybrid models include a combination of fuzzy inference system and a neural network, called adaptive neuro
fuzzy inference system (ANFIS) [41]. An ANN (to model the problem) and GA (to optimize the problem) have been
combined in [42].

3.2 Machine learning applications in additive manufacturing
Traditionally, process parameters are determined by the operator’s experience [1], the conservative technological
data provided by the additive manufacturing equipment manufacturers [9] and trial-and-error operations. This
leads to inconsistent machining performance since operator’s experience is limited and subjective while the
manufacturer data is based on safety-conscious principles and it only includes applications on certain machining
materials. New materials are constantly developed, for example titanium alloys, aluminum alloys, advanced
plastics, etc. Trial-and-error operations employ post-process techniques to inspect the quality of the finished
product [1]. This methodology includes a range of disadvantages: it is costly, time-consuming and it leads to
numerous defective and useless products which are only discovered once the process has been completed.

Machine learning addresses these resource efficiency challenges by determining the optimal process parameters
given an objective(s) through simulations without repeatedly producing physical products. Machine learning also
increases sustainability since it leads to the permanent availability of uniform, objective AM process knowledge
(manufacturers do not have to hire costly consultants repeatedly), it enables manufacturers to optimally benefit
from their machining equipment without the acquisition of new costly, carbon-footprint related equipment and
it reduces the usage of valuable resources including time, money, energy and natural resources. Machine learning
also enables product safety, since it can be used proactively to allow one to view the AM parameters before
application. Thus harmful or inadequate parameters can be identified before the process started.

Machine learning algorithms have been applied to a variety of additive manufacturing process types including 3D
printing (3DP), directed energy deposition (DED) [43], electron beam melting/manufacturing (EBM), fused
deposition modelling (FDM), laser engineered net shaping (LENS), laminated object manufacturing (LOM),
stereolithography (SLA), selective laser cladding (SLC), selective laser melting (SLM), selective laser sintering
(SLS) and wire + arc additive layer manufacture (WAALM). Table A in Appendix A provides a detailed summary of
the different additive manufacturing processes and the different machine learning algorithms applied in these
processes, according to the review. Fig. 3. illustrates the additive manufacturing processes supported by machine
learning applications. The percentages indicate the relative ratios. It is evident that FDM is the field in which the
most applications have been applied, followed by SLC, SLS and AM in general applications.

Fig. 3. Additive manufacturing processes supported by machine learning applications.

Fig. 4. illustrates the different types of machine learning algorithms which have been applied in AM processes.
ANNs are the most common application, followed by GA, regression modelling and RSM.
3.3 The process of applying machine learning techniques

From the systematic review, the author learned of the process of applying machine learning techniques in additive manufacturing processes, as illustrated in Fig. 5. The pre-settings on the additive manufacturing machine include the independent variables which the machine operator has control over. The sensors measure the dependent variables, which is a result of the additive manufacturing process and it takes the measurements continuously throughout the process. Pre-processing of the output data of the process include: labelling, dimension reduction techniques and frequency and time-frequency domain signal processing techniques. Labelling is the process of connecting the output value to the corresponding input variables. Labelling would be used in the case of preparing the training data so that the model can learn to accurately predict the objective value, by measuring its error of prediction and adjusting itself to minimize the error. Dimension reduction techniques are used to reduce the dimension of the input data of the machine learning technique by transforming the original data to a smaller dimension while the variance of the original data is preserved. This supports the model by ensuring that it is less computational intensive to develop. Next, the machine learning techniques are applied to the processed data and the resulting information undergoes post-processing. Post-processing of the information includes the validation of the model, testing of the model and comparing the performance of the model to other machine learning models.

4. Conclusion

In the manufacturing industry machine learning can lead to cost savings, time savings, increased quality and waste reduction. At the same time, it enables systems to be designed for managing human behavior. From the systematic review, the author learned of the different machine learning techniques which have been applied to additive manufacturing processes, the machine learning trends in these manufacturing processes and the process of applying machine learning techniques in additive manufacturing processes.

Appendix A. Different cutting processes versus different machine learning algorithms.
The following table shows the different additive manufacturing processes and the machine learning techniques which have been applied in them, per reviewed study. An ‘H’ superscript indicates that the study used a hybrid or combination of machine learning algorithms, while an ‘&’ superscript indicates that various algorithms were compared in the study.

Table A: Different additive manufacturing processes versus different machine learning algorithms.

<table>
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<tr>
<th>Machine learning method</th>
<th>ANN</th>
<th>FEA</th>
<th>Fuzzy</th>
<th>GA</th>
<th>Regression</th>
<th>RSM</th>
<th>SA</th>
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<th>SVM</th>
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REFERENCES


INVESTMENT CASTING OF ALUMINIUM ALLOY A356 USING PRIMECAST® AND PMMA ADDITIVE MANUFACTURING MATERIALS FOR SACRIFICIAL PATTERNS

N.P. Nkhasi1, W.B. du Preez2 and J.G. van der Walt3

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 manufactured using two additive manufacturing technologies and materials, namely PrimCast® and PMMA. Metrology was performed on all the castings through Micro-CT scanning and comparison of different features of the castings from the two types of patterns was done. Dimensional accuracy of the two pattern making approaches are discussed.

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1. INTRODUCTION

1.1 Investment casting

The investment casting process, dates back over 5 000 years to artists and sculptors of ancient Egypt and China [1]. The typical process consists of pattern making, investing (dipping and stuccoing), dewaxing and firing, casting, knock-out, cut-off and, testing and inspection. The term investment casting has been derived from the typical use of mobile slurry to form a hard shell. In this process a sacrificial pattern is coated with refractory ceramic slurry that can set at room temperature to produce a shell mould (or block mould). In order to obtain a good surface finish on the casting, the quality of the coating is important. The coating thickness should also be uniform across all features of the pattern to ensure even heat transfer properties during the casting process. A pattern is needed for every casting to be produced. Cast parts are formed by melting out (or dissolution) of the sacrificial pattern and pouring the molten metal into the mould cavity. After the metal has solidified within the ceramic mould, the ceramic shell is broken away and the casting taken out [2]. Wax was conventionally used to make sacrificial patterns, but in recent times it was found that patterns produced from Additive Manufacturing (AM) technology can also be used, especially during the development stage of new products or in small volume production [3].

1.2 Rapid investment casting

The use of AM sacrificial patterns for investment casting can be referred to as Rapid Investment Casting (RIC). AM sacrificial patterns were first used in 1989 [4]. In RIC the pattern is designed using Computer Aided Design (CAD) software and is then manufactured using an AM machine. Depending on the AM technology used, gates and vents are attached to the pattern. The vents are used to allow steam to enter the pattern during autoclaving and to allow airflow through the mould during burnout replacing oxygen used in combustion [5]. The assembly is then repeatedly dipped in ceramic slurry. The pattern is then melted or burnt out, leaving a cavity in the shape of the part to be cast. A metal alloy is melted, often in an induction furnace, and poured into the preheated shell. After cooling the shell is broken away and the gates and vents are ground off [6]. In RIC a key consideration is pattern modification to prevent shell cracking and minimize residual ash. Ceramic shells have a very low coefficient of thermal expansion, so any expansion of the pattern during the burnout cycle may cause the shell to crack [7]. During the burnout process, the pattern will combust and release some gas. The vents allow the gas to escape during burnout and promote air flow for combustion [8]. Since AM patterns expand more than the traditionally used wax, additional layers of the ceramic slurry are required to minimize shell cracking during the burnout process [9].

The key advantage of RIC is that it eliminates the need for wax tooling for low-volume production typical in prototyping, pre-series, customised or specialised component productions. Injection moulds for wax patterns are expensive and the building of the tool can take four to six weeks. Through using RIC patterns the tooling cost is eliminated and the lead time for a cast part is reduced to just 10 days on average. The ensuing mould preparation and casting process is the same irrespective of how the pattern was produced, be it using conventional wax techniques or RIC technology [10].

From the literature it was found that little research has been done. Initial work done by Dimitrov et al. [4] on rapid pattern making in investment casting of a light metal was found. In their study the comparison between patterns produced from three additive manufacturing technologies namely 3D printing, selective laser sintering and thermojet was done using a coordinate measuring machine (CMM). From the results found with aluminium casting after evaluating the descriptive statistics, features measured and the dimensional accuracy indexed, it was concluded that the selective laser sintering pattern produced the best casting in terms of dimensional accuracy.

A recent article from Tom Mueller [12] compares the patterns and castings from four AM technologies, namely stereolithography (QuickCast™), laser sintering (QuickForm™), Projet printing (Projet Wax™), and binder jetting (PMMA). In the first part of the article he compares the performance of the printers, the second part compares the operating costs and in the last part the four leading methods of creating printed patterns for investment castings are compared. The analysis was based on the author’s experience and it was concluded that there was no single “best” pattern printing technology. For each of the four technologies, applications existed for which they were the best alternative. Clearly, requirements for investment castings vary considerably depending on the application of the casting.

It was also found that there has been significant work done on PMMA [11, 12, 13, 14] and PrimeCast® [4, 8, 9, 15] trying to show that they can replace the lost wax process in investment casting. However, no research was found on direct comparison between the two AM materials for use as sacrificial patterns for investment casting.

1.3 Previous work

In previous work by Nkhasi et al. [16], sacrificial pattern geometry for investment casting that could be built with PrimeCast® and Poly(Methyl Methacrylate) (PMMA) was selected. Comparisons were performed on patterns built in PrimeCast® and PMMA respectively, which were produced using AM technology. The patterns were replicas of the casting to be produced and they did not include allowances for the expansion and contraction which occur
during the casting process. The investment casting patterns built in PrimeCast® were manufactured through laser sintering on an EOSINT P380 AM machine at Central University of Technology (CUT). Those that were built in PMMA were manufactured at Vaal University of Technology (VUT) using Voxeljet 3D printing technology, which is a binder jetting process. The patterns included features such as thin walls, cavities, different surface textures and angles that are challenging to produce using the mentioned AM technologies and the investment casting process. Metrology using micro computed tomography (micro-CT) scanning was performed on each of the produced patterns and results were reported. It was found that both technologies were able to produce the required part but it was also clear that they did not show the same accuracy. This paper is now reporting on the preparation of ceramic moulds (shell making, pattern extraction and firing), characterizing of the quality of the moulds, casting of the metal alloy into the moulds and metrology on the castings. A comparison of the moulds and different features of the castings from the two types of patterns is reported.

The focus of this study is more on the difference in dimensional accuracy of the two technologies. The manufacturing lead times for the two patterns were not considered in this study because both manufacturing processes are automated and the patterns can be built overnight. Furthermore, there is no discussion on the comparison of the cost associated with the manufacturing of the two AM patterns, but relevant information on where the two patterns were manufactured is shared.

2. METHODOLOGY

2.1 Mould making process

For research performed for this study, mould making and casting were done at Council for Scientific and Industrial Research (CSIR). The patterns were prepared by attaching gates and vents to the AM patterns. Ten vents were attached to the PrimeCast® pattern while no vents were used with the PMMA pattern as shown in Figure 1. The gating and vents were produced by wax injection using suitable dies at the CSIR. The assemblies were then cleaned using wax pattern cleaner and de-ionized water to remove any debris and carbon from the wax. The assemblies were then left to dry in air.

Once the assemblies were dry, they were dipped into the primary or face coat. The primary slurry consisted of inoculated cobalt aluminate. The assemblies were dipped into the slurry very slowly and carefully to make sure that no air was entrapped while dipping. When the assemblies were taken out of the slurry it was ensured that no bubbles were trapped on the assemblies and, if present, they were removed since this could affect the casting, this coat allows for the reproduction of fine detailed features. The dipping was followed by stuccoing with fine alumina sand and the assemblies were left to dry. The dipping and stuccoing were repeated four times, with subsequent drying for four hours. Lastly, they were dipped in the backup coat (fibre reinforced fused silica) and stuccoed with fine fused silica sand after the first dipping and then coarser silica sand after the last dipping. The assemblies were then left to dry for 24 hours at 22 °C. The flow diagram in Figure 2 below illustrates the process.

![Figure 1: Sacrificial patterns with gating and vents: PMMA (a) and PrimeCast® (b).](image1.png)

![Figure 2: The flow diagram of mould making.](image2.png)
2.2 Burnout Processes

2.2.1 Burnout Procedure for PMMA patterns
PMMA patterns were burned out in an autoclave, with the wax used for gates melting out first, leaving an opening for the patterns to flow through. The remaining amount of pattern was burned out in a furnace.

2.2.2 Burnout Procedure for PrimeCast® patterns
In the first attempt, the patterns were removed in the autoclave using the same setting as the PMMA patterns. However, shell cracking occurred during the autoclaving of the PrimeCast® pattern, so it was realised that a redesign was needed of the PrimeCast® pattern. Electro Optical Systems (EOS), the supplier of the PrimeCast®, was consulted on how to go about the redesign and burn-out procedure of the PrimeCast® pattern for suitability as sacrificial pattern for investment casting. The redesign included manufacturing the pattern with a low laser power setting and a special burnout process. The process included two stages: autoclaving and burn-out process. The vents were opened prior to autoclaving; the wax that was used for gates and vents was melted out completely at around 150°C using a boiler clave at the CSIR. The surface of the PrimeCast® pattern started to melt but could not flow out at this temperature. The pressure was then increased to 5 Bar and the temperature to around 200°C for 2 hours. Most of the pattern material started to flow out, leaving some residue on the shell walls as shown in Figure 3(a). During autoclaving the pattern could flow out of the shell as quick as possible through the vents. The shells were then taken to a furnace for burn-out and the temperature was gradually increased until it reached 650°C as shown in Figure 4. At this temperature the shells were white; this was an indication that all the PrimeCast® material had burned out completely as shown in Figure 3(b).

Figure 3: Shell with pattern residue (a) and White clean shell from the furnace (b).

Temperature vs Time

![Temperature vs Time graph](image)

Figure 4: Temperature profile used for the burn-out furnace.

2.3 Casting Process
When the entire pattern residue had been removed from the shell, the shells were cooled and the vent holes patched using high temperature glue. The shells were then preheated to 600°C just before pouring molten metal into them. The clay graphite crucible used with the furnace was pre-heated empty in order to minimise the temperature gradient across its wall. The crucible was preheated slowly to 200°C for 2 hours, to eliminate any moisture, and then gradually raised to 1100°C on full power to achieve a uniform bright red condition over the whole crucible. The temperature was then dropped to 700°C over 8 hours before the crucible was fed with aluminium ingots. It was important that the crucible body temperature was equivalent to or slightly above that of the molten metal in order to minimise thermal stress. The aluminium ingots were cleaned before they were...
placed into the crucible to avoid contamination of the molten metal or flame due to impurities. They were loaded into the crucible very loosely at the time until the required quantity had been melted so as to avoid the ingots expanding and cracking the crucible. The temperature of the molten metal was recorded just before it was poured into the shell cavity as shown in Figure 15 below.

Figure 5: The furnace and the recorded temperature during melting of aluminium alloy.

The liquidus temperature of aluminium A356 is 615 °C, therefore, the temperature of 670 °C was recorded as the pouring temperature for the molten metal. The oxide layer was removed prior to pouring. During the pouring the hot shells were removed one by one from the furnace and then filled with molten metal as shown in Figure 6. The filling was done carefully so that no air was trapped during filling. After the shells were filled with molten metal, they were left to cool in air. The final step was to clean-up the castings by removing the shells and grinding off the gates and vents.

Figure 6: Pouring of the molten metal into the shell (a) and the shell with molten metal left to cool in air. (b)

2.4 Metrology Process

Four castings, two produced from PrimeCast® patterns and two from PMMA patterns, were scanned at Stellenbosch University (SU) using a micro-CT scanner [17]. The castings produced from PrimeCast® patterns were labelled PC1 and PC2, while those from PMMA patterns were labelled PMMA1 and PMMA2. A General Electric Phoenix V|Tome|x L240 / NF180 machine was used for scanning. X-ray settings used were 200 kV and 200 µA. The machine acquires 3000 images in a full rotation with an image acquisition time of 600 ms per image. The micro-CT scanner settings were the same for all the samples scanned and are illustrated in Table 1 below. Detector shift was activated to minimize ring artefacts. The sample was positioned on the scanner’s rotating stand at such an angle so that no feature on the sample was parallel to the X-ray beam as it rotated. The sample was also fixed to the table to ensure that it would not move during scanning as shown in Figure 7. Background calibration was performed and the scan time was approximately 30 minutes per scan. Reconstruction of the sample was done with system-supplied Datos reconstruction software. Analysis was performed with Volume Graphics VGStudio Max 3.2 Voxel data analysis and visualization.

Table 1: Micro-CT scanner settings.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Detector</th>
<th>X-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voxel size</td>
<td>125 µm</td>
<td>Average 1</td>
</tr>
<tr>
<td>Magnification</td>
<td>1.6</td>
<td>Voltage 200 kV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Current 200 µA</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSIONS

Micro-CT scanners provide very accurate dimensions of scanned parts. Measurements were performed by comparing the CT model of a casting with the CAD model. The data includes both internal and external surface information. For the comparison to be done, the two models needed to be aligned and the alignment tool used was an automatic best fit. Once the two models were aligned, a simple 3D comparison option automatically creates a coloured view showing all the dimensional differences between the two models. Tolerance values were from -1.5 mm to 1.5 mm for all the comparisons done. All the dimensional differences between the CAD models and the CT surfaces are represented by colours. Tolerances indicating best fit are shown in green. Yellow denotes the areas where the CT scan measurements are larger than the original CAD model and blue indicates measurements smaller than the CAD model.

Each feature on the benchmark part had its own dimensional accuracy parameter to be measured, and the purpose for each feature is outlined in Table 2 below.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubes</td>
<td>Straightness, repeatability, linear accuracy</td>
</tr>
<tr>
<td>Rectangular Protrusion</td>
<td>Perpendicularity, linear accuracy</td>
</tr>
<tr>
<td>Pyramid</td>
<td>Angularity, accuracy</td>
</tr>
<tr>
<td>Sphere (half)</td>
<td>Symmetry, repeatability of a constantly changing sloping profile, axial runout, radial runout</td>
</tr>
<tr>
<td>Cone</td>
<td>Constant sloping profile, taper, axial runout, radial runout, symmetry</td>
</tr>
<tr>
<td>Free-form (conical)</td>
<td>Non-constant sloping profile axial runout, radial runout, symmetry</td>
</tr>
<tr>
<td>Free-form (sinkhole)</td>
<td>Non-constant sloping profile axial runout, radial runout, symmetry</td>
</tr>
<tr>
<td>Wedges</td>
<td>Angularity</td>
</tr>
<tr>
<td>Rectangular Hole</td>
<td>Perpendicularity</td>
</tr>
<tr>
<td>Cylindrical Hole/Hollow Cylinder</td>
<td>Concentricity, circularity, accuracy</td>
</tr>
<tr>
<td>Triangular Hole</td>
<td>Angularity, perpendicularity</td>
</tr>
<tr>
<td>Flat thin walls</td>
<td>Parallelism, thickness</td>
</tr>
<tr>
<td>Square base</td>
<td>Flatness, straightness, parallelism</td>
</tr>
<tr>
<td>Mechanical features</td>
<td>Competence of machine to build particular features (visual inspection)</td>
</tr>
<tr>
<td>Yes/No Features</td>
<td>Machine’s ability to build certain features (visual inspection)</td>
</tr>
</tbody>
</table>

Figure 8 shows the geometrical results obtained from the top and bottom of a casting as compared to the associated PMMA pattern and its deviation distribution from that PMMA sacrificial pattern. There are noticeable round smooth walled cavities and irregular shaped mass on the bottom of the casting. Blue and red are visible on the surface of the features where the symmetry was tested; features like half sphere, freeform (conical and sinkhole) and cone. The sharp corners and the fillet are well presented in green. Flat surfaces of the casting are also green showing the best fit, except the flat surface of the rectangular protrusion where there is blue toward the long corner edge. Angular surfaces of wedges and the small triangular hole show accurate results. The blue
and red are also noticeable on the inside and outside of the square base respectively. The hollow cylinder was also green with just small defects; this feature was used to test concentricity and circularity. The pyramid was covered in green as well as the rectangular hole. The two cubes and two half cubes were used to test for repeatability and they were situated towards the margin of the casting. Both cubes and both half cubes have almost the same colours, green is predominate on the top flat surfaces with traces of red on the vertical surfaces. The shape of the deviation distribution is skewed to the right, while the peak of the distribution peak is slightly off centre toward the left (-0.2 mm) and the tail stretches to the right. From the deviation distribution, green is spread from -0.7 mm to 0.7 mm showing the highest fraction (about 85%) of the total area of the casting. About 11% of the area is found in the range from -1.5 mm to -0.7 mm, denoted in blue. The remaining area, denoted by red, which is about 4%, is found in the range 0.7 mm to 1.5 mm.

The geometrical results for a casting from a PrimeCast® pattern showed only casting defects that could be associated with bubbles that might have been entrapped in the pattern wall by the primary slurry during mould making. They appear as small, smooth spherical or oval shaped excess metal on the casting on the corners and edges of some features. From Figure 9, it can be seen that red and blue are mostly seen on the features with repeatability of a constantly changing sloping profile (cone and sphere), non-constant sloping profile, axial runout (freeform (conical and sinkhole)), and on the inside and outside of the square base. The flat surface of almost every feature is green. The surfaces of the features that are perpendicular to the top surface of the part are blue and red. The hollow cylinder as well as the flat thin walls is green. The green on the sharp corners and the fillets indicate that they were exact replicas of the pattern. Blue is mostly seen of the surfaces of the features that are facing towards the margin of the casting, features such as half sphere and rectangular protrusion on top view of the casting. The surrounding walls are predominately blue outside and red inside. The hollow rectangle as well as the rectangular hole are green with drops of red.

The shape of the deviation distribution complies with a normal distribution, except that it has a large peak at the tail that stretches to the left. In the range -0.7 mm to 0.7 mm represented in green, the highest fraction of the total area, namely 68% is found. The range -1.5 mm to -0.7 mm is displayed in blue and represents about 20% of the total area, while the remaining area (about 12%) is red.

Figure 8: Casting results of the top (a), bottom (b) and the deviation distribution results from the PMMA pattern (graph below (a) and (b)).
An analysis was done on five selected features from each casting, which were cube, rectangular protrusion, cone, freeform (conical) and freeform (sinkhole), as well as for the full volume of a casting. The analysis results for these features are tabulated in Table 3, which also gives the minimum and maximum deviation, the mean and the standard deviation.

Table 3: Analysis from five selected feature of the castings.

<table>
<thead>
<tr>
<th>Castings</th>
<th>Full Volume</th>
<th>Cube</th>
<th>Rectangular protrusion</th>
<th>Cone</th>
<th>Freeform (conical)</th>
<th>Freeform (sinkhole)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left (mm)</td>
<td>Right (mm)</td>
<td>Mean (mm)</td>
<td>Deviation (mm)</td>
<td>Left (mm)</td>
<td>Right (mm)</td>
</tr>
<tr>
<td>PMMA1</td>
<td>-1.50</td>
<td>1.50</td>
<td>-0.14</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA2</td>
<td>-1.50</td>
<td>1.50</td>
<td>-0.11</td>
<td>0.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC1</td>
<td>-1.50</td>
<td>1.50</td>
<td>-0.14</td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC2</td>
<td>-1.50</td>
<td>1.50</td>
<td>-0.11</td>
<td>0.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA1</td>
<td>-0.75</td>
<td>0.53</td>
<td>-0.15</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA2</td>
<td>-0.63</td>
<td>0.45</td>
<td>-0.11</td>
<td>0.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC1</td>
<td>-1.62</td>
<td>1.29</td>
<td>-0.01</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC2</td>
<td>-1.77</td>
<td>1.54</td>
<td>-0.02</td>
<td>1.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA1</td>
<td>-1.76</td>
<td>1.63</td>
<td>-0.63</td>
<td>0.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA2</td>
<td>-0.78</td>
<td>1.47</td>
<td>-0.21</td>
<td>0.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC1</td>
<td>-1.46</td>
<td>1.44</td>
<td>-0.13</td>
<td>0.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC2</td>
<td>-1.46</td>
<td>1.38</td>
<td>-0.15</td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA1</td>
<td>-1.39</td>
<td>1.21</td>
<td>0.02</td>
<td>0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA2</td>
<td>-1.04</td>
<td>1.50</td>
<td>0.04</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC1</td>
<td>-1.20</td>
<td>1.30</td>
<td>-0.12</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC2</td>
<td>-1.48</td>
<td>1.98</td>
<td>-0.07</td>
<td>0.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA1</td>
<td>-1.49</td>
<td>1.03</td>
<td>-0.15</td>
<td>0.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMMA2</td>
<td>-1.48</td>
<td>0.98</td>
<td>-0.04</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC1</td>
<td>-1.01</td>
<td>1.14</td>
<td>-0.15</td>
<td>0.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC2</td>
<td>-1.47</td>
<td>1.22</td>
<td>-0.11</td>
<td>0.92</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
When the tolerances were set at -1.5 mm to 1.5 mm for full volume, the surface area within this range of PMMA1 and PMMA2 was 99.21% and 98.77%, respectively. The similar surface area for PC1 and PC2 was 98.62% and 97.85%, respectively. The mean deviation value for PMMA1 and PC1 is the same (-0.14) and similarly, the mean deviation value for PMMA2 and PC2 is also the (-0.11). However, their standard deviations are different. The standard deviation of PMMA1 and PMMA2 are smaller than that of PC1 and PC2. This means that PC1 and PC2 have more variability than PMMA1 and PMMA2 respectively. PMMA2 has the smallest standard deviation: its data values are most concentrated around the mean. With the cube, the tolerances range of the castings from the PMMA patterns was smaller as compared to that of the PrimeCast® patterns. Most of features on the castings from the PrimeCast pattern has wider deviation range than that from the castings from PMMA pattern.

The chart in Figure 10 below represent the comparison in relative surface area of the castings from the two patterns. The relative surface area denoted in green of the casting from the PMMA pattern is 85 % and it is 17 % more than that of the casting from the PrimeCast® pattern. Red and blue is more on the casting from the PrimeCast® than in the casting from PMMA pattern. The overall difference in dimensional accuracy in the set tolerances range between the castings from the two patterns 0.5 %, and this is because almost all the surface area of the both castings were within this range.

<table>
<thead>
<tr>
<th>Material</th>
<th>Deviation</th>
<th>Surface Area</th>
<th>Deviation</th>
<th>Surface Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA1</td>
<td>-1.44</td>
<td>0.98</td>
<td>-0.04</td>
<td>0.40</td>
</tr>
<tr>
<td>PMMA2</td>
<td>-0.87</td>
<td>0.75</td>
<td>-0.08</td>
<td>0.33</td>
</tr>
<tr>
<td>PC1</td>
<td>-1.51</td>
<td>1.46</td>
<td>-0.12</td>
<td>0.66</td>
</tr>
<tr>
<td>PC2</td>
<td>-1.49</td>
<td>1.64</td>
<td>-0.01</td>
<td>0.71</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

- The ability of PrimeCast® and PMMA materials to be used as sacrificial patterns for the investment casting process has been validated: Aluminium A356 was successfully cast from the two types of sacrificial patterns.
- Application of the RIC process has become the preferred choice for foundries that has adapted this technique, because of its suitability to manufacture complex parts with internal cavities, fast and cost effectively.
- The overall dimensional accuracy of castings from PMMA patterns show less differences in dimensional deviation compared to castings from PrimeCast® patterns.
- PrimeCast® patterns need more care during mould making and burnout processes compared to PMMA patterns. The need for removal of vents from castings produced from PrimeCast® patterns through grinding makes it easy to lose accuracy.
- Both AM materials burn out cleanly from the moulds and the final cast parts were acceptable.
- It is clear from the results obtained that for castings produced from PrimeCast® and PMMA patterns typical deviation of ±1.5 mm on average can be expected.
- Both PMMA and PrimeCast® patterns were impregnated with wax just after manufacturing. The sacrificial patterns produced from these two AM technologies are characterised by a significant porosity due to the manufacturing technique used therefore the impregnation is required. Impregnation can affect the dimensional accuracy of both patterns.
• Although there was visible difference in surface roughness between the castings from the two AM patterns, the surface roughness measurements were not performed because of the fact that impregnation also ensures low surface roughness.

• From the results it is not possible to tell which type of pattern produced the best castings; each pattern type had its advantages and limitations that will influence selection depending on the end user’s application.

ACKNOWLEDGEMENTS

The active support and funding of the South African Department of Science and Technology through the CSIR for the Collaborative Program in Additive Manufacturing, Contract No.: CSIR-NLC-CPAM-15-MOA-CUT-01, are gratefully acknowledged.

The authors are grateful to Pierre Rossouw, Senior Researcher at CSIR, Material Science and Manufacturing, who is an expert in investment casting and led the casting trials.

The Centre for Rapid Prototyping and Manufacturing (CRPM) is also acknowledged for facilitating in redesigning of the PrimeCast® pattern.

REFERENCES


We present printed sensing radio frequency identification (RFID) tags on different paper and flexible substrates towards low-cost, automated connected sensor solutions. Combining the Internet of Things (IoT) with printed electronics and low-cost substrates, this work showcases 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 prototyping of printed ultra-high frequency (UHF) RFID sensing tags operating in the 868 MHz range. The tags were 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 [1] 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. The substrates used in this work are low cost, lightweight, flexible and accessible, and can be readily disposed of through incineration. Tag devices can be manufactured and instructions or information can be printed directly on to the devices. In addition, scale up of device manufacture is feasible using existing roll-to-roll printing technologies, which further supports the approach taken in this work.

UHF RFID is an advantageous technology as it affords longer read ranges than for example near field communication (NFC), with multiple instantaneous 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 onto various flexible substrates has been achieved [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 focussing 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. The SL900A chip provides a versatile solution as resistance, capacitance, voltage and current measurements are possible. The IC complies with the Electronic Product Code (EPC Gen2 1.2), operating in the UHF band. Read distances in the cm to m range are achievable for a wireless solution to be realized using a straightforward dipole antenna design that can easily be printed.

This single chip solution allows for a simple, compact RFID tag design to be realized, with capabilities for identification and tracking of devices. Logging of data in real time is also possible using the SL900A chip with a built-in EEPROM, and an on-board temperature sensor provides useful monitoring of environmental conditions. Previous work using the SL900A for sensing applications has been carried out [3] and printing of tags using the SL900A integrated circuit (IC) on to various substrates has also been explored [4].

This work assesses the feasibility of using different low-cost paper and flexible substrates for implementing manually screen printed and assembled sensing RFID tags. Printed features were characterized, along with read range measurements in both passive (without a battery) and active (battery-assisted) modes to assess the performance of the low-cost tags for sensing and data logging applications. Practical functionality of the tags towards low-cost connected sensor solutions is illustrated through logging of temperature and battery voltage values, demonstrating the potential for these tags to be printed directly onto packaging or onto labels that could be applied to various objects or surfaces.

2. METHODS

RFID tag designs were based on the SL900A development kit (SL900A-DK-STQFN16, AMS, Austria), consisting of a printed dipole antenna and electronic tracks, a 39 nH surface mount inductor (WE-MK multilayer ceramic, Wurth Electronic, Germany), SL900A chip and a 3 V coin cell battery (CR1220, RS Pro, RS Components, South Africa) [4]. Tag designs were screen printed on to three different low-cost flexible substrates, namely standard printing paper, cardboard packaging and transparent adhesive vinyl (Table 1) using a silver screen printable ink (AG-800, Applied Ink Solutions, USA). Screen printing was carried out using a modified ZelPrint 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 (71/180-55 PW, SEFAR® PET 1500). Printed devices were cured in the oven at 90°C for 15 mins, after which components were assembled using a silver epoxy conductive adhesive (186-3616 RS Pro Silver, RS Components, South Africa). The battery was secured and connected using copper adhesive tape (3M Copper Foil Tape 1126, Digikey, USA).

Printed features were analysed using a brightfield microscope (Meiji Techno EMZ-8TR, Japan) and a laser scanning microscope (LSM 5 Pascal, Carl Zeiss, Germany). Brightfield microscopy was performed at 7× and 45× magnification to assess the consistency of the printing, the edge irregularities and resolution of fine detail, specifically for the IC pads. Laser scanning microscopy was carried out to measure the surface roughness for each substrate as well as the printed layer on each substrate. Roughness measurements were carried out at 200× magnification, with an average taken over three measurements taken at different positions along the printed layer. Surface roughness was calculated using the arithmetic mean roughness value (Ra).

Thickness measurements were also performed for the printed layers on each substrate using laser scanning microscopy. A theoretical wet print thickness of 28 µm is expected from the screen mesh used, and a corresponding reduction in thickness down to 30% can be expected for the dried ink thickness, resulting in expected print thicknesses of approximately 8.4 µm.
Read range measurements were carried out to assess the performance of the printed tags. The screen printed RFID tags were compared to printed circuit board (PCB) devices of the tag antenna as a benchmark, including the development kit and a milled PCB of the tag antenna manufactured and assembled in-house. The development kit reader recommended for use with the SL900A was used to perform read range measurements (AS3993-QF_DK_RFermi reader, AMS, Austria). The set-up consists of a monopole antenna (gain = 2.2 dBi) connected to a reader module with a transmission power of 22 dBm. The reader setup was mounted on a sliding mechanism for ease of adjusting the distance between the tag and the reader. The reader IC sensitivity was set to the default of -68 dBm. RFID frequency settings were set to the 917 – 920 MHz range in the user interface as this aligns with the standard South African frequency range for RFID (915 – 919 MHz).

Measurements were carried out for three tags for each type of substrate, both in passive and active modes. For each tag, the maximum read range at which the tag could be detected was recorded, as well as the maximum read range at which a sensor value could be read out. The temperature read-out from the on-board temperature sensor of the SL900A was recorded as an example.

In active mode, logging of sensor data can be implemented through a built-in EEPROM in the SL900A, even when the tag is not in the range of the reader. This was demonstrated for temperature and battery voltage readout over a period of time using the printed tags.

3. RESULTS

Figure 1 shows examples of the printed and assembled tags on three different substrates. Brightfield microscopy results of the printed features are shown for each substrate. Laser scanning microscopy images are also shown for both the substrate and the printed layer in each case. Surface roughness measurements are summarized in Table 1. Thickness measurements were between 6 and 9.5 µm, aligning well with the expected print thicknesses of approximately 8.4 µm. Four probe resistance measurements using an LCR meter (LCR-8110G, GW Instek, Taiwan) yielded acceptable conductivity for all substrates, ranging from 0.047 to 0.073 Ω/sq.

![Image of assembled printed RFID sensing tags](image_url)

**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.

<table>
<thead>
<tr>
<th>Substrate description</th>
<th>Product and manufacturer</th>
<th>Roughness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Blank substrate</td>
</tr>
<tr>
<td>Standard printing paper</td>
<td>Typek White Paper A4 80 GSM Premium, SAPPi, South Africa</td>
<td>4.96</td>
</tr>
<tr>
<td>Cardboard packaging</td>
<td>Typek White Paper packaging box, SAPPi, South Africa</td>
<td>5.05</td>
</tr>
<tr>
<td>Transparent adhesive vinyl</td>
<td>Grafitack Promo P100 Transparent Film, Grafityp Selfadhesive Products N.V., Belgium</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Figure 2 shows the maximum read range results for each of the low-cost, flexible substrates compared to the development kit and the milled PCB tags. For each type of tag, read ranges for both passive and active modes were record. In each case the read ranges for tag detection as well as the read range for temperature sensor readout were recorded. Figure 3 shows the results of data logging of a printed tag on adhesive vinyl for
temperature and battery voltage read-out over 140 samples, with readings taken each minute. The reader user interface displays the data recorded in the EEPROM directly, as shown in Figure 3b, but EEPROM data (Figure 3a) can also be accessed and processed separately when additional sensors are connected.

![Figure 2: Maximum read ranges in both active and passive mode for tag detection and temperature read out 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.](image)

4. Discussion

This work demonstrates printed UHF RFID tags on to different low-cost, paper and flexible substrates to implement sensing and wireless communication functionalities. Manual screen printing and assembly processes enabled prototyping of printed, low-cost and functional RFID sensing tag devices.

Surface roughness measurements for paper-based substrates (both standard printing paper and cardboard packaging) were high with large standard deviations as a result of the fibrous texture of the substrates. The printed layers on these substrates were less rough, with the ink coating the fibres and filling the porous spaces in between the fibres. The smoother adhesive vinyl substrate had a much lower surface roughness, but the printed ink layer had a higher roughness than the substrate. Variations in the thickness measurements are as a result of the manual screen printing process utilized.

Read range measurements showed successful operation of all the tags assembled and tested. Minimum read ranges of 100 mm were achieved for tags in passive mode, with read ranges of up to 500 mm in active mode. Read ranges when reading out a sensor value were slightly lower than the read range for tag detection alone. Maximum read ranges for the development kit in this work were around 900 mm in active mode and 360 mm in passive mode. The lower read ranges and variations in read ranges measured for the printed tags are a result of the manual printing and assembly procedures. In addition, the tags were tested in a standard laboratory, where reflections in the RF signal can occur, affecting the read range measurements. Impedance mismatch and poor antenna gain can be caused by printing, and could be improved by printing thicker, more uniform layers [5]. Although this affects the performance of the RFID tags, practical and reliable tag detection and sensor readout are still achievable, and is the ultimate goal of this work. If the working distances are chosen to be in the range of 50 - 100 mm, functional tags can be realized on any of the three low-cost, flexible substrates utilized in this work.
Figure 3: Example of temperature and battery voltage data logging, using screen shots from the AS3993 Reader Suite software (AMS) to show a) wireless read-out values stored in the EEPROM of the SL00A, and b) temperature and battery values plotted over time from a tag printed on adhesive vinyl substrate.

Logging of data was also successfully demonstrated, showing promise for the integration of various sensing capabilities with the printed RFID tags. Printed low-cost sensors for read-out from low-cost paper-based point-of-care diagnostic tests, tamper detection, environmental monitoring, and various other applications could be investigated and incorporated in to the printed tag devices.

Automated screen printing could be used in future development once successful prototypes have been realized, and can be scaled up for mass production using roll-to-roll techniques and further lowering the cost of the RFID sensing tag devices.

5. CONCLUSION

Prototyping of printed, 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.

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 and electronic circuit designs implemented by different research teams from Africa are highlighted. The advanced open labware workshop enabled teams to develop setups 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.

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1. INTRODUCTION

Similar to open software or hardware, open labware entails lab equipment designs that are openly shared and that enable people to build solutions at a very low cost compared to commercial equipment. This movement has resulted in collaborative projects such as Open-Labware.net (https://open-labware.net/) where designs of free and open source hardware and software projects are shared, with focus on scientific laboratory or research settings. A comprehensive review on open labware [1] shows various projects that have been explored, including low-cost microscopes, centrifuges, thermocyclers and waveform generators. These projects cover various areas and are applicable to different laboratories in fields of molecular biology, electrophysiology, fluidics and microscopy, to name a few. A number of articles and open projects are available through channels such as the PLoS Open Hardware Collection (https://channels.plos.org/open-source-toolkit), highlighting the growth of open projects in recent years.

A number of workshops focused on open labware have been held in the past few years to create an awareness of these open principles and projects, with the aim of transferring knowledge and skills to researchers in developing countries. Initial work entailed formulating processes to be able to promote neuroscience education and research in Africa [2], which formed the foundation for the workshops.

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 (South Africa), Tuebingen (Germany), Sussex (United Kingdom) and Oxford (United Kingdom), as well as the Council for Scientific and Industrial Research (CSIR, South Africa) and funded by the Volkswagen Foundation. Initial teaching of open source principles has been carried out in previous TReND workshops to provide a foundation of open hardware and software development [3]. Stemming from this, an advanced workshop was organized to allow for teams to utilize 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 utilized across campuses and countries to solve problems; this can also be adapted to solve other problems as a result of the generic approaches followed.

Assessment of the course success was carried out through surveys, as well as informal interactions and feedback sessions. 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 public repositories such as GitHub.

2. METHODS

The workshop was held in Muizenberg, Cape Town, South Africa 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, South Africa and Germany. Teams were required to submit proposals for their projects, and successful candidates were asked to formulate and submit a bill of materials required for the project. The various components were procured prior to the workshop and distributed on the first day to the teams to streamline the progress of the projects.

The course took place over 2 weeks (6 days per week) from the 16th of April until the 28th of April. The daily schedule was structured with a morning presentation or lecture session at 09h00 and then building sessions for the remainder of the morning. Building continued in the afternoons after lunch, and the days were typically wrapped up with an hour long dedicated documentation session for groups to be able to capture the progress made and challenges faced, ultimately to feed back into the open labware space for others to utilize and build on to their work.

As an introduction to the workshop, each team gave a presentation. The teams discussed the equipment they wanted to make, and highlighted their existing skill sets and the skills they hoped to acquire. Many of the teams had overlaps in terms of the types of equipment they wanted to create, which indicated a high possibility of good inter-team collaboration. There were also overlaps in skill gaps - such as PCB design and GitHub, which suggested useful content for tutorials to be presented as part of the workshop.
A 3D printer (Zortrax M200) was utilized during the workshop to assist in development of a number of the projects (Figure 1a). Numerous lectures and tutorials were given throughout the workshop (Figure 1b), with focus on open source hardware and software development and 3D printing design and manufacture.

![Figure 1: a) 3D printing of various components during the workshop and b) one of several tutorial sessions on hardware and software development aspects provided as part of the workshop.](image)

Additionally presentations were given by some of the facilitators to highlight their research and areas of expertise and interest. Presentations included:

1. Open source and open design - including examples of open hardware projects and companies started up on global scale. Gathering for Open Science Hardware (GOSH) community forums and upcoming events were also highlighted, along with open source toolkits, for example [https://channels.plos.org/open-source-toolkit](https://channels.plos.org/open-source-toolkit).

2. GitHub - installation, set-up and general functionality and implementation for documentation, collating and sharing of work. Hands-on interactive sessions were also carried out to ensure that all teams could utilize GitHub effectively for their projects.

3. Open 3D printing design programs - covering various programs with brief overviews of the functionality of each program. Pros and cons of each program for developing designs were presented according to user skills and preferences.

4. Documentation - the importance of keeping up to date documentation on the work being done and suggestions as to how to most efficiently do this.

Emphasis was placed on important design considerations for those who were inexperienced in 3D printing design, including the use of a bottom support base, support structures when creating bridges, and avoiding thin, tall structures. Different programs covered included OpenSCAD, Google SketchUp, FreeCAD and Tinkercad, to allow participants to design the customized parts required for their projects. Programs such as OpenSCAD employ a coding/programming approach with variables to determine dimensions and achieve different shapes from standard objects. With FreeCAD, different surfaces or edges are selected and operations are applied to the selected part. Google SketchUp and Tinkercad employ a drag and drop approach for creating and combining shapes.

Key points of the teaching methods of the workshop included a) planning to publish from the build experience and b) planning for open source documentation. There was also discussion about ensuring the maximal usage of the shared expertise by having break-away groups with members for different teams to discuss challenges as part of the daily schedule. Documentation of project work and progress was carried out by teams for the last session of each day of the workshop.

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.

3. **RESULTS**

The various projects incorporated 3D design and printing, laser cutting and various electronic components. Arduino UNO and Raspberry Pi boards were utilized as processing, control and interface platforms. Tinkercad was a popular 3D design program choice for many of the teams as it employs a drag and drop approach for ease of adding and combining shapes. Many teams had no previous experience with 3D printing design programs or laser cutting and design processes. Some of the teams had experience with Arduino platforms, and where expertise was lacking, online forums were utilized. Interaction between teams was also commonly exploited where expertise was lacking and other teams had experience and insights to give.
The projects that formed part of the workshop 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 2a).

- **Bird assessment project** (South Africa): Bird perch and nest modified from PrintedNest Project (http://www.printednest.com/) with the addition of a camera and load cell system to visually assess and weigh birds. The bird nest was 3D printed (Figure 2b), 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 2c). Housings and brackets for positioning light sources and detector arrays were 3D printed.

- **Locomotor activity testing project** (Ghana): Infrared transmitter and receiver arrays in a box to detect rodent activity and speeds within the set-up (Figure 2d).

- **Multipurpose chamber for image and activity capture project** (Nigeria): chamber for activity capture of animal via camera imaging with constant lighting and ultrasonic sensors for passing through a doorway inside the setup. 3D printed brackets and housings were used for the camera setups.

- **Micropipette puller and Electroantennogram (EAG) project** (Malawi and Nigeria): development of automated micropipette puller and EAG system for insect olfactory research. A micropipette puller is required to produce glass electrodes for probing of the insect antenna and was implemented using heating elements.

- **Fluorometer project** (Germany): fluorescence detection of DNA samples using specialized dyes. This project was fairly advanced, and the team’s experience with spectrophotometry was utilized by other teams to accelerate their project development during the workshop.

- **Bee hive monitoring project** (Germany): implementation of various sensors for bee hive monitoring and environmental parameters, with long-range wireless communication of data collected. This project was in the advanced stages, so the team could assist others with rapid development and troubleshooting where they had already overcome challenges.

The two projects from Germany were further advanced than the other projects, with optimization and improvements being the main goal for these teams during the workshop. The idea was to encourage cross-collaboration between the groups that were further along with implementation than those just starting with the development, with the more advanced groups giving insights into potential hurdles and how they overcame these to speed up development in the early phases for the other teams.

![Figure 2: Development of 3D printed solutions during the workshop, including projects such as a) an analytical shaker, b) a smart bird nest, c) laboratory spectrophotometer, and d) locomotion activity test set-up. Image credit: Agnieszka Pokrywka (https://flic.kr/s/aHsmup89ze).](https://flic.kr/p/JtA8zE)

There were challenges with regards to components not arriving on time that were addressed using local distributors, but impacted on the initial progress made during the first week of the workshop. This should be considered for potential future workshops, particularly when held in locations where local distributors may not be a feasible option.
With many of the teams needing access to a 3D printer, securing one for use in the venue had to be prioritized and proved challenging in terms of setup. In future, arrangements to make this a smooth process during the workshops should be planned before the workshop commences.

Surveys were conducted during the course of the workshop to assess the workshop expectations and success. Survey 1 was carried out in the beginning stages of the workshop and assessed the participants’ background and reasons for wanting to participate in the workshop (Table 1). In all cases, participants applied to the workshop with the aim of learning how to use and implement tools to further or assist in their research careers. In cases where participants had previously worked on open labware projects, this was typically during previous TReND workshops, or in a few cases, during hackathons. Preparation time for the workshop typically ranged from a few days to 4 or 5 months across the teams, and in many cases, online or email discussions were the only options prior to team members meeting up at the workshop.

Survey 2 was carried out halfway through the workshop and assessed the skills and knowledge learned as well as areas where skills were lacking and that could potentially be improved on for future workshops (Table 2).

Survey 3 was carried out towards the end of the workshop and assessed the future goals and implementation plans for the projects after the workshop (Table 3).

**Table 1. Workshop Survey 1 results summary to assess background and experience of participants. 21 responses were recorded.**

<table>
<thead>
<tr>
<th>Survey question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before the workshop, had you ever heard of the open source philosophy?</td>
<td>19 (90.5%)</td>
<td>2 (9.5%)</td>
</tr>
<tr>
<td>Was this workshop your first project involving open labware?</td>
<td>13 (61.9%)</td>
<td>8 (38.1%)</td>
</tr>
</tbody>
</table>
### Table 2. Workshop Survey 2 results summary to assess the learning process. Number of responses recorded varied as participants opted not to answer all questions.

<table>
<thead>
<tr>
<th>Survey question</th>
<th>Responses given</th>
<th>Number of responses</th>
</tr>
</thead>
</table>
| What are you enjoying the most about the workshop?                             | 1. Collaborations within and across teams  
2. Learning new skills  
3. Tutorial sessions  
4. Interdisciplinarity                                                         | 13 (68.4%)  
4 (21%)  
1 (5.3%)  
1 (5.3%) |
| What are you finding the most challenging about the workshop?                  | 1. Lack of skills in programming, hardware and troubleshooting  
2. Restrictions in terms of time, equipment and space  
3. Access to components                                                        | 3 (37.5%)  
3 (37.5%)  
2 (25%) |
| What key skills have you gained during the workshop?                           | 1. 3D printing design and programs  
2. GitHub  
3. Electronics  
4. Programming  
5. Documentation  
6. Communication skills  
7. Problem solving                                                              | 6 (18.2%)  
6 (18.2%)  
5 (15.2%)  
5 (15.2%)  
4 (12.1%)  
4 (12.1%)  
3 (9%) |
| Are there additional types of skills you would like to acquire?                | 1. Programming  
2. Electronics  
3. Writing of scientific papers  
4. GitHub advanced usage  
5. Hardware design  
6. 3D printing expertise                                                        | 4 (26.7%)  
3 (20%)  
3 (20%)  
2 (13.3%)  
2 (13.3%)  
1 (6.7%) |

### Table 3. Workshop Survey 3 results summary to assess future implementation of projects resulting from the workshop. Number of responses recorded varied as participants opted not to answer all questions.

<table>
<thead>
<tr>
<th>Survey question</th>
<th>Average ranking (standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>When you take your equipment home, what will be the biggest challenge for you? Rank 1 to 5, with 1 being the biggest challenge.</td>
<td></td>
</tr>
<tr>
<td>1. Getting funds to maintain and upgrade your equipment</td>
<td>2.4 (1.7)</td>
</tr>
<tr>
<td>2. Getting parts to maintain your equipment</td>
<td>2.7 (1.2)</td>
</tr>
<tr>
<td>3. Issues of power and connectivity</td>
<td>2.9 (1.6)</td>
</tr>
<tr>
<td>4. Getting reagents/consumables for your equipment</td>
<td>3.4 (1.1)</td>
</tr>
<tr>
<td>5. Integrating your equipment into your existing laboratory environment</td>
<td>3.8 (1.3)</td>
</tr>
<tr>
<td>Do you think there would be aspects of open labware that would discourage your colleagues from taking up this option? Rank 1 to 8, with 1 being the highest.</td>
<td></td>
</tr>
<tr>
<td>1. Lack of funds to buy hardware</td>
<td>3.3 (2.4)</td>
</tr>
<tr>
<td>2. Lack of access to tools for building (i.e. 3D printers)</td>
<td>4.0 (2.5)</td>
</tr>
<tr>
<td>3. Lack of expertise (or perceived lack of expertise)</td>
<td>4.1 (2.3)</td>
</tr>
<tr>
<td>4. The time it takes to build the equipment</td>
<td>4.1 (2.5)</td>
</tr>
<tr>
<td>5. Concerns about publishing data made on open labware</td>
<td>4.7 (2.2)</td>
</tr>
<tr>
<td>6. Lack of on-site technical support</td>
<td>4.8 (2.0)</td>
</tr>
<tr>
<td>7. Problems of calibration and data verification</td>
<td>4.8 (2.6)</td>
</tr>
<tr>
<td>8. Lack of institutional support</td>
<td>5.3 (2.1)</td>
</tr>
</tbody>
</table>

### 4. DISCUSSION

Survey 1 (Table 1) showed that more than 90 % of the participants had heard of Open Source, but not necessary Open Hardware. More than 60 % of the participants had never engaged in an Open Hardware project before. Those who had, had done so through various sources, primarily workshops.

Survey 2 (Table 2) highlighted that the main contributor to the enjoyment of participants during the workshop was learning from others and collaborations. The biggest challenges faced varied across participants, and included lack of skills along with restrictions in time, equipment and components. Participants felt that various
skills were gained during the workshop, particularly in 3D printing and sharing work on open platforms, but also that skills could be further developed, especially in software programming, electronics, and documentation.

Survey 3 (Table 3) summarized the biggest challenges faced by participants, along with the aspects of open hardware that could discourage their colleagues from taking this approach, with rankings from highest to lowest.

Although the answers varied regarding the biggest challenges, funding remained the largest concern for maintaining and upgrading of equipment once taken back home. Participants also highlighted the lack of access to tools for building (e.g. 3D printers, laser cutters, etc.) as development hurdles in the adoption of open labware at their home institutions, although answers again varied in terms of rankings.

5. CONCLUSION

The workshop assisted participants in resource-limited settings across Africa, as well as the rest of the world, to develop the skills to realize 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 basic design and implementation skills towards realizing practical solutions and to contribute to open labware developments, particularly through utilization of 3D printing techniques. Most teams were able to successfully complete the required 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 and be able to teach others in their communities about open labware design processes and principles. Challenges regarding available funding and support mechanisms at the home institutions of the participants were highlighted, and future endeavours could include follow ups to track this progress.

ACKNOWLEDGEMENTS

Special thanks are extended to Samyra Cury Salek and the other members of the workshop organizational team for all their efforts in making the workshop a success, Thomas Euler for providing funding for Andre Maia Chagas as well as Volkswagen Stiftung for funding the workshop (grant number 92065).

REFERENCES


ABSTRACT

Biomimicry in additive manufacturing often refers to topology optimization and the use of lattice structures, due to the organic shape of the topology-optimized 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. In this paper we report on the production of body armour models in metal (Ti4Al4V) and analyze the resulting mechanical properties, assessing their potential for impact protective applications. This is the first biomimetic study using metal additive manufacturing to date.
1. INTRODUCTION

Biomimicry refers to the discipline that studies nature's best ideas (i.e. biological structures and mechanisms) and consequently imitates these in an attempt to solve engineering problems [1]. The term is often used in the context of additive manufacturing, when design is done using topology optimization techniques and when lattice structures are used, often with no real biological imitation in mind. The reference to biomimicry in this case is due to the organic or “bionic” shape of the resulting topology-optimized 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.

Topology optimization and the use of lattices is a fast-growing field of design for additive manufacturing and a very promising avenue for new applications of the technology. The complexity of design allowed by additive manufacturing can be fully exploited in these designs, making light-weighting, tailored stiffness, and many new material designs possible in a variety of materials. The state of the art in topology optimization based design is reviewed in [2].

Besides organic shapes and biologically-plausible lattices, real biomimetic design may be incorporated into the design process (even as part of a topology optimization workflow), as is suggested in [3]. In this proposed workflow, the design engineer makes use of a biological database for bio-inspiration ideas or inputs in the design process. For example, when light-weight structures with good flexural properties are required, wood or bamboo design parameters are used. This latter work moves closer towards real mimicry of natural structures.

An even more detailed biomimetic approach is to analyze the detailed structural information of a natural system which has some desirable property and use this information to reverse-engineer simplified structures for engineering applications. The design parameters of the model structures can be varied, and simulations performed or physical models tested to analyze the performance of the models for the application in mind. This is the process used in [4], where a specific biological structure was analyzed in great detail, reverse-engineered simplified models generated with some design variations, and its performance analyzed for energy absorption and hence impact-protection applications. In this work, the natural body armour was analyzed 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.

The analysis technique used in this work is X-ray micro computed tomography (microCT), which is widely used for detailed 3D analysis of biological structures, see for example [5,6]. As analysis technique it is especially useful to analyze the inner structural details of samples, such as the lattice or foam core parameters in a natural light-weight system. The resulting strut thickness distributions can be used as inputs in a traditional design process, for replicating similar models, with more regular lattice designs suitable for engineering structures.

The body armour of the glyptodont, an extinct mammal related to modern-day armadillos, is the focus of the biomimetic design in this work. The reason for this particular body armour is due to its unique impact protective role - these animals are known to have been involved in intraspecific conflict involving tail-club blows, making its body armour crucially important. It was previously shown that the body armour of lizards might have multiple competing functions, such as thermoregulation and protection, depending on environmental and ecological conditions as shown in [7]. However, a physiological role of body armour is expected to be relatively unimportant in glyptodonts given their taxonomic position (i.e., ability to regulate body temperature metabolically). Therefore we assume that the main function of body armour in glyptodonts was protection as described in more detail in [4].

In this previous 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 [8,9], but the use of an additive manufactured system for this purpose was not investigated prior 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. In contrast to previously reported results based on laser sintered plastic samples, this work focusses on metal body armour units (Ti6Al4V). In addition to the reported properties of the first biomimetic impact protective metal samples to date, the produced samples are analysed by microCT showing impressive quality even for thin struts, making the results applicable for other work using lattice designs.
The glyptodont body armour comprises of adjoining hexagonal units called osteoderms - bony plates embedded in the skin. A selected glyptodont (*Glyptotherium* sp.) osteoderm was scanned by high resolution microCT using the hardware described in [10] and the morphological analysis including strut thickness and density was reported previously, as was the design of the reverse engineered simplified model [4]. Briefly, the osteoderm size and shape was replicated (28 mm diameter hexagonal shape, 12 mm high), with the “solid” cortical bone modelled as a solid shell of 1 mm and the internal foam core (trabecular bone) modelled as regular “diagonal” lattice. The lattice-shell combinations were created in Materialize Magics, with varying design parameters according to the specifications in Table 1. As shown here, the parameters investigated where the unit cell size, the lattice porosity and the shell thickness. The variation of the unit cell size of the lattice varies only the strut thickness but not the total density. Besides the lattice strut thickness, porosity and shell thickness, a model with no internal lattice and only shell was produced for comparison.

Table 1: Design parameters for samples tested in this work.

<table>
<thead>
<tr>
<th>Sample description</th>
<th>Shell</th>
<th>Unit cell size, mm</th>
<th>Design internal lattice core porosity</th>
<th>Design strut thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference reverse engineered lattice</td>
<td>1 mm</td>
<td>3 mm</td>
<td>80%</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Sample 1: thinner strut, same density</td>
<td>1 mm</td>
<td>1.5 mm</td>
<td>80%</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Sample 2: thicker strut, same density</td>
<td>1 mm</td>
<td>5 mm</td>
<td>80%</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Sample 3: thicker strut, same unit cell size as reference</td>
<td>1 mm</td>
<td>3 mm</td>
<td>62%</td>
<td>0.9 mm</td>
</tr>
<tr>
<td>Sample 4: thicker strut, same unit cell size as reference</td>
<td>1 mm</td>
<td>3 mm</td>
<td>43%</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Sample 5: thicker shell, no lattice core (same total density as reference)</td>
<td>1.5 mm</td>
<td>3 mm</td>
<td>100%</td>
<td>0 mm</td>
</tr>
<tr>
<td>Sample 6: thinner shell, thinner struts (same density as reference)</td>
<td>0.5 mm</td>
<td>3 mm</td>
<td>74%</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Sample 7: no shell</td>
<td>0 mm</td>
<td>1.5 mm</td>
<td>80%</td>
<td>0.3 mm</td>
</tr>
</tbody>
</table>

Ti6Al4V ELI samples were produced on an EOS M280 (200 W) machine using recommended process parameters for this material and 30 µm layer thickness. Stress relief heat treatment after the build was done at 650 °C in Ar atmosphere for 3 hrs. Samples were removed from the build plate and washed in ultrasonic bath. Two of the produced samples are shown in Figure 1, with the shell versions having holes added to the top and bottom shells to allow unconsolidated powder to be removed. Three samples of each type were produced, one of each was subjected to mechanical compression test, and one of each subjected to microCT scans [11]. MicroCT scans showed no remaining powder inside the samples.
Figure 1: Two of the produced Ti6Al4V biomimetic samples - lattice-only model (left) and a lattice-shell combination (right).

Quasi-static compression tests were performed using an Amsler press with 250 kN max and crosshead displacement measurement sensor attached. Energy absorption can be calculated from the stress-strain data as in [4,12]. In this work a qualitative assessment is made from the force-displacement curves, as all samples have the same geometry. The compressive strength of solid Ti6Al4V is expected to be roughly 900 MPa [13].

3. RESULTS AND DISCUSSION

The lattice-only model (number 7 in Table 1) is used to demonstrate the microCT analysis as it is relatively easily visualised. Figure 2 shows microCT results of this actual produced sample, in cross-sectional and 3D views.

Figure 2: MicroCT images of produced sample with lattice-only design (sample number 7).
Subsequent detailed microCT data analysis of the produced parts demonstrate the successful production of diamond-lattice struts with mean diameter of 0.2 mm as shown in Figure 3, which is excellent considering the single-track width is only in the region of 0.1 to 0.15 mm, depending on exact scanning parameters. The bi-modal strut thickness shown is due to the strut junctions which are thicker than the struts themselves. Similar work was reported on the manufacturability of microlattices of the same material type using the same process parameters indicating smaller strut thickness can be achieved [14].

Figure 3: MicroCT analysis of wall thickness of produced biomimetic lattice sample (number 7), showing strut thickness 0.2 mm and joints 0.27 mm.

Figure 4 shows the mechanical test results for the lattice-only model (sample number 7) to full densification. The initial yielding 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 (indicated in dashed line), before full densification. This typical response for lattice failure is useful for energy absorption and protection applications.
In the biomimetic reference design, a solid shell is combined with an internal lattice. The lattice core provides impact protection as it fails incrementally and yielding takes place continuously until final densification, as explained above. The shell provides additional strength, making the initial yield force higher for increasing shell thickness as shown in Figure 5 for a series of samples with no shell, 0.5 mm shell and 1 mm shell. In this case the initial yielding takes place at 12, 57 and 88 kN respectively. However, the yielding after initial failure differs: in the case of the 0.5 mm shell, the recovery is reasonable, with a plateau at approximately 35 kN. For the 1mm shell, the failure is more catastrophic, with the plateau after initial yielding below 10 kN. The sudden onset of initial failure creates damage to the internal lattice, removing its protective role, in the case of the thicker shell with very porous core. In this case, as the shell is made thicker, the lattice core is made more porous, hence having thinner struts.

The lattice core plays a role not only in the energy absorption and impact protection, but also a fundamental role in the system’s initial yield strength, as seen in Figure 6 - for denser lattice core (with same shell thickness of 1 mm), the strength is increased, and the plateau load is also increased. In this case the two denser models are significantly better for impact protection. The peak load of 180 kN is also impressive, considering it maintains a high plateau and hence protective role as well.
Finally, Figure 7 shows the effect of a variation of unit cell size in the internal lattice. In all three cases the initial yielding is at 85-90 kN indicating that this parameter does not affect the initial strength, as it is most affected by the shell thickness. In all three cases here, the plateau recovery and energy absorption is low, indicating yielding causes damage to the lattice irrespective of the strut thickness.

Figure 7: Effect of unit cell size - effectively strut thickness is varied while keeping porosity total constant. The strength is effectively identical, indicating that strut thickness (due to cell size change) does not play a significant role in the mechanical properties of a sample with relatively thick shell.

4. CONCLUSIONS

This work reports the first biomimetic study using metal additive manufacturing to date. In this work it was specifically shown that biomimetic impact protective samples could be manufactured by laser powder bed fusion in Ti6Al4V. Mechanical test results were reported, and samples show good strength and energy absorption as indicated by the force-displacement curves. It was shown that the lattice-shell combinations can combine to create good strength and high energy absorption during yielding, to provide impact protective properties. However, when the shell becomes too thick relative to the lattice core, the onset of initial failure causes damage to the internal lattice, removing its protective role. Conversely, lack of shell provides little strength against damage and low energy absorption in total. There are therefore ideal combinations of shell thickness and lattice porosity. The results indicate that for the size and thickness of this biomimetic body armour unit in Ti6Al4V, a 0.5 mm shell with 80% porous lattice core provides a good response, or thicker shell (1 mm) with denser internal lattice (60% or 40% porosity only) for higher strength and energy absorption.

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X-RAY MICRO-CT SUPPORTING THE SOUTH AFRICAN ADDITIVE MANUFACTURING COMMUNITY

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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 non-destructive quality inspection of additive manufactured parts; and also for advanced process optimization. These new capabilities are all locally available but not yet utilized to their 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.

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1. INTRODUCTION

Micro computed tomography (microCT) is now widely accepted as a powerful non-destructive testing method especially valuable for additively manufactured (AM) parts. As a non-destructive analysis method it has numerous industrial applications as reviewed in [1], where AM is also mentioned. The method had evolved over the last decade from a qualitative imaging technology to a quantitative materials science tool, with particular applications in understanding internal material structures [2]. It is widely known for its ability to visualize internal features, and is most widely known and used for porosity or flaw detection. This is particularly relevant to additive manufactured parts, as porosity and even major flaws might be present especially when process parameters are not optimized. The non-destructive inspection of complex AM parts is therefore crucial and is required for the qualification of such parts and the processes that produce them for particular applications [3]. The qualification and standardization needs for AM has been reviewed recently and microCT is a crucial aspect [4,5]. Besides the use of microCT for defect detection, many other microCT capabilities are still underutilized and some are still being developed as discussed in a recent review paper on the use of microCT in AM [6]. These new microCT capabilities have evolved due to recent improvements in hardware and software, especially with customized image analysis procedures, coupled with improvements in computing resources. These new capabilities include measurements of surface roughness, localized 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 were all mentioned in [6], but are discussed here in the context of their usage in local projects. Technical details are not included but details about the X-ray microCT facility and optimization of parameters may be found in [7,8].

2. POROSITY AND FLAW DETECTION

The Stellenbosch microCT facility, which is described in more detail in [7] was first officially launched in April 2012, with interested AM users from CUT attending this event and providing test samples. In these first analyses of an AM Ti6Al4V part, porosity and layered defects were observed in the complex shaped part. This sample was known to have been produced under non-ideal conditions but it was not known if there were flaws present inside the part. This interesting layered defect was later published after additional HIPping of the same part, to see if these defects could be closed by the HIP process [9]. This type of defect is caused by stop-start cycles and are more recently referred to as stop-start flaws. In the same year (2012), another type of defect was observed: near-spherical pores arranged in 3D in a regularly-spaced checkerboard pattern. This was later reported in a paper [10] without details of its origin, as an example of directionality of porosity in AM parts. As shown in Figure 1 in a cross-sectional view, the pores are arranged in a checkerboard pattern in this case with a 0.2 mm spacing. This spacing corresponds roughly to the track width and might be the result of lack of fusion occurring between tracks in the same layer (between individual parallel tracks), but the subsequent 90 degree rotated layer of tracks does the same, effectively remelting the areas with porosity in the previous layer also, to leave only the intersection areas with pores. This requires further investigation and might be complicated by scan strategy but similar results were reported for different scan strategies also using microCT analysis in [11]. It was recently confirmed that there were scan errors in this system since 2012. Clearly the ability for microCT to detect and visualize the 3D distribution of the porosity might in future assist to more easily and quickly identify such manufacturing errors, and thereby ensure high density parts with good mechanical performance. This use of non-destructive testing has also been mentioned as part of process monitoring, for correlating in-situ detection with post-process analysis and thereby build a better understanding of the process [12]. More recently the production of AM parts with induced pores and cavities were used to test acoustic detection methods and used microCT to correlate the detection capability of the acoustic methods, as a “ground truthing” [13].

![Figure 1: Two orthogonal thin slice views of the same sample showing regular pore spacing of 0.2 mm: (a) side view, (b) top view.](image-url)
also be inspected, which can be done non-destructively. This may be critical for high performance parts and for medical implants. Over the last few years, medical implants produced by CUT have been tested often prior to implantation into the patient. The microporosity is always minimal and usually < 0.1% with mean pore sizes of 30-50 µm as reported in [14]. However, there have been isolated cases where microCT identified critical flaws and the part has had to be built again. While a full implant cannot be analyzed at the highest possible resolution by microCT, it can identify major flaws such as stop-start flaws, and in case of such detection, the area of interest can be scanned at higher resolution for a more clear view of the extent of the defect (and possibly a more quantitative assessment). For this reason microCT forms part of the ISO accredited workflow for the production of additively manufactured implants at CUT.

The ability to detect porosity and internal voids in AM parts was investigated in detail with test parts produced and is reported in [15]. Furthermore, the shape of porosity in AM parts was analyzed in tensile test parts at different stages of loading, indicating pore coalescence prior to tensile fracture [16].

3. SURFACE SCANNING COMBINED WITH MICRO-CT

This example showcases a new capability which is surface texture scanning, combined with microCT scanning. By scanning the same sample with a handheld scanner (Artec Eva or Spider) and by microCT allows the ability to produce realistic 3D textures of the surface while also allowing internal analysis of the microCT data. This is demonstrated on a bracket built in Ti6Al4V, shown in Figure 2. The main advantage of this new combination of data sets for additive manufacturing, is the cross-referencing capabilities - when a part is too large or dense, microCT data is noisy and might lose surface information in places - at these locations the surface scan could be used. On the other hand microCT is often more accurate and provides additional internal information and information from hard-to-reach locations.

Figure 2: Surface scan combined with microCT - surface texture combined with microCT data is a new data merging capability. The bracket in the image to the right contains evenly distributed porosity at a level of 0.3%.

4. POROSITY HOTSPOT ANALYSIS

In the above example in Figure 2, evenly distributed porosity is seen in the bracket, at an average level of 0.3%. Even when the average porosity is much lower, the size and location of these pores are important, as they may be in a line, in a layer or clustered. Clustered pores may be analyzed by a new local porosity hotspot analysis which is demonstrated for AM parts for the first time here. The density of this part is excellent, and it contains minimal porosity at an average value of less than 0.01%, but as shown in Figure 3, the porosity is clustered right below the top surface, especially in flat areas - this indicates the origin of this type of porosity might be due to processing conditions in the finishing step, which are optimized for surface finish rather than microporosity.
5. DENSITY

While porosity analysis is popular, often samples are subjected to Archimedes tests for density. The Archimedes test is well known and very accurate for ideal samples - however there may be open porosity, inclusions, incorrect alloy content, or bubbles attaching to the rough surface of as-built parts, causing erroneous measurements. By using microCT data and sub-voxel precise surface determination, it is possible to calculate volume and hence density directly from microCT scans, without the need for detection of porosity in the images. This requires very high scan quality and advanced software tools to allow sub-voxel precision, something which is not always available and was not available at the Stellenbosch CT facility until 2014. Prior to this, various analyses were possible, but precision was limited to basic edge determination tools as shown in a Rapdasa proceedings paper in [17]. The advanced surface determination is demonstrated on a 10 mm Ti6Al4V cube in Figure 4, showing the 3D interpolation of grey values to determine the exact surface location - with high scan quality this can be as accurate as 1/10th the voxel size. This allows accurate measurement of volumes, which allows effectively a direct microCT density measurement method.
6. SURFACE ROUGHNESS

Another important development is the capability to use a precise surface as shown above, and measure the surface roughness of as-built parts. This only works for small samples, for example 10-15 mm in size or diameter. When this is the case, the voxel size is approximately 15 \( \mu \text{m} \), in which case 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 (compared to traditional line-mapping for roughness), and the possibility to detect undercuts and hidden irregularities, even non-flat geometrical surfaces such as cylinders can be assessed as shown in Figure 5. This part was produced on an Optomec LENS system at CSIR.

7. DIMENSIONAL MEASUREMENT AND CAD VARIANCE

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. The bracket shown in Figure 6 is compared with its CAD design showing warping of up to 0.5 mm on the top parts (inwards). The STL design data is visualized as a wireframe in yellow in this case. It is also not so widely known that the microCT data can be easily exported in the form of a surface STL file. This simple data type and overlap of data is useful to assess the location of holes or important features in a built part, compared to its design. One important application of microCT in the near future might be analysis of the part geometry after HIP processing. HIPping is often used to close porosity, even very large pores can be closed effectively as shown in [18]. However, as shown in this study, near-surface pores might not be effectively closed, and these pores might be the critical ones for good fatigue life of the parts, as cracks may form between the surface and near-surface pores under cyclic loading. Furthermore, HIPping may force open near-surface pores, or cause other forms of macroscale deformations as shown in [19]. Such deformations may be analysed effectively by CAD variance analysis, and the
additional benefit of using microCT is the ability to visualize the internal details (eg. is there a large pore sub-surface at the location of a surface indentation after HIP?).

Figure 6: MicroCT analysis of complex parts for geometrical accuracy - using a CAD variance analysis. The yellow wireframe shows the CAD design.

8. STRUCTURAL MECHANICS SIMULATIONS ON REAL PARTS

Finite element modelling (FEM) is often used to assess a new design, but it has also recently become possible to directly make such simulations on microCT data. As shown in Figure 7, a jawbone implant was produced by AM, containing microporosity and its exterior as-built geometry was significantly different than designed. When a simulation is applied, the stress distribution can be analysed and at the locations of high stress, the interior can be assessed for porosity and wall thickness, to assess the risk in using the part. This method therefore uses the actual geometry of the part and its internal pores, which provides a more accurate estimate of the stress distributions and displacements across the part, assuming linear elastic material properties. This method has not yet been used widely but was recently used in a study of biomimetic design of lattice structures [20] and its use is well documented in supplementary material in [21]. The method was also used to analyse the effect of large casting porosity on the stress distribution and resulting mechanical properties of cast Ti6Al4V in [22]. While this latter work is not focused on additive manufacturing, the effect of pores on the mechanical properties is very relevant and this work showed that even large pores (4 mm diameter) do not strongly affect the static tensile strength of cylindrical tensile bars 8mm in diameter, when the pores are deep inside the material (not on surface). This is not a general statement but indicates the added value brought about by direct simulation including pores, especially for complex geometries and irregular pores. The stress concentrations found by these simulations might be indicative of fatigue life also as demonstrated with the same method applied to additive manufactured brackets in [23].

Figure 7: MicroCT-based structural mechanics simulation highlighting high stress region in as-built jawbone implant.
9. OTHER IMAGE BASED SIMULATIONS

Other image-based simulations are also relevant to additive manufacturing, especially the simulation of permeability. This was recently used in a study comparing various lattice structure designs meant for additive manufacturing [24]. An example is shown in Figure 8 of a minimal surface unit cell design, with permeability simulation showing velocity flow lines. It is also possible to make such simulations on real produced sample data, thereby incorporating rough surfaces, warping or unconsolidated powder stuck inside the lattice.

Figure 8: Permeability simulations directly on voxel data.

10. ADVANCED MORPHOLOGICAL ANALYSIS

Some advanced methods of analysis are possible for application on structures such as lattices produced by additive manufacturing - in the image in Figure 9, individual struts are selected and thickness analysis applied using a method measuring the largest sphere that fits the strut. In this way it can be easily visualized that the vertical strut is thinner than the horizontal strut, and the values can be quantitatively measured for comparing different samples, for example.

Figure 9: Thickness analysis of horizontal and vertical struts in a cubic lattice structure.
11. PLASTICS

Since 3D printing of plastics is mainly used for prototyping and not for critical parts, microCT is not widely used for this type of material. However, there have been some local projects where ABS and PLA filaments were analyzed by microCT showing the presence of dense particles which could block the nozzle [25] – present in some filament types. In another study the quality of 3D printed models were compared by microCT for two different filament types on two different 3D printers [26]. Since plastics are used for prototypes, they can be used to better visualize 3D models especially from microCT scans of interesting objects such as museum specimens as shown for a mummy falcon [27,28] and more recently to visualize a hairy stalagmite – a complex biological root system in a stalagmite, of which a part of the model was 3D printed to better understand the complex interconnections [29].

12. AUTOMATION AND STANDARDIZATION

One of the major drawbacks of microCT is its cost and complexity as each part needs custom analysis workflows. In a recent development, a series of methods were developed for simplified analysis workflows using standard sample sizes, scan settings and image analysis procedures. These may contribute to the higher usage and lower cost of the technique, and its more productive use in additive manufacturing. The methods involve the production of a 10 mm cube, which is used for detailed microporosity analysis – this can be used for process optimization and validation [30]. The same cube than then also be analysed for its bulk density using microCT volume and scale mass [31]. The same data can be used to assess surface roughness as demonstrated in [32]. A 15 mm rod can be built during the production of a complex part and this witness specimen can be scanned with fixed parameters irrespective of the complex part size – this also contributes to standardization in the analysis process and allows detection of potential layered flaws [33]. A standard method for analysis of powders was also developed [34]. The automation of the analysis workflow will greatly contribute to higher throughput, but this is still under development. A first round robin test were parts were produced at various facilities and tested using these standard methods was completed and can be found in [35]. A second round robin test is currently underway, where 3 selected parts from this first test, is analysed at various microCT facilities worldwide using the standardized workflows.

13. CONCLUSIONS

This paper has shown the many ways in which microCT can support the AM community, with a variety of new methods that have recently been developed. South African examples are provided of each of these methods, with some of them being the first such cases reported in scientific literature. Furthermore, interesting use cases of microCT in AM over the last few years in South Africa were highlighted. Not all projects were mentioned as some were not published and many were meant only as preliminary investigations. The development of standardization techniques was discussed and work in progress in this domain is set to improve the simplicity and ease of use of the technique. MicroCT will continue to support the quality inspection and improvement of AM part integrity.

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INVESTIGATION OF IN-SITU ALLOYING GRADE 23 Ti WITH 5at.%Cu BY LASER POWDER BED FUSION FOR BIOMEDICAL APPLICATIONS

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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 homogeneity, porosity and process parameters were studied.

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1. INTRODUCTION

Infection is one of the common reasons for postoperative complication if a patient received a bone implant. As indicated by Goldfarb et al. (2017) in their review, after orthopaedic replacements, the most common complications are: infection, impaired healing, and bleeding affected by surgical and patient risk factors [1]. Bacterial infection of a prosthesis is a severe complication because, in general, the infected prosthesis implant has to be removed in order to cure the infection and a re-implantation operation 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 to prevent infection [3, 4]. Cu additions at the bone-implant interface reduce the risk of bacterial infection and therefore implant failure [3-5].

The advantage of laser powder bed fusion (LPBF) is that complex shapes can be produced which enables production of custom once-off components, for example bio-medical implants shaped to fit the patient and the exact requirements for bone replacement, but the part quality depends on the manufacturing parameters used. To avoid problems in LPBF; careful selection of process parameters and manufacturing strategies for employed powders by different LPBF systems should be used to avoid porosity from incorrect processing parameters or build conditions, surface roughness and cracks, and reduce high residual stresses and deformation during processing. Due to these challenges, especially for high value and critical parts, such as those for aerospace or medical applications, require process qualification and part quality must be validated. This is discussed in a general review of additive manufacturing (AM) [6] and a review of the use of micro computed tomography for overcoming these issues [7].

The goal of this work was to find optimal process-parameters (based on density and homogeneity of Cu distribution) for LPBF Ti6Al4V-5 at.%Cu in-situ alloyed material for biomedical applications and to study the resulting microstructure.

2. METHODOLOGY AND RESULTS

2.1 Materials and methods

Argon atomized Ti6Al4V (ELI) and Cu powders with spherical particles were used. Chemical composition for Ti6Al4V (ELI) was 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 (TIS Solutions, LLC). The 10 th, 50 th and 90 th percentiles of equivalent diameter (weighted by volume) were respectively 12.6 µm, 22.9 µm, 37.0 µm for Ti6Al4V (ELI) powder and 9.45 µm, 21.9 µm and 37.5 µm for Cu powder, which means the powder sizes were practically identical. To produce the Ti6Al4V-5 at.% (6.5 wt%) of 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 without protective atmosphere, to increase powder flowability. To determine optimal laser power and scanning speeds, single tracks with length of 20 mm, single layers and 10 layer samples with size 5 mm x 5 mm 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 speeds and 340 W at double the scanning speed accordingly (0.8-2.8 m/s). The powder layer thickness was about 50 µm for single tracks and 30 µm for 3D samples. The building chamber was filled with Ar. Experiments were done on Ti6Al4V substrates with 3 mm thickness.

Single tracks were analysed from top view and then cross-sectioned by wire cutter. Porosity and microstructure of 10-layer samples were studied by optical and scanning electron (SEM) microscopes. SEM was carried out with LEO 1350 FEG operated at 20 kV.

2.2 Results

The morphology of single tracks depends on the laser power and scanning speed. Balling effect started at 1.2-1.4 m/s for 170 W and at 1.6 m/s for 340 W (Fig. 1). Similar results were found by Yadroitsava et al. (2015) for pure Ti6Al4V ELI powder without Cu addition: at 45 µm powder layer, a balling effect started for 170 W laser power at scanning speeds above 1.4 m/s. Further analysis of single tracks showed that at a lower scanning speed of 0.4 m/s more satellites occurred at lateral sides of the tracks (Fig. 2).

For 170 W, the width of the tracks varied from 110 µm at high scanning speeds and shorter interaction time (laser spot diameter divided to the scanning speed) up to 220 µm at 0.4 m/s (Fig. 3a). In terms of linear laser energy density (the ratio of laser power to the scanning speed) no significant difference was found in track width for the similar laser power density (Fig. 3b) which is in accordance with previous results [8]. Analysis of the profile of single tracks shows that at 340 W tracks at scanning speeds V=0.8-1.2 m/s had a smoother surface than the 170 W tracks (Fig. 4).
Fig. 1. 3D reconstruction of single tracks using SmartZoom 5 digital microscope: at 170 W (a) and 340 W (b).

Fig. 2. Satellites at 170 W laser power and 0.4 m/s scanning speed.
Fig. 3. Top view measurement of track width versus scanning speeds (a) and linear energy input (b).

Fig. 4. Profiles of tracks at 170 W (a) and 340 W (b) laser power and 1.2 m/s scanning speed.

Analysis of the cross-sections revealed that keyhole mode of laser melting was at 170 W and 0.4-0.6 m/s and for 340 W laser power at 0.8 m/s (Figs. 5 and 6). High laser power lead to high temperatures and when the absorbed energy was sufficient to cause evaporation of the metal, a vapour cavity enhanced the absorption and the laser beam created very deep (V-shape) molten pool (Fig. 6a, scanning speed 0.4-0.6 m/s and Fig. 6b, scanning speed 0.8 m/s). For all other cases, transition or U-shape molten pool, was found. Conduction mode or semi-cylindrical shape of the molten pool was not found.

As Khairallah et al. [9] described, for LPBF, high temperature gradients below the laser beam creates gradient of surface tension that is highly temperature-dependent. That, in turn, creates Marangoni effects and drives the melt flow from the hot laser spot toward the “cold” areas. The recirculated melt flow cools molten metal and leads to spattering, as liquid metal with low viscosity ejects away from the surface. Liquid forms build-up (or “bow wave”) that leads to spattering. The high vapour surface flux (or “gas plume”) exerts a pressure force that ejects liquid metal. When the liquid metal pool elongates, it thins out and breaks up into small droplets due to surface tension tendency to minimize surface energy. The elongation is in the radial direction to the laser spot and pointing away from the melt pool. Thus, more expressed sparking and balling effects can explain stronger variation of width of the tracks at higher laser power.
Fig. 5. Penetration depth versus scanning speeds (a) and linear energy inputs (b).
Fig. 6. Cross-sections of single tracks at 170 W (a) and 340 W (b).

By taking the width of the powder tracks into consideration, 80 µm hatch distance was chosen for overlapping for the 3D samples with 10 layers.

Collapse of the created cavity in keyhole mode can leave voids in solidified material. This was clearly seen in cross sectioned analysis of 3D samples (Fig. 7a). It must be noted that big pores were produced in the 170 W samples. At lower laser power the collapse of keyhole happened quicker and created bubbles which did not have enough time to reach the melt pool surface before solidification. Higher laser power led to higher temperature and, respectively, lower viscosity of molten pool which facilitates gas bubbles to escape to the surface of the molten pool. The walls of the capillary are unstable and oscillating in keyhole mode during laser welding and the formation of porosity is very sensitive to the shape of the molten pool at the laser end time [11]. In LPBF, similar phenomena were found [12]. Since small perturbations in the process can cause porosity from LPBF samples during keyhole mode, process-parameters such as 0.4–0.6 m/s, 170 W and 0.8 m/s at 340 W with a powder layer thickness about 50 µm can’t be considered as optimal process-parameters for this in-situ alloyed material.
Fig. 7. Cross-sections of 10 layer samples at 170 W, 0.4 m/s (a) and 340 W at 0.8 m/s (b), keyhole mode.

As it has been shown earlier [13, 14], balling effect provoked porosity in 3D samples. Big pores were found in 3D samples processed at 170 W and 1.4 m/s. Unfused powder particles are clearly visible from the cross-section (Fig. 8a). Interlayer pores were also found at 340 W laser power when scanning speeds were above 1.6 m/s and balling effect occurred (Fig. 8b).

Fig. 8. Cross-sections of 10 layer samples at 170 W, 1.4 m/s (a) and 340 W and 2.4 m/s (b), balling effect. Black colour is porosity.

At laser power 170 W and scanning speed 0.8-1.0 m/s and 340 W and scanning speed of 1.2 m/s, and hatch distance of 80 µm non-porous 10 layer samples were formed (Fig. 9).

Distribution of elements in the 10-layer samples were not always perfectly homogeneous (Fig. 10). According to SEM EDS, a gradient zone, where the substrate contributed in the chemical composition of the coatings started at 200-250 µm in depth. Point chemical analysis showed that variations of Cu are present within the layer. For example, areas with about 25 wt.%Cu and 15 wt.%Cu were observed in specimen manufactured at 170 W 1.0 m/s, and 340 W 2.0 m/s respectively.

Fig. 9. Cross-sections of 10-layer samples (etched by Kroll’s reagent) at 170 W and 0.8 m/s (a) and 340 W and 1.2 m/s (b). Images by optical microscope.
The most homogeneous were specimens manufactured at 170W and 0.4 m/s and 340 W and 0.8 m/s. Nevertheless, those specimens contained porosity and were manufactured in a keyhole regime. Higher energy input has positive effect on the homogeneity of the elements; this could be ascribed to fluid flow caused by higher temperate gradients and the re-melting of previous layers due to the large penetration depth (approximately 4 times powder layer thickness see Fig. 5).

![Image of comparison between maximum and minimum energy input at the different laser powers.]  
**Fig. 10.** Comparison between maximum and minimum energy input at the different laser powers. BSE SEM images.

No unmolten Cu particles were observed in any specimens. Some round particles observed on etched cross sections were, according to the EDS observations unmolten particles of Ti6Al4V alloy as shown in Figure 11.

![Image of EDS observations of unmolten Ti6Al4V alloy particles.]  
**Fig. 11.** EDS observations of unmolten Ti6Al4V alloy particles at 340 W and 2.8 m/s (indicated by arrows). Scanning electron image (a) and inhomogeneous copper distribution in white (b).

Possibly due to volatilization, concentration of Cu compared to the nominal values of the feedstock, the specimens were slightly lower than nominal 5 at% Cu in powder mixture.

All recorded data is presented in Table 1. Non-porous and homogeneous samples can be produced at 170 W, between 0.6 and 1.0 m/s and 340 W near 1.2 m/s.
### Table 1: Summary of findings for all parameters.

<table>
<thead>
<tr>
<th>Energy (W)</th>
<th>Low porosity</th>
<th>High porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>170 W</td>
<td>Big pores, elements homogeneous</td>
<td>Small porosity, elements homogeneous</td>
</tr>
<tr>
<td>340 W</td>
<td>Small porosity, elements homogeneous</td>
<td>Non-porous, elements homogeneous</td>
</tr>
<tr>
<td>0.6 m/s</td>
<td>Non-porous, elements slightly inhomogeneous</td>
<td>Small pores, elements inhomogeneous</td>
</tr>
<tr>
<td>1.0 m/s</td>
<td>Non-porous, elements slightly inhomogeneous</td>
<td>Pores, elements inhomogeneous</td>
</tr>
<tr>
<td>1.2 m/s</td>
<td>Unmolten Ti6Al4V, pores, elements inhomogeneous</td>
<td>Unmolten Ti6Al4V, pores, elements inhomogeneous</td>
</tr>
<tr>
<td>1.4 m/s</td>
<td>Unmolten Ti6Al4V, pores, elements inhomogeneous</td>
<td>Unmolten Ti6Al4V, pores, elements inhomogeneous</td>
</tr>
</tbody>
</table>

### 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 could be carried out includes investigation of the distribution of the elements at higher layer thickness with similar parameters, and further fine tuning of optimal parameters. This paper showed that the process window is very small and homogeneity of copper within this zone needs further refinement. Antimicrobial activity, mechanical properties and microstructure of in-situ alloyed Ti6Al4V-5 at.% Cu needs further investigation.

### REFERENCES


INVESTIGATION ON THE SUITABILITY OF POLYMERS FOR SELECTIVE LASER SINTERING USING NOVEL MID-IR LASERS

L. Wu*, W. Koen, A. Singh and A. Sharma

ABSTRACT

Selective laser sintering (SLS) 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-infrared 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 infrared spectroscopy and laser transmission welding experiments. Some of the suitable materials include high-density polyethylene (HDPE), acrylic (PMMA) and the biopolymer polylactic acid (PLA).

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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. This AM technique enables the production of rapid prototyping tools as well as complex actual end-use parts. There is a growing demand to process a greater variety of polymer materials than is currently available in the market, presently limited to a handful of polymer types. It has been reported that polyamides comprise 90%-95% of all laser sintered parts [1]. This dominance is due to the high number of technical constraints that are placed on the material characteristics which must be specially developed for AM processes, and is a major stumbling block towards the progression of SLS technology.

In the SLS systems used to produce polymer parts both commercially and in R&D laboratories, the lasers employed are predominantly CO2 lasers ($\lambda=10.6\ \mu m$) [2]. These laser systems are convenient because many polymers exhibit significant absorption around that wavelength. Nevertheless, certain polymers such as polyolefins (e.g. polyethylene and polypropylene) are highly transmissive at 10.6$\ \mu m$, and are not laser processible without the introduction of additives (e.g. carbon black) to modify its absorption behaviour. This constrains the colour choice of polymers available for use in SLS parts. On the other hand, thermally sensitive biopolymers such as polylactic acid (PLA) exhibit such strong absorption at 10.6$\ \mu m$ that attempts at 10.6$\ \mu m$ SLS have been unsuccessful thus far as a result of rapid heating and consequent material degradation. A modified SLS using 1$\ \mu m$ laser was able to process PLA, but it required the incorporation of absorbing additives [3]. Similarly, processing of other polymers using 1$\ \mu m$ lasers or other high power near-IR diodes suffer from high optical transmission and absorbing additives are needed to melt the polymers [4].

The advent of 2$\ \mu m$ wavelength lasers offers an attractive alternative in laser processing of polyolefins and several other polymers which exhibit moderate 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.

Before SLS process optimisation can take place, the properties of the polymer powder needs to be evaluated first. These include various intrinsic material properties (thermal, rheological and optical) and extrinsic powder properties (powder flowability, distribution, shape) [2].

This work aims to identify, amongst a large variety of polymers, some of the thermoplastic polymers that are processible with 2$\ \mu m$ lasers with a view toward SLS applications.

1. METHODOLOGY

1.1 Materials

A selection of common thermoplastic polymers (PMMA, PC, PP, POM-C, HDPE, PA6), each being 1mm thick, were locally procured for these experiments. PC and PMMA (polycarbonate and acrylic, respectively) are amorphous and transparent, while the others (polypropylene - PP, polyacetyl copolymer - POM-C, high density polyethylene - HDPE, and nylon 6 - PA6) are semicrystalline and semi-transparent to white in colour. Black PMMA and HDPE sheets, doped with absorbing additives, were also obtained. These six polymers were chosen based on their expected absorption around the laser wavelength of the 80 W Tm-doped fibre laser ($\lambda=1940\ nm$) used for this study. The PLA-based thin film (~50$\ \mu m$ thick) was supplied by CSIR Materials Science & Manufacturing, and is a semicrystalline material. Transmittance in the infrared spectrum was measured using an ABB MB3000 Fourier transform infrared (FTIR) spectrometer.

1.2 Laser system configuration

A continuous wave 1940 nm fibre laser, with output power levels up to 30W, was used to determine the extent of laser-polymer interactions. A scanning system was built and configured to enable sweeping of the laser beam across the polymer strip(s) at a speed of 460mm/min. The beam diameter was 410$\ \mu m$ and remained unchanged across the path of the scanned region. Polymer strips are clamped vertically in a xyz-translation stage and the entire setup is enclosed and purged with dry air.

1.3 Laser-polymer experiments

Laser-polymer interactions were explored in three stages: Firstly, to determine the laser power threshold at which the thermoplastics begin melting. Secondly, attempt to overlap weld clear/neutral to black polymer sheets together using the commonly-used transmission laser welding (LTW) method. Thirdly, perform joining of clear-to-clear polymers via through transmission welding (TTW).
LTW is the traditional method for lap welding of polymers, but this technique restricts the lower polymer layer to be absorbing and dark in colour, while the upper layer must be transparent to the laser beam. These requirements limit the colour combinations in the welding of polymer sheets. Preferential energy deposition takes place at the heat affected zone (HAZ), where melting and diffusion of the material in the interfacial/weld plane occurs and a weld formed. Figure 1 illustrates the principle of LTW.

![Figure 1 Laser transmission welding of two polymer sheets, comprising a laser-transparent upper layer, and an absorbing lower layer.](image)

On the other hand, 2µm lasers remove such a requirement in TTW, enabling the welding of clear-to-clear and other colour combination polymers. Note that the joining of clear-to-clear polymers cannot be done using conventional CO₂ lasers or near-IR diodes (λ~900nm) without introducing additives.

The quality of the laser welds were inspected by using a Thorlabs Model OCS1300SS swept-source optical coherent tomography (OCT) system, with a lateral resolution of ~20μm.

2. **RESULTS AND DISCUSSION**

2.1 **Laser Absorption by Thermoplastics**

Figure 2 shows the measured FTIR transmission spectra for the various thermoplastics sheets and film. Absorption features from the -C=O 2nd overtone and -OH combination vibrational modes are present in the chemical make-up of all the selected polymers and can be observed at wavelengths around ~1.95µm and ~2.1 µm, respectively. The moderate absorption (30 - 83% transmittance around 2 µm) in these polymers implies that they should therefore be laser processible. The decreasing transmittance towards the shorter wavelengths is ascribed to scattering from crystallites present in the semicrystalline polymers (PP, POM-C, HDPE, PA6, PLA), and is not as a result of material absorption. This decrease is not found in the amorphous polymers PC and PMMA.

![Figure 2 FTIR transmission spectra of 1 mm thick neutral or clear polymer sheets and a PLA film (~50 µm). The scale for PP was magnified by 50x for ease of comparison.](image)
Optical micrographs of some of the neutral or clear polymers exposed to a single laser scan are shown in Figure 2. All of the polymers tested had melted under laser radiation. The thickness of the melt tracks depended on the laser power, material absorption, the crystallinity of the polymer and its thermal conductivity.

It is evident that natural or clear polymers, containing no additives, can be processed and melted with 2µm lasers. Both of the polyolefins HDPE and PP, not processible by CO₂ lasers and NIR diodes without additives, have shown heat-induced melting upon exposure to the 2µm laser beam at power levels no larger than 30W.

With the exception of PMMA at low power levels (~3.5W), it was also noticed (not shown) that all other laser processed polymers contain raised features, or beading, on the surface along the melt tracks. These features can also be seen in the welding results in the next section.

![Figure 2 Top view optical micrographs of laser-melted tracks on (a) HDPE, (b) PA6, (c) POM-C, (d) PP, (e) PMMA, and (f) welded PLA films.](image)

### 2.2 Laser Welding of Thermoplastics

Two of the polymers were further selected as examples, one semicrystalline (HDPE) and another amorphous (PMMA), to affirm their processibility with 2µm lasers. Two different forms of lap welds (LTW and TTW) were successfully used to join two 1mm thick HDPE sheets, as well as two 1mm thick PMMA sheets together. Cross-sectional images of these laser welds, collected using the non-destructive OCT imaging technique, are shown in Figure 3.

At the interface between the laser transmission welded (LTW) neutral-on-black HDPE, in the red circled region there are faintly visible boundary lines between them, implying little change in the refractive index and no air-gap. There was a small round white feature in the centre, however, which is indicative of some splash back and non-uniform mixing between the neutral and black layers in the HAZ due to excessive heat.

In contrast, for the clear-on-clear TTW of HDPE and PMMA sheets, no splash back can be observed. Much lower energy reached the interface, 1 mm below the surface, due to some absorption by the material of the 2µm laser radiation. There is, however, some splash back on the surface, due to the higher incident laser energy and rapid absorption. The melted surface expands quickly and then cools down, resulting in bead formation [5].
It is seen that conventional LTW using 2µm lasers was already achieved at very low power levels of 3.5W for both semicrystalline HDPE and amorphous PMMA. Weld thicknesses of ~780µm and 400 µm for LTW of HDPE and PMMA, respectively was measured. For TTW, the weld thicknesses were 260µm and 390µm For TTW of HDPE and PMMA, respectively.

The HDPE weld seam is smaller than PMMA at the same laser input power because of crystallite scattering experienced in the semicrystalline material; hence less energy is transmitted through to the interface. In SLS processing, HDPE will need higher laser power to process compared to PMMA.

![Figure 3 Cross-sectional OCT images of welded 1mm thick polymer sheets (a) HDPE LTW at 3.5W, (b) HDPE TTW AT 8.0W, (c) PMMA LTW at 3.5W, and (d) PMMA TTW at 8.0W.](image)

The PLA films also welded well with a seam width of ~500 µm (see Figure 2(f)), which is slightly larger than the laser beam width but with no apparent visible 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.

For the fabrication of SLS parts within reasonable timeframes, the scan speed needs to be much higher than the current welding setup and linked to that, an increase in laser power.

The successful welding of HDPE, PMMA and PLA sheets and films are a good indication that particles (of average ~50µm in size) produced from these materials can be melted and subsequently sintered together with very little difficulty.

It also demonstrates that transparent and white polymers (HDPE, PMMA and PLA), unlike in 1µm SLS systems, can also be laser processed using 2µm lasers and therefore for 2µm SLS. Thus far, the only commercial SLS powder available for 1µm SLS systems is a grey-black nylon powder [6]. Furthermore, polyolefins such as HDPE, not processible using CO2–based SLS systems without incorporating additives, was shown to be possible at 2µm.

3. CONCLUSIONS

A number of thermoplastic polymers were experimentally verified to be processible with 2 µm lasers. Successful laser welds were demonstrated on amongst others white or transparent HDPE, PMMA sheets and PLA films. These imply favourable melting and sintering characteristics for 2 µm SLS systems. Further polymer characterisation, including DSC and TGA, will assist in determining the process parameter space to be used for SLS.

SLS using 2µm lasers should find favour over NIR diodes and 10µm lasers as they are considered “eye-safe”, in addition to being able to process transparent polymers without any additives.
ACKNOWLEDGEMENTS

The authors wish to acknowledge Dr S. Muniyasamy of CSIR Materials Science & Manufacturing (Polymer & Composites) for supplying the PLA-blended film used in this work.

REFERENCES

MAXILLOFACIAL PROSTHESES PRODUCTION THROUGH COMPUTER-AIDED DESIGN AND MANUFACTURING TECHNOLOGIES - REVIEW OF STATE OF THE ART

I. Van Heerden\textsuperscript{1*}, A. Fossey\textsuperscript{2} and J.G. van der Walt\textsuperscript{3}

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.

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1. INTRODUCTION

The incidence of trauma has shown a constant upward trend worldwide. Many people suffer one or other disfigurement. Facial trauma has been shown to be strongly associated with road traffic accidents, assaults, burns and cancer [1]. The World health Organisation has estimated that more than 3,000 people are killed every day on the road; at least 30,000 others are injured or disabled; over 1.2 million people are killed, and as many as 50 million injured each year. More than 50% of patients with these injuries have multiple traumas requiring coordinated management among various disciplines of anaesthesiology, otolaryngology, trauma surgery, plastic surgery, ophthalmology, and oral and maxillofacial surgery [2]. The high incidence of road traffic accidents and assaults in South Africa, also add to the statistics of facial trauma patients; many from disadvantaged communities.

Globally in 2004, the incidence of burns severe enough to require medical attention, was nearly 11 million people and fourth in all injuries, after road traffic accidents, falls, and interpersonal violence. This number is greater than the combined incidence of tuberculosis and Human Immunodeficiency Virus (HIV) infections, and just slightly less than the incidence of all malignant neoplasms [3]. Burn injuries constitute one of the most important public health issues in developing, as well as in the developed countries [4]. Burns in South Africa have also been considered as one of the major contributors to facial trauma. In South Africa, burns affect 3.2% of the population annually, and are particularly common in children and young adults [5]. Shack fires and primus stoves are of the major sources of burns in South Africa [6].

Congenital or acquired facial disfigurement presents a serious psychological and social challenge to the individual who has to cope with an appearance that is obviously different, hard to conceal, and subject to social stigma [7]. People with facial disfigurements are faced with the challenges of social reactions and their own psychological responses to looking different [7]. They fear of not being accepted in society, being treated as outcasts and often suffer severe depression and social rejection [8]. As a consequence, patients with abnormal facial characteristics are not only rated as significantly less attractive, but also as less honest, less employable, less trustworthy, less optimistic, less effective, less capable, less intelligent and less popular [9]. Therefore, patients suffering maxillofacial disfigurements usually visit medical practitioners requesting some or other reconstructive intervention. Many of these interventions require the reconstruction of anatomical body parts, requiring the manufacturing of facial prostheses.

Prosthetics are a category of medical devices intended to replace missing body parts, either inside or on the surface of the body. As such, the category can include both external prostheses, artificial limbs, and internal prostheses such as joint replacement devices. Maxillofacial prostheses are either external in nature, or internal or both, and are considered by many the primary choice of treatment for functional rehabilitation, aesthetic reconstruction and for the rebuilding of a patient’s confidence [10]. Maxillofacial prostheses provide comfort and support to a patient on many levels. These patients demonstrate improved mental health, social engagement and are able to lead productive lives [11]. A good quality and appropriate prosthesis thus has a significant impact on the level of independence of the user and reduces the need for formal support services.

Additive manufacturing (AM) is fast becoming one of the greatest breakthroughs in healthcare. In the field of prosthetics, AM and related technologies are increasingly becoming more established in this health sector [12]. Although this sector of the market is in its infancy, the expectations are high. In 2012, the medical segment of the AM market was only $11 million, but as the cost of the technology decreases, the market is expected to grow to $1.9 billion in 2025 [13]. The promise is to print in remote locations by local distributors and service providers. This, delivery of goods will no longer be a restriction [12]. It is estimated that at least in excess of 100 million people (1.5% of the world’s population) are in need of prosthesis, therefore, it is expected that AM can solve these medical problems with extensive benefit to humanity [11].

2. CONVENTIONAL MAXILLOFACIAL PROSTHESSES DESIGN AND PRODUCTION

Until recently, most maxillofacial prostheses manufacturing processes have been ‘subtractive’ in nature. In these manufacturing processes, the desired artefact is produced by removing undesirable or superfluous material from a three-dimensional preliminary product. The methods differ depending on the type of disfiguration for which a prosthesis is manufactured [14, 15].

Conventionally, external maxillofacial prostheses are fabricated by hand carving the missing anatomic defect in wax and creating a mould into which pigmented silicone elastomer is placed [16]. These conventional techniques include several complex steps and rely on the artistic ability of a maxillofacial technician and the skills of a clinician [15, 17]. 1) An accurate impression of the area requiring prosthesis is taken. This is achieved by selecting the suitable impression material according to the site and size of the defect, and presence or absence of any undercuts in the area of the defect. Impression materials range from soft/flexible to hard/rigid and include hydrocolloid alginates, elastic silicone polymer, and rigid materials such as plaster of Paris [15]. Although plaster of Paris can achieve excellent details of the defect, it cannot be used in the presence of severe undercuts, as fracture of the impression material will occur on removal and/or damage to the soft tissue might occur. Therefore, it is preferable to use flexible or elastic material in cases of moderate to severe undercuts. Pre-
Finally, a silicone prosthesis is cast in a similar way as in the conventional method.

Taking process, which is replaced by obtaining 2D digital images in Digital Imaging and Communications in Medicine (DICOM) format (DICOM) with computed tomography (CT) or magnetic resonance imaging (MRI) (Figure 1) [25]. In contrast to the negative impression of the conventional method, the digital images are a positive representation of the patient’s skin colour. A fitted facial prosthesis is in contact with human skin/mucosa for lengthy periods and may absorb skin/oral secretions including sweat, sebaceous secretions and saliva, which may contribute to the degradation of the prosthesis material [15]. The service of maxillofacial facial prostheses is further limited by exposure to sunlight and changes in temperature, humidity and hand contact during cleaning, as well as the use of adhesive on a daily basis [19, 20].

3. NEW APPROACHES TO MAXILLOFACIAL PROSTHESSES DESIGN AND PRODUCTION

The rapid development of three-dimensional printing (3-D printing), also known as AM or rapid prototyping (RP), and the proliferation of design software have brought about new approaches to customised, personalised prosthetic manufacturing [21]. These combined technologies are generally referred to as Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) and covers a broad range of production technologies that are used to fabricate products layer-by-layer, enabling three-dimensional objects to be ‘printed’ on demand [22].

The medical industry has found revolutionary ways to implement these technologies [12]. Although AM has existed for over 30 years; only recently has this technology risen in popularity in the field of prosthetic manufacturing [12]. Fabricating custom implants such as hearing aids and prosthetics was one of the first ways that AM transformed the medical industry [23]. Its uptake has been somewhat slow and regarded as being more as experimental [10]. This delay in shift to AM technology in prosthetics can be attributed to a lack of understanding of the AM processes, slow rate of approval of use of new biocompatible AM materials, and possibly the loyalty of doctors to familiar brands of prostheses [10]. Increasingly, CAD/CAM technologies are becoming part of the discourse in the medical field.

AM has been referred to a disruptive technology that will fundamentally influence many processes such as production, supply chain design, logistics and consumer behaviour [24]. AM has the potential to replace many conventional manufacturing processes and to stimulate a plethora of new business models, new products and production, supply chain design, logistics and consumer behaviour [24]. AM has the potential to replace many conventional manufacturing processes and to stimulate a plethora of new business models, new products and product supply chains. Two important characteristics of AM’s disruptive potential are: Firstly, it enables direct production of physical objects from digital design data, and provides new opportunities for freedom of design. Customised products can be manufactured without high surpluses of conventionally connected with one-of-a-kind manufacturing [24]. Secondly, AM allows private and industrial users to design and produce their own goods.

CAD/CAM technologies in maxillofacial prosthesis manufacturing, follows broadly the same major steps as the conventional method. In the conventional method, data collection of a patient’s anatomy involves the impression taking process, which is replaced by obtaining 2D digital images in Digital Imaging and Communications in Medicine format (DICOM) with computed tomography (CT) or magnetic resonance imagining (MRI) (Figure 1) [25]. In contrast to the negative impression of the conventional method, the digital images are a positive representation of the patient’s anatomy. The DICOM file is then exported to medical imaging editing software. A skilled medical designer compiles and reconstitutes a virtual 3D view of the patient’s anatomy, referred to as a geometry. The geometry is further processed through volume rendering functions to display a 3D image of all tissues, after which the digital data of the patient’s anatomy of interest is isolated. At this stage, the digital data can be exported as a stereolithography (STL) file to a 3D printer or to CAD software for further design enhancements and corrections [26]. Once a final geometry has been designed, a digital mould is also designed for the geometry and 3D printed. Finally, a silicone prosthesis is cast in a similar way as in the conventional method.
In the process chain for the manufacturing of maxillofacial prostheses using CAD/CAM technologies, human and non-human material components exist. Typically, the human agents are the client, designer and the maker [27]. In the production of a maxillofacial prosthesis, the client is represented by the medical practitioner, who is responsible for collecting the digital data from the patient and for the description of the specifications for the design of the proposed maxillofacial prostheses. The specifications and digital data are then used by a medical designer to create the geometry for the manufacturing of the proposed maxillofacial prosthesis by the maker, who is represented by engineers or manufacturers. Several iterative communication and action events support the successful outcome of this process chain. Figure 2 demonstrates that the medical designer may communicate with the medical practitioner, as well as with the manufacturer. Similarly, the manufacturer may also have to engage in discussions with the medical practitioner. In this process chain, the medical designer is both a receiver of instructions (specifications) and a creator of an interim artifact, the geometry. The action events result in different non-human components, which include the digital input data, specifications of the proposed maxillofacial prosthesis, the geometry design and the maxillofacial prosthesis.

There are several advantages in using CAD/CAM technologies in maxillofacial prosthesis manufacturing. A major advantage is the production of a customised digital model without the need for a physical impression. The process of digital image taking has the advantage of being more accurate than conventional impression taking [28]. This eliminates extended clinical time, the risk of leakage of the impression product into the natural facial cavities of the patient and poor tolerance of the patient [29]. These technologies also circumvent the possibility of tissues drooping during the application of the impression material, which may result in a modified configuration. In addition, since silicone prostheses have a limited lifetime, it is a major advantage to have computer backups of the prosthesis designs, allowing for the manufacturing of limitless identical prostheses [30]. Editing and design software provides extensive geometric design freedom, which is not restricted by tool access or material flow limitations [31]. CAD software also provide techniques such as “mirroring”, allowing for designing mirror images of contralateral anatomical structures, such as ears. These CAD/CAM technologies thus offer a cost-effective and
efficient systems to design and manufacture perfect-fit and custom-made maxillofacial prostheses [32]. A further major advantage is the ability to work remotely.

3.1 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 prosthesis, maxillofacial facial prosthesis 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, as listed in Table 1. 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.

Table 1: Prominent medical image editing software currently used in craniofacial reconstruction.

<table>
<thead>
<tr>
<th>Software name</th>
<th>Developer</th>
<th>Proprietary/open Source</th>
<th>Total number of literature sources</th>
<th>Number of literature sources - Internal prosthesis</th>
<th>Number of literature sources - External prosthesis</th>
<th>Estimated cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mimics®</td>
<td>Materialise®</td>
<td>Proprietary</td>
<td>22</td>
<td>12</td>
<td>4</td>
<td>&gt;R180K</td>
</tr>
<tr>
<td>OsiriX</td>
<td>Pixmeo®</td>
<td>Proprietary</td>
<td>9</td>
<td>13</td>
<td>2</td>
<td>&gt;R9K</td>
</tr>
<tr>
<td>3D Slicer</td>
<td>The Slicer Community</td>
<td>Open Source</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>Free</td>
</tr>
<tr>
<td>InVesalius</td>
<td>CFI (Renato Archer Information Technology Center)</td>
<td>Open Source</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>Free</td>
</tr>
<tr>
<td>iPlan®</td>
<td>Brainlab®</td>
<td>Proprietary</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>Not available</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>42</td>
<td>33</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

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, as listed in Table 2. 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.

Table 2: Prominent computer-aided design software currently used in craniofacial reconstruction.

<table>
<thead>
<tr>
<th>Software name</th>
<th>Developer</th>
<th>Proprietary/open Source</th>
<th>Craniofacial reconstruction</th>
<th>Internal maxillofacial prosthesis</th>
<th>External maxillofacial prosthesis</th>
<th>Estimated cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomagic®/FreeForm®/Geomagic® (Plus)</td>
<td>3D Systems®</td>
<td>Proprietary</td>
<td>33</td>
<td>9</td>
<td>7</td>
<td>&gt;R150K</td>
</tr>
<tr>
<td>Geomagic Studio®</td>
<td>3D Systems®</td>
<td>Proprietary</td>
<td>28</td>
<td>14</td>
<td>9</td>
<td>&gt;R150K</td>
</tr>
</tbody>
</table>
4. CURRENT STATE OF MAXILLOFACIAL PROSTHESES DESIGN AND PRODUCTION IN SOUTH AFRICA

The uptake of the newer technologies such as, digital imaging technologies, CAD/CAM, in maxillofacial prosthesis production has been relatively slow 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 prosthesis production is mostly followed, whereby the new technologies are applied sparingly, depending on the availability of skilled practitioners and funds.

5. CONCLUSIONS

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 prosthesis, 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.

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DETECTING DEFECTS DURING POWDER DEPOSITION IN ADDITIVE MANUFACTURING

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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 build [2, 3]. 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 consolidating the powder with the rest of the part. Preliminary results will be shown of defects identified after a new powder layer has been deposited.

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1. INTRODUCTION

In additive manufacturing (AM) parts are fabricated by consolidating material layer-by-layer using an energy source and a three-dimensional computer aided design (CAD) of the part. In the work presented we make use of an AM technique called Selective Laser Melting (SLM) to create parts utilizing a powder bed system. A recoater is used to spread a thin layer of metal powder across the build area to smoothen the surface of the powder across the bed. A laser source then selectively scans over the bed according to the layer data, generated from the CAD file, melting the powder and consolidating it into a homogeneous part. The material not forming part of the design model is left untouched and acts as a support structure for the part. The build platform is now lowered by a layer thickness typically 20-100 $\mu$m. This procedure is repeated for each powder layer until part completion is achieved. Fig. 1 shows a schematic overview of a typical SLM machine using a powder bed system.

![Figure 1: An example of a typical AM machine making use of a powder bed system (Source: empa.ch).](image)

This technology has the advantage over current industrial subtractive manufacturing (SM) (milling and turning) as it allows building of highly geometrically complex parts [4]. These two techniques are drastically different from one another, and as such the adoption of standards and certification of quality from SM to AM is not possible. New standards and part certification is required for AM as it is a new technology completely different from SM [5, 6]. Verifying the quality of a part is mainly done after part fabrication which does not allow the operator to act upon defects observed during the actual build.

It is critical that in-line process monitoring systems are implemented to circumvent this deficiency. One can distinguish between two types of in-line process monitoring systems: powder bed monitoring for powder deposition defects [2] and melt-pool monitoring to probe the dynamics related to melted powder and the formation of a homogenous part [3]. It was demonstrated by T. Craeghs et al. [2] that it is possible for in-line process monitoring of recoater related defects during powder deposition 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.

The type of defects one can detect include, but are not limited to:

1. Recoater damage,
2. Extrusion (super-elevation) of sections of the part beyond the new powder layer,
3. Powder deficit and
4. Powder recoater hopping because it is a mechanically moving part.

Each of these can lead to different types of metal powder consolidation defects [1]. Recoater damage and recoater hopping lead to high surface roughness. Part extrusions lead to more powder deposited next to the extrusion than the rest of the powder bed. During powder-solid metal consolidation the extra powder at the extrusion leads to the extrusion growing in size each layer added. Powder deficit causes the solid part to re-melt, leading to rising temperature gradients and high stress levels on the metal surface which ultimately lead to cracking and delamination. As example fig. 2 shows recoater damage which leads to high surface roughness.
If defects on a new powder layer can be detected before laser melting occurs, a new layer may be suitably recoated or the process can be paused for user controlled rectification [7].

This work will present an image based system to collect information of powder layer deposition defects using the shadow casting method. A few main defects during recoating will be identified and analysed to establish the severity and possible impact of the defects on metal powder consolidation. For this, a software package was developed to auto-detect defects. This is aimed towards developing a system which in the future will contribute to quality assurance.

2. METHODOLOGY AND EXPERIMENTAL PROCEDURE

The technique we consider to detect powder layer defects is dependent on the formation of shadows on the powder bed (denoted working chamber in fig. 1) as a result of a light source positioned on one end of the bed and illuminating each powder layer across the powder bed. We implemented a strip LED as the light source where the initial location of the strip was parallel to the powder bed and was positioned 300 mm above and 500 mm right from the centre of the bed.

As shown in fig. 3(a), a single layer of powder is illustrated as an oscillating wave of peaks and troughs. If the light source is positioned on the right with a camera above the bed, the light impinges on the positive slope of the powder and illuminates extrusions with shadow regions formed over the troughs. This is also true of the light source positioned on the left; however, the opposite of the case above occurs. Hence, the light intensity captured by a camera (represented as a grayscale intensity measurement) can provide information regarding the surface...
To resolve a feature on the powder bed the required resolution is at least twice the object to image transformation. This implies that with the current system in place at best we can only resolve defects the size of 300 µm and larger. To simplify mathematical computations during image processing, a square section of the image was selected leading to a field-of-view 20.8 x 20.8 mm (1400 x 1400 pixels). Experimentally, it was necessary to induce powder bed defects mainly based on recoater damage to ensure their adequate detection and sampling. This was achieved using an old recoater which created several defects on the power bed after powder deposition (shown in fig. 4(a)). The defects include (1) Recoater damage, (2) Super-elevation of parts, (3) Powder deficit and (4) Recoater hopping due to momentary mechanical failure of the recoater. Such defects can lead to the fabrication of a poor quality part or even part failure.

Figure 4: (a) 2D representation of powder bed defects artificially created on the powder bed. (c) Defects include: (1) Recoater damage, (2) Super-elevated part, (3) Powder deficit and (4) Recoater hopping due to momentary mechanical failure of the recoater. (b) Shows the 3D representation of imaged object.

As previously stated, the defects shown in fig. 4(a) are typically identified through a visual inspection of the powder bed which necessitates the presence of an operator at all times. In future, this will be circumvented using an in-situ imaging system with complimentary software to identify the defects.

Within the 2D representation (fig. 4(a)) of the powder bed imaged, the broken boundaries for the various defects are not easily differentiated. A 3D representation (fig. 4(b)), of the 2D image taken shows the noisy information landscape but not the powder deficit defect. A more comprehensive software analysis tool is required to identify the outlines of defects as the standard procedures of edge detection algorithms are not adequate.

3. DATA ANALYSIS AND RESULTS

Software was developed to automatically identify and analyse the powder bed defects shown in fig. 4. Images of the powder bed were captured in a standard laboratory environment where the powder bed was exposed to several ambient light sources. The light source used to illuminate the powder bed was also not a point source, but consist of an array of LEDs. These all lead to increased background noise which needed to be suppressed as far as possible before locating the powder layer defects.

The data from the camera images are greyscale values that range from black, zero intensity (0) to white, maximum intensity (255). A 2D polynomial fitting function was utilized to establish the localized image averages (considered as background noise) and subsequently subtracted it from the original image. This changes the data boundaries from -255 to 255 which were renormalized to range from -1 to 1. A 2D smoothing algorithm was then
applied to the image (weak filtering) which reduced the effective resolution, but ironed out sharp contrast
differences between neighbouring pixels not associated with the formation of shadows from the illumination
light source. Depending on the type of defect, different image processing methods were utilized to identify the
powder layer defects. The subsections that follow demonstrate the procedures implemented to identify some of
the powder bed defects shown in fig 4.

3.1 Recoater

Recoater related defects appear as lines parallel to the recoater coating direction across the powder bed. In our
case, this is seen as bright and dark vertical lines in fig. 5(a).

![Recoater defects](image)

**Figure 5:** (a) Unfiltered images taken of the powder bed exhibit vertical lines which is associated with
recoater related defects. (b) A cross-sectional cut ((a), pink line) perpendicular to the recoater coating
direction is selected for processing to search for recoater damage. The data from (b) undergoes several
filtering processes (c) to clean-up the information before finally being subjected to intensity filtering to
isolate the locations of recoater damage (d).

Recoater related defects can be identified by selecting a horizontal cross-section (as illustrated in fig. 5(a), the
pink line) of the 2D camera data as shown in fig 5(b). Fig. 5(c) is the processed data after background subtraction
showing the greyscale values below and above the averaged greyscale value. Not all the lines in fig. 5(a) are due
to recoater damage. There is a tolerance in the acceptable layer flatness (or surface roughness) which relates
to the particle size being coated as well as the surface roughness of the recoater. The roughness of the recoater
is typically in the nanometre range for a new recoater which implies that the surface roughness will typically be
of the order of the particle sizes which in general range between 20-100 µm.

To identify recoater related damage, we determined the steepness between neighbouring pixels where 2
standard deviations from the average greyscale value (fig. 5(d)) is considered as recoater damage. Recoater
damage was primarily observed on the right side of the powder bed due to its close proximity to the light source
where the light intensity is higher and thus produces more scattering. The low light intensity on the left side of
the powder bed resulted in the software not adequately identifying recoater damage. This problem can be
mitigated by implementing a secondary light source on the left of the bed. Two images may then be successively
captured for each light source and superimposed to illustrate a fully illuminated bed. In this particular case the
cross-section was selected in the middle of the vertical axis. To improve recoater damage related defect
detection several of these cross-sections across the image along the vertical axis may be selected and averaged.

3.2 Extrusions and super-elevated parts

Super elevated parts are sections of the built part which extends beyond the newly recoated powder layer. These
can be identified by comparing the build outline (from the computer generated slice files) with the powder bed
images taken after powder deposition. Extrusions, however, not related to the actual part (for instance large
sputtered particles); require the complete powder bed to be evaluated and not only the areas where a build is
in progress. From fig. 4 it is clear that the vertical lines created by the recoater dominates and will influence
most procedures used to identify other powder layer defects. To prevent this we sampled over the horizontal
axis with a gradient based algorithm while searching for local centre of mass locations within the image. This
allowed us to identify a super-elevated part as shown in fig. 6 (left). Fig. 6 (right) is zoomed in on the location
where the super-elevated part was detected.
Figure 6: (left) Defect number two in fig. 2 which is an extrusion of the part beyond the powder bed powder layer. (right) Zoomed into the area where the extrusion is observed.

In this particular case we were searching for the defect with the largest gradient differences in relation to its neighbourhood. In general, detecting extrusions are not only based on gradient detection methods, but also incorporate algorithms searching for the physical transverse size (number of pixels) of the defect. Due to the low camera resolution it is possible for a single pixel to represent part of an extrusion as well as part of the background if the defects are small. In this case our current approach may not be successful due to the poor contrast of the elevated section in comparison to its neighbourhood. Detecting smaller defects on the powder bed can only be achieved by using higher resolution cameras or by reducing the field-of-view considered.

3.3 Powder deficit

Identifying locations of powder deficit is more difficult than part extrusions due to the low signal to noise ratios observed at the edges created between high (normal) and low (deficit) powder levels. In our experiments the low camera resolution complicated our efforts to detect powder deficits. The powder deficit associated edges consisted of roughly 8 pixels exhibiting poor contrast leading to poor resolvability of the edges. Furthermore, in certain cases the image at the edge comprise of defects from both the recoater and powder deficit as shown in fig. 7 (a1, orange dashed circle). In this section the edge is broken by a distance of roughly 15 pixels which extends beyond the thickness of the edge itself and therefore cannot properly be reconnected using edge connection algorithms without connecting other unrelated sections to the edge. The location of the light source on the right side of the powder bed also lead to good resolvability for edges facing the light source (fig. 5(a), red dashed line) while edges facing away from the light source lead to poor resolvability (fig. 5(a), yellow dashed line).

Figure 7: (a1) Powder deficit observed due to scraper defects. The orange dashed circle show overlap between defects from scraper damage and the edge created between the low and high powder levels. The red dashed line (a2) show an edge facing the light source which can be resolved while the yellow dashed line faces away from the light source and is poorly resolved. (b) Shows low intensity filtering combined with gradient based algorithms to identify the edge between low and high powder layer levels. (c) Shows the deficit locations identified after thresholding.

Converting the grayscale images to binary white (1) and black (0) allowed us to partially resolve the edges by suppressing data below a preselected threshold value. Unfortunately this also removes in part information related
to the edge between high and low powder layer levels. Fig. 7(c) shows the part of the edge identified. The edges on the left of the powder bed weren’t identified due to too low signal to noise ratios.

3.4 Recoater hopping

Recoater hopping does not necessarily lead to a single horizontal line, but can lead to several closely located lines as shown in fig. 8(a) as it consist of intermittent areas of dumping to much powder or pressing into the new created powder layer forming a powder deficit section. Similar to the case for detecting powder deficit one finds the signal to noise ratios very low for recoater hopping associated defects. Furthermore, the defect lines are perpendicular to the light source orientation leading to low light scattering henceforth small shadows with low contrast. A similar approach was taken as in the case of detecting powder deficit. Similar to the defect of powder deficit only part of the hopping could be identified as shown in fig. 8(c).

![Figure 8: Recoater hopping observed as intermittent sections of too much powder deposited as well as sections of the recoater pressing into the new layer deposited. (b) Filtered data before thresholding. (c) Filtered data after thresholding showing the section of the recoater hopping defect identified.](image)

More work is required to create proper identifiers for the various defects which is necessary to deploy in machine learning. This work highlights the importance of identifying alternative algorithms which might lead to a higher success rate.

4. FUTURE WORK

In this work, we have developed software approaches to identifying defects. Further success in identifying powder bed defects strongly correlates with an improvement in the optical measurement system. The two main contributors to poor defect resolvability in this work were:

1. Poor lighting conditions
2. Low camera resolution

In our experiments, defects were best detected in regions closest to the light source due to high scattering levels leading to higher signal to noise ratios. A close to collimated light source over the bed will result in more evenly detected defects across the left and right side of the powder bed. Furthermore, light sources on different sides of the powder bed are proposed to enhance edge features pointing away from the light sources. To be able to resolve smaller features and provide sufficient information on defects, high resolution cameras will be implemented in subsequent work to obtain a resolution of approximately 50 µm/pixel.
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Figure 9: (a) Different areas considered for future work. This includes imaging the powder bed after metal powder consolidation as well as constructing an imaged 3D model of the built to investigate dimensional mismatches between the parts built and the CAD of the build. (b) Powder consolidation defects one would like to identify. (1) Balling effect of particles, (2) part extrusion, (3) delamination of the part.

This new system will be extended to also monitor the part after metal powder consolidation to quantify how powder layer defects influence consolidation (fig. 9(a)) [8, 9]. Fig. 9(b) shows 3 different features one could detect using the same setup as that for the powder bed monitoring. Future work also includes the construction of an imaged 3D model of the build to investigate dimensionality mismatches between the built part and the CAD of the build.

5. CONCLUSION

Certifying AM parts plays a key role in the success of the adoption of AM built parts in industry. We have performed preliminary monitoring experiments and developed complimentary software to detect powder bed defects. To achieve this we made use of several different approaches leading to the successful identification of recoater damages as well as part extrusions. The main contributors to poor defect resolvability have been identified while also providing possible solutions. In future this will aid us to improve our current detection system to also resolve powder deficit and recoater hopping defects successfully.

The final output for this work will provide fundamental information regarding consolidation defects related to powder layer deposition towards part qualification by process monitoring.

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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.

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1. INTRODUCTION

In the field of additive manufacturing, especially when using powder bed fusion technologies, failed prints can become very costly due to the high cost of the raw material and related labour costs [1]. Parts with printing defects, as displayed in Figure 1, must be reprinted to ensure clients receive good quality parts and that the structural integrity of the part is not affected. Re-coating errors was identified as a key factor that causes failed prints and printing defects, which reduces the reliability of the technology [2].

![Figure 1 Effect of Re-coating errors on parts.](image)

Re-coating errors, as identified in the following research study, could directly be linked to re-coater short feeding and debris that may fall onto the surface of the powder bed. Currently, the binder jetting type of powder bed fusion technologies has no method of determining the quality of the re-coating process [2]. Powder bed monitoring technologies have been developed. However, they are solely focusing on the metal-based powder bed fusion technologies [3] [4] [5]. This indicated the need to develop an active re-coating 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.

2. ACTIVE RE-COATER MONITORING SYSTEM SETUP

The active re-coater monitoring system that was designed and installed, made use of computer vision technology to monitor the surface quality of the powder bed. The system consists of a camera module, Raspberry Pi 3 microcomputer and lighting fixtures as shown in the block diagram in Figure 2.

![Figure 2 Active Re-coater Monitoring System Design.](image)

The voxeljet VX500 was identified as a suitable platform which allows the integration of the monitoring system. The camera was positioned in such a way that it captures the entire surface of the powder bed in a single image after each re-coating cycle [6]. The standard machine light luminaire was used to illuminate the powder. The light is mounted at a 50-degree angle in relation to the powder bed.

An image processing program was developed to process the images captured by the camera. The developed program made extensive use of the OpenCV library. The OpenCV library is an open source computer vision and machine learning software library that contains 2500+ optimised algorithms [7]. It can be integrated into a variety of programming languages including C++ and Python. The image is divided into 16 equally sized quadrants, using a 4 x 4 matrix. Each quadrant is processed individually and displays the probability of a defect in the specific quadrant. The probability is expressed as a percentage value as demonstrated in Figure 3b. The identifier number of each quadrant is displayed in Figure 3a for reference. However, the identifier is not indicated on the processed image to reduce clutter on the processed image. After processing the captured image, both the original and processed images are stored. The first stored image is the original captured image, and the second image is the originally captured image after it has been processed by the algorithms with all the information overlaid onto the image. Each of the two images is stored with the date-time stamp as the file name for easy identification during the post-build analysis.
Once all the quadrants have been processed, the probability values are then also recorded into a CSV file along with the layer number and date-time stamp so that the data can easily be matched with its captured image. Each quadrant in the image is assigned a number in the data file, and can be correlated to a specific quadrant as shown in Figure 3a. The quadrant numbers are overlaid on the image only for illustration purposes and reference and is not displayed on the final processed image. Once the build had completed, the recorded data in the CSV file can be plotted graphically for easier analysis as demonstrated in Figure 4.

As indicated by the legend in Figure 4, the data recorded for each of the 16 quadrants has a uniquely coloured line on the line graph. This makes it easier to match spikes on the graph to specific quadrants without necessarily having to refer to the captured image. When identifying a specific spike that is of interest, the graph can also be cropped to the specific area of interest. The layer number where the spike occurred is indicated by the X-axis.

The system was also first tested using a series of replicated defects to determine the optimum parameters for the various image processing functions. However, these tests do not form part of this research study as it was used as an initial benchmark of the system. Once the system provided satisfactory results, using the replicated defects, the in-production monitoring could commence.

3. **CASE STUDY METHODOLOGY**

For the following research study, a single build was monitored using the active re-coater monitoring system with the aim to determine the system’s effectiveness to detect re-coating errors during production. From the results obtained, a threshold value could be determined which can be used to identify re-coating errors. The threshold value can be defined as the minimum probability value that must be recorded before a detected feature is considered a defect. To determine the threshold value, all the spikes on the recorded data will have to be reviewed together with all the captured images to determine the severity of the recorded spikes, as well as determine if the recorded spikes were from defects present on the powder bed. From this defect data, a minimum threshold value can be determined based on the average values of the spikes.

The build that was selected for the following case study consisted of 1946 layers and contained several large and small parts stacked throughout the build volume. The build took approximately 16 hours to complete.

The first step, after the build was completed, was to plot the recorded data as a line graph as shown in Figure 5. This makes the analysis of the defects that were detected easier to identify. There were several spikes present.
on the graph, and the most significant of these spikes had been highlighted and will be closely examined and discussed.

![Graph](image1)

**Figure 5 Case study build data.**

The smaller spikes were also examined; however, a large number of these smaller spikes were very fine defects and were defined as non-critical, they will only be discussed briefly.

The first spike that was investigated occurred on layer no. 48. When examining this spike on the graph, it is apparent that a significant spike in the probability value had been recorded from the image. The cropped portion of the graph as displayed in Figure 6 shows the spike that was recorded by the system for layer no. 48.

![Graph](image2)

**Figure 6 Defect Data for Layer no. 48.**

After consulting the legend on Figure 6, the recorded defect spanned over quadrants 5, 6, 7 and 8. This means that the defect had occurred in the direction of re-coating and is shown in Figure 7.

![Image](image3)

**Figure 7 Processed image for layer no. 48.**

When examining the image in Figure 7, it can be seen that a major defect had occurred across the entire length of the powder bed. The defect also appears to be deeper than a single layer. However, upon review of the images for layer 47 and 49 in Figure 8, there is no defect on either the preceding or subsequent layer.
Thus, the only reasonable explanation is that a piece of debris or clump of powder was stuck on the re-coater arm, causing the line to form on the powder bed across the entire length of the powder bed.

The second spike on the graph that was investigated occurred on layer no. 216. The zoomed-in portion of the graph as demonstrated in Figure 9 shows that a total of 11 quadrants had recorded a spike in the probability values. However, the quadrants that had recorded the spike did not seem to follow a discernible pattern across the length or width of the powder bed.

When examining the image captured for layer no. 216 as displayed in Figure 10, it became apparent the system had captured an image of the re-coater arm during the re-coating process. A possible explanation for this may be that EMI (electromagnetic interference) may have triggered the camera to capture an image at the wrong time. Although the circuit was designed to deal with most types of interference, there is still a possibility that interference may have triggered the camera. Therefore, as part of the future research, a new triggering system will be developed that is more resistant to external interference.

The third spike on the graph that was investigated occurred on layer no. 262. When zooming in on this portion of the graph as shown in Figure 11, a spike had been recorded in quadrants 3 and 4.
Upon examination of the graph, it can be seen that the value recorded for quadrant 4 is significantly higher than quadrant 3. Because of this higher value for quadrant 4, it can be assumed that a larger portion of the defect was present in quadrant 4 than quadrant 3. In order to verify this assumption, the image captured for layer no. 262 as shown in Figure 12 had to be reviewed.

Upon closer inspection of the image, the defect that had occurred over quadrants 3 and 4 can be clearly identified. The image also confirmed that the defect recorded in quadrant 4 was larger than the defect recorded in quadrant 3.

The fourth spike that was investigated occurred on layer no. 286. The graph displayed in Figure 13 shows a definite spike recorded in quadrants 13 and 14.

However, the value recorded by quadrant 13 was significantly higher than the value recorded by quadrant 14. Thus, it can be assumed that a much greater portion of the defect was present in quadrant 13 than 14. In order to verify this assumption, the image shown in Figure 14 that was captured for layer no. 286 will be examined.
The processed image for layer no. 286 as displayed shows that a small defect had occurred on the top right-hand corner of the image. This corresponds to the data that was recorded on the graph in Figure 13. It was also confirmed that the defect only occurred on a single layer after inspecting both layer 285 and 287. However, due to space constraints the images captured for these layers will not be displayed.

The fifth spike on the graph that was investigated occurred on layer no. 807 and 814. The first defect that was recorded occurred on layer no. 807 in quadrants 3 and 4. The second recorded defect had occurred on layer no. 814 in quadrants 10 and 11.

However, upon examination of the recorded data, it appears that both the defects had been repaired by the subsequent re-coating cycles. This means that both the defects were singular defects that only occurred on a single layer. To verify this assumption, it is important to review the images captured for these layers to ascertain what may have caused these defects. The processed image displayed in Figure 16 shows the image captured of layer no 807.

When examining the processed image of layer no. 807, it is evident that a smaller defect had occurred in the direction of re-coating. When comparing the image to the data recorded in Figure 15 for layer no. 807, it can be verified that the defect had occurred in quadrants 3 and 4. Sometimes, this type of defect is also caused by clumps that form in the powder being re-coated onto the bed and causes small defects until the clump is broken up. When examining the image of the subsequent layer, the defect had been repaired by the following re-coating cycle. However, due to space constraints the image captured for this subsequent layer will not be displayed.

The processed image displayed in Figure 17 shows the defect detected for layer no. 814.
Upon examination of the processed image for layer no. 814, it can be seen that a defect had occurred over quadrants 10 and 11. This coincides with the data that was recorded as shown in Figure 15. However, it can also be seen that even though both quadrants recorded an increase in the probability values, quadrant 11 recorded a value significantly higher than quadrant 10. This can be attributed to the fact that a larger portion of the defect is present in quadrant 11. However, both quadrants recorded a spike in values that clearly indicated the presence of the defect in that specific area.

The sixth spike that was investigated occurred on layer no. 1085. The zoomed-in portion of the graph for layer no. 1085 is shown in Figure 18.

When examining the graph in Figure 18, there are four quadrants that had recorded a sharp increase in values. The quadrants that recorded the sharp increase in value can be identified as 9, 10, 11 and 12. From the results, it could be assumed that the defect occurred in the direction of re-coating. To verify this assumption, the image captured for layer no. 1085 will be examined and is shown in Figure 19.

The image, shown in Figure 19, demonstrates a small defect that runs along the length of the powder bed. The image confirmed the assumption that the defect had occurred in the direction of re-coating. It is important to note that the defect is very fine and not clearly visible to the eye due to the fact that the defect only occurred on a single layer, as there was no defect present in the preceding layer and had been repaired by the subsequent re-coating operation. This type of defect was defined as a non-critical defect, but it shows the system’s capability to detect small defects.

The next region of interest that was examined is the large area on the graph highlighted as point no 7. The zoomed in portion of the graph for layers 1200 - 1946 is displayed in Figure 20.
Upon initial examination of the graphical data, a definite upwards trend of the probability value is immediately evident across all the quadrants. The initial increase in the probability value was recorded at layer no. 1300. It can also be seen that values increased exponentially in the last 150 layers. A possible explanation could be that a series of defects occurred on the powder bed, and the condition of the powder bed kept on deteriorating as the build progressed. In order to properly investigate the cause of the growing defect, it is necessary to review the images that was captured during this period. For this purpose, images were selected from layer no. 1400, and thereafter for every 100 layers to demonstrate what may have caused the gradual degradation of the powder bed surface. Considering the images for layers 1400 and 1500 as show in Figure 21, smaller defects are visible on the powder bed surface, however, they are not as severe and can still be repaired.

However, layer 1600 shows that the defect grew more severe. At layer 1700 the defect had grown to such a point where it would have started causing structural damage to the parts in the build. The defect could be linked to re-coater short feeding due to a low powder flowability. This causes the re-coater to apply very little or no powder over certain areas of the powder bed, causing these lines and holes to form on the surface.
Figure 22 Advanced Powder bed deterioration.

Upon examination of the final layer displayed in Figure 23a, it is very clear that the surface of the powder bed has deteriorated to the point where the build has failed completely and parts have been damaged beyond the point of repair. Considering the processed image of the final layer, shown in Figure 23b, it can be seen that all the quadrants had recorded defects on the surface of the powder bed. Also, due to the severity of the different defects, some of the probability values were quite significant, indicating the seriousness of the error.

Figure 23 Images of Final Layer.

Upon final review of all the captured images of the build, there were several very small defects that had occurred on the powder bed. The small defects shown in Figure 24 were identified as non-critical. The defects in Figure 24 resulted in smaller spikes on the graph, which could be identifiable from the data. It is worth noting that even though these defects posed no risk to the success of the build, the system still proved its capability to detect very small defects on the powder bed.
4. FUTURE WORK

For future research, a classification system must be developed in order to classify defects according to size and severity. Once the defects can be classified, the system can further be developed to automatically take the appropriate corrective measures to either repair the defect or stop the build prematurely to prevent the further waste of resources and raw materials. This will give the system the capability to detect, classify and possibly rectify any defects that may be caused by re-coating errors.

5. CONCLUSION

Considering the build, monitored for the purposes of this case study, several defects and re-coating errors that occurred during the build. Some of the defects that had occurred were repairable and was repaired by subsequent re-coating operations. However, during the last portion of the build, the re-coater started short feeding due to a low powder flowability and subsequently caused the remainder of the build to fail as this error was unrecoverable without user intervention. The defects that occurred during the build did, however, provide and excellent case study for the active re-coater monitoring system. The results showed that the active re-coater monitoring system did manage to successfully detect all of the defects during the printing process, thus proving the capabilities of the system. Finally, a threshold value that determines whether a detected feature can be classified as a defect or not was also determined. This value is determined by reviewing all the peaks on the recorded data and comparing these peaks with the images captured for those specific layers to ensure that there are defects present on those peaks. Upon careful examination of the recorded data and the captured images, it was found that features with a probability value of less than 0.07% are non-critical defects. Thus, the threshold value was selected at a value of 0.07%. Unfortunately, this type of technology produces a large number of non-critical defects during the re-coating process, and thus the threshold value was selected to be higher than the average probability value of the non-critical defects.

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ABSTRACT

Advances made in Additive Manufacturing (AM) or 3D printing led to the 3D printing of sand moulds and cores used in the foundry industry. Ideally, the mechanical properties of the 3D printed moulds and cores should be uniform throughout the 3D printed part. This will ensure that the casting produced from the 3D printed mould has uniform properties throughout the mould. The following study investigated the effect of the printing location and part orientation in the AM machine used to produce the 3D Printed mould on the bending strength property of sand parts. Several printing orientations and angles were considered in the investigation. Descriptive statistics was used to assess and interpret the results.
1. INTRODUCTION

Additive manufacturing (AM) processes in the form of three-dimensional sand printing, offers an alternative to conventional mould manufacturing methods used for metal casting applications. This process presents several advantages, which includes: reduction of weight due to better design, increased geometric complexity and the saving of lead time compared to traditional mould making technologies.[2] Several commercial three-dimensional printing systems are available on the market. The most popular platforms include: Exone and Voxeljet.[4,5]

The Furan process is the most predominant chemical process used in three-dimensional sand printing technologies.[6] The later process is a no-bake process, consisting of a sulphonic acid coated sand bonded with a furfuryl resin. The furfuryl is selectively deposited on to the sand using a printing head. Silica sand is very popular in the printing process due to its availability and good properties (strength, permeability, thermal stability, collapsibility and reusability).[9]

Traditional mould and core making processes rely on a sand compaction process where the three-dimensional printing process uses a layer by layer adhesion process. A study by Nyembwe et al, compared the mechanical properties of three-dimensional printed parts to parts produced using traditional hand ramming.[1] The investigation revealed that the post processing of printed part, by baking, made their mechanical properties comparable to that of conventional produced parts.

AM processes can be applied as a substitution for or in combination with conventional processes. In the foundry industry the strength of sand moulds and cores needs to be homogeneous to ensure good casting results.[9] The cost of printing sand moulds and cores was identified as a possible technology uptake inhibitor, as 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.[3]

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.[1] In addition, literature showed that the printing orientation in AM produced parts had an effect on the part’s mechanical properties. This study was therefore aimed at determining the effect of the build orientation and position on the mechanical strength of Voxeljet VX1000 printed parts.

The bending strength is the property used for the assessment and control of resin bonded sand moulds. This mechanical property provides a reliable indication of the resistance of sand moulds to casting defects related to the metallostatic pressure of the molten mould and sand erosion during the pouring of the molten metal in the mould cavity.

Only the bend strength was considered in the paper, as the following pilot study will be used as motivation for the comprehensive research study. The results of this study will be used to determine the bend strength variance of parts printed at different positions and orientations within the VX1000 building envelope, and whether if conforms to the bending strength specifications specified by Voxeljet[9].

2. DESIGN OF EXPERIMENT

The methodology adopted in this study could be broken down into three consecutive steps namely: Printing of sand test specimens, testing and data analysis.

2.1 Printing of sand test specimens

A Voxeljet VX1000 three-dimensional printer was used for the following study. Standard operating conditions were maintained including a printing layer thickness of 300µm. The printing material was limited to imported silica sand recommended by the original equipment manufacturer (OEM). The sand was pre-coated with 0.3% wt sulphonic acid activator.

The building envelope of the Voxeljet VX1000 is 600mm (X-axis) x 1080mm (Y axis) x 500mm (Z-axis). The full building envelope of the Voxeljet VX1000 was considered in the following study to investigate the possible variation of bending strength of parts printed within a single build process. Test specimens were placed at different orientations and angles throughout the building envelope.

The printed sand specimens conformed to the recommendations of the American Foundry Society (AFS) for bend strength samples (25.4mm x 25.5mm x 203.3mm).[7] All the samples were numbered with an alphabetic and numeric digit for identification purposes. The alphabetic digit indicated position in the built and the number indicated orientation.
Five print orientations and angles were considered in the following study (X, Y, Z and a 45° offset in the X & Y direction). All five of these orientations were placed at six different locations within the building envelope, as shown in Figure 1. Alphabetic digits were assigned to each position and selected as not to be misleading when printed into the grainy sand specimens.

From an operator perspective position C & I will be the closest to the operator, H & B in the middle of the build and G & A the furthest away from the operator. Direction X will be from position C to I as depicted in Figure 2. Direction Y will be from position C to A as depicted in Figure 2. The print head will first print in the primary movement direction after which it will adjust in the secondary movement direction where the process will repeat itself. The re-coater will recoat in the opposite direction as the primary movement direction. The re-coater will recoat the full bed with one layer immediately after the print head is finished printing that particular layer.

The position of the sand test specimens and the direction of sand printing can be seen in figure 2.

![Figure 1: Building orientation of samples in the building volume.](image1.png)

![Figure 2: Building envelope with test sample layout.](image2.png)

2.2 Curing and testing of specimens

The specimens were cured at 110°C for 2 hours to ensure maximum part strength. The curing took place immediately after the parts were removed from the Voxeljet sand printer. The bend tests were done the following day, within 24 hours of curing as specified by AFS procedures. The tests were performed on a Ridsdale and Dietert Universal machine as shown in Figure 3. [8]
2.3 Analysis of results

The test results were analysed using both IBM SPSS statistical analysis and Microsoft Excel software, which included the central tendency, standard deviation and the normal distribution of the different print orientations and angles. The results were compared to the minimum required bend strength of 220 N/cm² (0.22 kPa), as specified by Voxeljet.[5]

3. EXPERIMENTAL RESULTS

The bend test results of the different test samples are shown in Table 1, indicating the different orientations and angles within the building envelope. The results indicated that the bend strength of samples (I,Z) and (C,YZ) were lower than the minimum recommended OEM value. However, the bend strength of the remaining samples were more that the recommended 220 N/cm².

The position mean values, shown in Table 1, demonstrated that position I and C had lower values than position H, B, G & A. Orientation mean values show that the Z direction were lower than the other orientations.

The test results confirmed that the print orientation and position had an effect on the bend test results.

<table>
<thead>
<tr>
<th>Position</th>
<th>Y</th>
<th>Z</th>
<th>YZ</th>
<th>XZ</th>
<th>X</th>
<th>Mean (position)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>269</td>
<td>188</td>
<td>288</td>
<td>250</td>
<td>294</td>
<td>258</td>
</tr>
<tr>
<td>C</td>
<td>269</td>
<td>238</td>
<td>188</td>
<td>281</td>
<td>306</td>
<td>256</td>
</tr>
<tr>
<td>H</td>
<td>275</td>
<td>231</td>
<td>319</td>
<td>300</td>
<td>375</td>
<td>300</td>
</tr>
<tr>
<td>B</td>
<td>256</td>
<td>238</td>
<td>306</td>
<td>306</td>
<td>269</td>
<td>275</td>
</tr>
<tr>
<td>G</td>
<td>319</td>
<td>244</td>
<td>313</td>
<td>294</td>
<td>363</td>
<td>306</td>
</tr>
<tr>
<td>A</td>
<td>338</td>
<td>281</td>
<td>294</td>
<td>300</td>
<td>338</td>
<td>310</td>
</tr>
<tr>
<td>Mean (orientation)</td>
<td>288</td>
<td>236</td>
<td>284</td>
<td>289</td>
<td>324</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4 shows a radar chart of the position mean bend test results.

It confirms that position I and C have lower bend strength in comparison with positions H, B, G and A. This chart indicates that location in the build has an influence on bending strength. The chart also shows that H, B, G and A has similar result and I & C also has similar results. Position I & C is located next to each other and are also the furthest point from the source of sand thus compaction or curing rates could have had an influence.
a. Central tendency

The mean values of the different print orientations can be seen in Table 2.

Table 2: Directional descriptive analysis.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>6</td>
<td>256.00</td>
<td>338.00</td>
<td>287.67</td>
<td>32.79</td>
</tr>
<tr>
<td>Z</td>
<td>6</td>
<td>188.00</td>
<td>281.00</td>
<td>236.67</td>
<td>29.74</td>
</tr>
<tr>
<td>YZ</td>
<td>6</td>
<td>188.00</td>
<td>319.00</td>
<td>284.67</td>
<td>48.74</td>
</tr>
<tr>
<td>XZ</td>
<td>6</td>
<td>250.00</td>
<td>306.00</td>
<td>288.50</td>
<td>20.69</td>
</tr>
<tr>
<td>X</td>
<td>6</td>
<td>269.00</td>
<td>375.00</td>
<td>324.17</td>
<td>41.39</td>
</tr>
</tbody>
</table>

The bend test results of specimens printed in the Y, YZ and XZ directions are similar to previous studies, which are above the Voxeljet recommended bend strength of 220 N/cm². It also became clear that the bend test results of the specimens printed in the X direction were greater than the results of previous studies and that of other orientations in this study.

The mean strength of test specimens printed in the Z direction was found to be the lowest of all the printed orientations as depicted in Figure 5. Z direction also produced the lowest bend strength in 5 of the 6 different origins. Therefore, it may be an indication that parts printed with maximum Y or X or at 45 degrees will have a
stronger bend strength compared to the same part positioned in the Z direction. The Z orientation represent the test samples with the smallest area amongst the different orientations that is covered by furan resin per layer by the print head.

b. Standard deviation

The standard deviation of the test results are shown in Figure 6. The figure shows that not all the directions provide the same variability of bend results. This variability ranges between 20 and 50 N/cm² which could be considered significant. The YZ orientation showed the largest variation. The lowest variation were obtained in the XZ orientation.

![Figure 6: Bend test Standard deviation.](image)

The box plot in Figure 7, demonstrates that the highest bending strength were obtained in the X orientation. The lowest strength tested were in both the Z and YZ orientation. This figure also shows four outliers. An outlier indicates that the value is more than 1.5 times the interquartile range above or below the upper or lower quartile. An outlier may be the most important data depicted and in this study two outliers indicates bending strength below the Voxeljet reference value.

![Figure 7: Whisker plot of bend test results.](image)

4. CONCLUSION

The following study investigated the variation of the bend strength of printed components at different print orientations and angles. The results showed that the majority mean value of parts printed in all the orientations are more than the reference supplied by Voxeljet. Although the mean values compare positively to Voxeljet’s
reference value, results showed that some individual test parts were below this value. Although this is statistical
correct and acceptable it must be noted that the quality of a part may be impaired.

It was also determined that the build orientation has an influence on the part strength. Parts printed in the X
direction yielded the best bend strength, whilst parts printed in the Z direction showed the lowest bend strength.
A variation in the bend strength was found throughout the build volume as peak values were more prominent in
certain printing locations. A possible explanation for this variation could include: Particle sizes and building
temperature, which will influence the homogeneous bonds between the particles.

The results in the following pilot study will be used as motivation to a comprehensive study to investigate the
effect of the building orientation and angle on the mechanical properties (bend, tensile and friability) of the
printed parts. Future research will also identify the printing factors (sand distribution, sand temperature etc.)
responsible for the variations in the part strength.

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ABSTRACT

This paper intends to illustrate and discuss three 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 third approach involves CNC cutting a slip-casting mould and dip-casting into ceramic slip. 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 casting slip’ (a mixture of dry clay, water and deflocculants) is poured into a mould made from a hygroscopic plaster most commonly Plaster of Paris. The porosity of the Plaster of Paris (recommended mixture 1.3kg of Plaster to 1l water, for optimum strength and porosity) 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, usually between 7 and 10 minutes, determined by the desired wall thickness on the part/vessel, the remaining liquid slip is poured out of the mould back into the slip bucket or container. As the clay dries, it shrinks and pulls away from the sides of the mould and can be released for further drying, fettling and firing [1].

![Figure 1: Slip Casting Process. Online.](image)

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 form 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 [4]. The process of modelling is heavily time intensive and requires a great amount of skill and craftsmanship. Furthermore, master models made from materials such as clay, wax and foam, can only be used to create one mould as they are distorted or destroyed when removed from the plaster mould. Therefore multiple identical master models need to be made if more than one mould is required. From a design point of view, this is a limiting factor as the form giving, level of detail or complexity and replication that can be achieved is limited to the skill of the maker.

The process of building the mould itself can also be a time and labour intensive process when a multiple part mould is required. First, the maker identifies and accurately marks out the split lines/ seam lines on the part, ensuring that there are no undercuts. The number of mould parts is determined by the form of the final product and the defined split lines. Second, a frame or box in which to cast the plaster must be built or assembled. Clay walls are then built around the part (along the split lines) sectioning areas in which to pour each mould part. Once the first part has been cast it must be left to dry sufficiently (drying time is dependent on mould size, wall thickness, ambient temperature and moisture). Alignment keys are then hand carved into the part prior to casting the next section. These steps are repeated for the casting of each section of the mould.

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2 Deflocculants evenly suspend and align particles the clay-water suspension, increasing fluidity [3]
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 three 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.

### Table 1: Various methods tested and discussed within this paper.

<table>
<thead>
<tr>
<th>Method 1</th>
<th>Method 2.1</th>
<th>Method 2.2</th>
<th>Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Printed Master Model + Slip Cast</td>
<td>CNC Cut Moulds + Slip Cast</td>
<td>CNC Cut Positive Mould + Dip Cast</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Master Model</th>
<th>Plaster Mould</th>
<th>Casting Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D printing master model</td>
<td>3 Part Pourd plaster mould (Rough cut + Spiral cut)</td>
<td>Slip Casting</td>
</tr>
<tr>
<td>No model needed</td>
<td>1 Part CNC cut plaster mould (Rough cut + Parallel finishing)</td>
<td>Slip Casting</td>
</tr>
<tr>
<td>No model needed</td>
<td>3 Part CNC cut plaster mould (Rough cut + 2 different spiral cuts)</td>
<td>Dip Casting (Variant of Slip Casting)</td>
</tr>
</tbody>
</table>

#### 4. METHOD 1: 3D PRINTING MASTER MODEL AND SLIP CASTING

The incorporation of 3D printing in this sequence allows for a master model to be created directly from a CAD model using 3D printing. The sequence illustrated below illustrates an example of this in the creation of a small faceted planter to be cast from black ceramic casting 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. The printing of the 3D Pattern was done with a hollow honeycomb fill to decrease material use and lower the problems of warpage. The 3D printed master model was smoothed and finished with various spray filler, primer and sand paper grades prior to it being used to create a 3 part poured plaster mould. The creation of the 3 part mould was done with conventional ceramic practices where a structure is built around the pattern to create the 3 mould parts in three stages. Following the traditional slip casting process, the faceted planter form was slip-cast. Figure 3 shows the 3D printed master model, the 3 part mould; and final fired geometric planter.
The part was fired to low stoneware, 1200°C, higher than the recommended firing temperature of 1160°C, resulting in bubbles and imperfections in the part surface. A second firing at 1180°C yielded a much more satisfactory outcome with less warping and surface imperfections. Once fired to full temperature, shrinkage is generally around 7%, however this final ceramic form was measured and compared to the 3D print allowing for the final shrinkage rate to be identified as being 8.5%. Now that the shrinkage is known to be 8.5%, any future products made from CAD models can be scaled up in the CAD environment prior to 3D printing, allowing the final fired outcome to be as near as possible to the intended final size.

5. METHOD 2.1: CNC CUT, ONE PART MOULD (NO PATTERN NEEDED)

The second method attempts to eliminate the pattern making and mould building step/process altogether by 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 soap 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 4.

6. METHOD 2.2: CNC CUT, 3 PART MOULD (NO PATTERN NEEDED)

To further test the complexity achievable with this method of mould making, the development of a 3 part mould was undertaken using SolidWorks. This allowed for the calculation of the shape of the form to allow effective staking. The intended function of this vessel was to be a small stacking pot for spices or tea-bags. Once the CAD file seemed suitable, the NC code was prepared to cut the file directly out of several blocks of pre-cast plaster. Cutting was done when the plaster was not completely dry, but slightly damp. It was suggested that the plaster, if slightly damp, would prevent chipping in the plaster (ensuring a neater cut) and reduce the generation of and inhalation of fine dust (Figure 6).
The cutting bit used was a standard 6mm High Speed Steel drill bit (HSS) because no other router bit was available to reach to required cutting depth. It ended up cutting the plaster relatively effectively as the double flute allowed for effective chip removal. Although it may not perform as effectively as a dedicated CNC cutting bit, it has the benefit of being very low cost and easily replaceable for around R20 from any hardware store (figure 6).

A problem with the CAM cutting sequences was that it was problematic to select specific faces to be highly finished, and some faces to be left with rough surface marks. This may be restrictions in the NC software (several years old), or in the limited understanding of the CAM software (figure 6, far right). The mating faces of the moulds were therefore smoothed with a craft knife until the parts fitted together effectively (to avoid running of slip between mould parts, and the need for extra fettling after casting). Black casting slip was poured through a sieve (to remove any clumps of clay particles which would cause impurities or bubbles in the part’s wall) and into the mould cavity. After 8 minutes, excess slip was drained from the mould (figure 7 sequence).

Once the cast was leather hard (hard enough to handle without distorting the form), it was removed from the mould and allowed to dry overnight. Thereafter, the rim and split line were fettled by hand using a fettling knife. These casts were fired at 1170°C (60°C per hour to 200°C, to remove all moisture from the part, and then 100°C per hour to 1170°C). A lower temperature was used in order to avoid warpage, especially in this case of achieving a stackable vessel. The final stacking pots are illustrated in figure 9. The pot with the white surface pattern was done by drizzling white casting slip into the inside of the mould cavity prior to filling with black slip.
Figure 8: Firing the ceramic casts undertaken using ramp cycle totalling approximately 16 hours, with a maximum temperature of 1170°C.

Figure 9: Final fired stacking pot showing colour, stacking and surface detail.

The outcome effectively shows the ability for the forms to stack, as well as provide evidence that the cutting texture of the drill bit also created a unique and interesting aesthetic (figure 8). Additionally the gritty texture of the clay added to the digital hand-made outcome.

7. METHOD 3: CNC CUT MOULD (POSITIVE) AND “DIP CASTING”

While researching different approaches to ceramic casting, the following video was seen online where a positive form was dipped into a bucket of slip as opposed to slip being poured inside of a mould (figure 10). This alternative approach allowed for the layer of slip to form on the outside of the plaster form, and once dry enough, will fall off of the form. That is with the suitability of the plaster form to allow this to be removed. This seemed like an interesting approach and we decided to replicate this, however with a CNC cut master model.

Figure 10: Chudy and Grase Dipped, a ceramic dipping structure, Online.[5].
The cutting of the positive dip casting mould was done with the same CAM sequence preparation as was used in the previously described 3 part mould. The source plaster was cast in a 220mm diameter by 70mm cylinder stock. The form was created in SolidWorks with a basic Revolved Protrusion command (Figure 11), the file brought across into Rhino, and the CAM sequence created with RhinoCam. The cutting sequence included rough cutting layers at 150% bit thickness to remove the majority of the material, thereafter 2 different spiral cut steps with a 66% and 80% step-over respectively. This large step-over would allow for pronounced cutting lines adding to the aesthetic of the form. The centres of the spirals were deliberately placed away from the centre of the form as the asymmetrical pattern was desired. The form of this part could not be too deep as the shrinkage of the casting slip while drying would pull onto the form as opposed to pulling away from the mould as in the standard slip casting process.

Figure 11: CAD modelling and CAM sequence prepared for the Dip-Casting form.

The plaster mould (in this case the 220mm diameter plaster form) was attached to a piece of pine brandering, to allow it to be held in place and suspended in the ceramic slip bucket. The casting slip was thoroughly mixed while still in the storage bucket. The Plaster form was then lowered into the slip bucket allowing the slip to completely surround the edge of the pattern (Figure 12). This allowed for the plaster to then start forming a layer of hardened slip over the form. The plaster form was suspended in the slip for a total of 12 minutes resulting in a wall thickness of approximately 5mm.

Figure 12: Dip casting the plaster form into the bucket of black slip. Barstool for added support.

This was then carefully removed from the slip bucket, and flipped over to allow the clay to continue hardening over the form (Figure 13 left image). Initially, the ceramic part was left on the plaster mould to dry overnight. As it dried, the part began to shrink onto the plaster form, resulting in a large crack in the part. For the second attempt the cast was left to rest inverted for only 3 hours, allowing it to harden somewhat, before removing it from the plaster form and resting it on the lip of a large bowl for support overnight. Once leather-hard (the next day) the rim of the part was smoothed using a fettling knife and damp sponge.
The fact that the mark of the machine cutting bit in the plaster surface is something not to hide, but rather to accentuate, it means that the actual cutting tool can be an interesting aspect of the final design aesthetic. The final form was fired together with the previously discussed 3 part mould spice pots at 1170 °C and created a very interesting visual outcome (figure 14).

It is evident that the tooth marks from the cutting bit (6mm HSS drillbit) are able to leave intricate and extremely prominent marks in the surface of the form. It is obviously of personal preference, however the fact that the mark created by the NC cutting sequence is at the centre of the final design aesthetic and allows for the interesting digital handmade aspect of the outcome. If however a perfectly smooth surface is required it would need a more suitable cutting bit, smaller CNC step-overs resulting in a longer cutting time.

8. 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. Furthermore if additional moulds need to be manufactured or if a ceramic with a different shrinkage rate is used, then this can be re-manufactured to a more appropriate scale.
- 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. Again relying on accuracy in the CAD environment and CAD calculated shrinkage rates allows for closer tolerances and more complex products to be manufactured using Ceramic slip-casting.

9. 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 three variations where experimentation has yielded satisfactory outcomes. There are most definitely many more areas of exploration and striving to incorporate additional aspects of additive and subtractive manufacturing techniques within the field of ceramics and we look forward
to constantly pushing these boundaries in attempting to find new and effective cross-overs between the digital fabrication and traditional manufacturing methods.

REFERENCES

SULFONIC ACID COATING OF REFRACTORY SAND FOR THREE-DIMENSIONAL PRINTING APPLICATIONS

O. Dady¹, K. Nyembwe² and M. Van Tonder³

ABSTRACT

Rapid sand casting processes by additive manufacturing are predominantly based on furfuryl alcohol resin bonded sand catalysed with sulfonic acid. The prior coating of the refractory sand with sulfonic acid is a crucial process to ensure the suitability of the sand for three-dimensional printing applications. The present paper investigated the sulfonic acid coating process of a local silica sand, which was found to have potential for three-dimensional printing applications in previous studies. Experimental conditions included sulfonic acid catalyst addition and mixing time. Coated sand was assessed for flowability and mechanical properties of test specimens produced by three-dimensional printing using a Voxeljet VX 1000. The optimum catalyst addition ranged between 0.3 and 0.6% yielding to transverse strength in the order of 110 to 165 KN/m² and tensile strength ranging from 710 to 770 KN/m²

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**1. INTRODUCTION**

Three dimensional printing (3DP) technology is nowadays successfully applied for the manufacturing of sand moulds and cores for casting applications. As with the conventional moulding and core-making methods, the refractory materials include siliceous and non-siliceous refractory materials such as silica sand, chromite sand, olivine sand, synthetic sand [1].

Commercial 3DP processes for rapid sand casting applications in use are essentially based on the furfuryl alcohol resin bonded sand process [2]. The latter is a no bake process in which the sand self-setting at room temperature catalysed by an acid such as the sulfonic acid. The sand used for 3DP is coated with sulfonic acid. A printer head selectively dispensed the resin during the layer-by-layer manufacturing. Well-known 3DP systems working on this fashion include ExOne and Voxeljet [3].

The hardening mechanism of the furfuryl alcohol resin in the presence of the sulfonic acid catalyst is well-explained in the literature [4]. Essentially, the addition of an acid activator to a furan resin triggers an exothermic poly-condensation reaction, which hardens the binder. The condensation reaction produces water, which has a tendency to retard the cure rate (dehydration). The bond generating reaction is the further polymerisation of these chains with cross connecting. Within the presence of strong acids, prepolymers of furfural and furfuryl liquor form polymer films that act as fasteners. The curing rate is specifically relative to the measure of acid and a two-part system can be detailed with a very much controlled curing time [5].

In the case of 3DP, the flowability of the sulfonic coated sand is an important property to be considered prior to the actual hardening of the resin as explained above. The flowability property is a measure of the ability of the sand to free flow during layer-by-layer manufacturing. This property of the coated sand will influence the recoating behaviour during three-dimensional printing process, which is required to be flawless in order to prevent glitches [6]. Experimentally, the flowability of a powder material is measured by calculating the angle of repose formed by the free flow of sand on a cylindrical support. Multiple images are taken by the use a camera focusing on the position of the interface sand/air. The angle of repose is therefore calculated determining the angle of the isosceles triangle, which has the same surface as the heap of granular materials [7].

Previous studies have investigated the importance and effect of sand properties including particles size, clay content, pH level, acid demand, refractoriness, surface morphology and angularity of local sands on the mechanical properties of 3DP sand specimens [8]. It was found that not all the local silica sands are suitable for three dimensional printing as the mechanical properties were inferior and recoating problem during additive manufacturing were encountered.

Three-dimensional printing is available in South Africa. However, due to the limited availability of suitable local silica sand and the complexity of the sulfonic acid coating, imported refractory sand from overseas is used, making the 3DP process expensive and unaffordable to the local foundry industry. This state of affair possibly prevents the full adoption of the AM technology by South African sand casting foundries [8].

This research focuses on 3DP material preparation consisting of the coating of a local silica sand with sulfonic acid in order to determine the optimum sulfonic acid addition for required mechanical properties of sand parts. The overall aim of the study is to localize the manufacturing of silica sand for three-dimensional printing applications.

**2. METHODOLOGY**

2.1 Raw materials

The raw materials used in the study include silica sand and sulfonic acid produced locally. The properties of the silica sand are presented in table 1. The size distribution of the sand is shown in figure 1. This sand used by local foundries in the Gauteng region was found to have suitable properties for 3DP [9].

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

**Table I: Sands characterisation results.**
Figure 1 shows the sands grain size distributions obtained with a particle size distribution analyser (Filta).

2.2 Experimental Procedure
The followings steps were conducted in the experimental procedure:

2.2.1 Sand coating
The sand coating consisted of addition sulfonic acid to 50 kg of silica sand in a foundry batch sand mixer. The sulfonic acid addition was determined at 0.3, 0.6 and 0.9% per weight of the sand. The mixing time was maintained constant at 5 minutes per batch of sand. The prepared coated batches of silica sands were then stored in sealed plastic buckets prior to additive manufacturing in order to prevent them from acid evaporation and moisture pick up.

2.2.2 Flowability measurement
The sand flowability was measured immediately after mixing, after 24 hours and 48 hours to determine the influence of storage time on the flowability. Figure 2 schematically illustrates the determination of the flowability in terms of angle of repose.

![Figure 2: Illustration of sand granule on a cylindrical support displaying an angle of repose $\alpha_r$.](image)

2.2.3 Three dimensional printing
The manufacturing of transverse and tensile test specimens were produced on a Voxeljet VX 1000 three-dimensional printer. The geometries and dimensions of specimens were according to the AFS standards [10]. The standards specimens were then oven cured at 105-110°C to allow complete bond sand particles.

2.2.4 Testing
The mechanical properties of the test sand specimens produced by 3DP were assessed in terms of tensile and transverse strengths. A universal strength test machine was used for strength determination following the American Foundry Society mould and core test procedures [10].

3. RESULTS

3.1 Coated sand pH
Figure 3 shows the variation of the coated sand pH for the different addition of catalyst as a function of the storage time after mixing and prior to the three-dimensional printing. It appears that the pH for the different batches of sand
in terms of catalyst addition increases as time elapsed. This variation of pH over time could possibly suggest a loss of sulfonic content in the sand with time. This could be due to evaporation of the catalyst at room temperature.

The above phenomenon could affect the effectiveness of the catalyst in hardening the furfuryl alcohol resin bonded sand during three-dimensional printing, resulting in the production of weak sand parts.

![Figure 3: pH changes as function of time.](image)

### 3.2 Flowability measurement

Figure 4 shows the variation of the angle of repose for the different addition of catalyst as a function of the storage time after mixing and prior to the three-dimensional printing. It appears that:

- The flowability of the sand decreases (higher angle of repose) as the percentage of sulfonic acid addition increases. This suggests that too much addition of catalyst could cause recoating problems during the additive manufacturing process. The coating could be serving as a glue preventing mobility of the sand grains.
- The flowability of the coated sand appears to improve (lower angle of repose) as time elapses. As the sulfonic acid content decreases with time, the flowability of the coated sand evolves towards the flowability of the uncoated sand, which is better (lower angle of repose).

![Figure 4: Flowability results as function of time variations.](image)

From the above, it appears two competing phenomena are at play: the loss of the catalyst with time and the increase of flowability with time. The first phenomenon will impact on the hardening process of the three-dimensional printing, while the second phenomenon will affect the layer by layer manufacturing.
3.3 Three Dimensional printing

Figure 5 shows the 3DP sand specimens produced on the Voxeljet VX 1000 printer after baking only for 0.3% and 0.6% addition of sulfonic acid in the silica sand. The 0.9% sulfonic acid coating could not be used for three-dimensional printing of sand specimen due to clogging of the printer’s recoater as shown in figure 6. The 0.9% sulfonic correspond to the lowest flowability of the coated silica sand. The effect of storage could not improve the flowability for this sand to make usable for the 3DP.

Figure 5: Transverse bars and tensile specimens.

Figure 6: Image (a) shows sand lumps formed in the re-coater and image (b) shows clogging of the sand feeder.

3.4 Moulding properties assessment

Figure 7 shows the mechanical properties of the 3DP sand specimens in terms of tensile and transverse strengths. Strength appears to increase slightly with sulfonic acid content. An increase of 8.7% was obtained for the tensile strength while and increase of 5% was found for the transverse strength from 0.3 to 0.6% addition of sulfonic acid. No data were reported for the 0.9% sulfonic acid due to unavailability of sand specimens as explained in the sections above.

Figure 7: Tensile and transverse strengths data - 48 hours storage time.
4. CONCLUSION

The study attempted to understand the sulfonic acid coating of silica sand for three-dimensional printing applications based on furfuryl alcohol resin bonded sand. The study showed that the sulfonic acid content in the sand and the storage time of the coated sand after preparation are important factors in determining the manufacturability of the coated sand and the final mechanical properties of 3DP sand parts. In this study, it was possible to successfully coat a locally available silica sand, which could produce 3DP sands specimens meeting the requirements of mechanical properties with acceptable addition of sulfonic acid in the range of 0.3 to 0.6% addition. Further work will investigate the performance of different types of refractory sands including chromite sand and ceramic sand.

REFERENCES

PATIENT SPECIFIC DYNAMIC HAND SPLINTS PRODUCED THROUGH SELECTIVE LASER SINTERING

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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 prosthetics environment. Current available dynamic hand splints are not always 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 live hinges and in-process assembly of parts were utilized to produce a dynamic hand splint with improved functionality. This allows for hand motion in a specific direction while restricting and supporting undesired abnormal positions and movements of the fingers as a result of spasticity.

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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. In order for the hand to be considered functional, excellent integration between a complex structural arrangement of bones and joints to provide stability, an intricate system of muscles, tendons and blood vessels to facilitate movement, and an elaborate system of nerves controlling action is required. The hand (Figure 1) consists of a stable wrist joint, the palm and five fingers. The wrist is composed of eight carpal bones that articulate with the ulna and radius on the proximal side and the five metacarpal bones on the distal side. The five metacarpals make up the palm of the hand and articulate with the phalanges. The proximal, middle and distal phalanges make up the fingers and thumb. The wrist and hand therefore consist of 21 major joints that are controlled by 28 muscles in a coordinated manner to perform multiple, complex and dexterous grasps required to facilitate both gross and fine motor task performance [1]. These movements can be either conscious or reflexive in nature and are dependent on feedback received from the multiple sensory mechanisms in the hand [2]. The proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints are found between the phalanges of the fingers, both have one degree of freedom. The metacarpophalangeal (MCP) joints, the joints between the proximal phalanx and the metacarpal bone have two degrees of freedom [1].

![Figure 1: Skeletal features of the hand [3].](image1)

The hand is composed of extrinsic and intrinsic muscles. The extrinsic muscles - the long tendons of the wrist, thumb and fingers based in the forearm - are considered more important than the smaller, intrinsic muscles (within the hand). The flexor tendons (Figure 2) run through the carpal tunnel and the tunnel of Guyon, and their action performs wrist flexion, radial and ulnar deviation and flexion of the fingers to form a fist. The extensor tendons pass through the extensor tendon compartments and the extensor retinaculum and their actions perform dorsiflexion of the wrist and extension of the fingers to make a flat hand [2].

![Figure 2: Joints and tendons of the finger [4].](image2)

The hand contains a high density of several specialised nerve endings in the joints, muscles and skin. A large area of the motor and sensory cortex in the brain is focused on the interpretation of sensory input received from the sensory receptors in the hand and the resultant motor response. These sensory receptors ensure that the
brain is provided with tactile (pain, temperature, light touch, deep pressure) and proprioceptive (information regarding joint angle, muscle length and muscle tension) input to guide and direct responses in order to perform movements and to protect the structures from damage [5]. Should any one of the integral aspects of hand function mentioned above be damaged either temporarily or permanently, the optimal functioning of the hand will be negatively influenced. It is therefore essential that devices be developed that assist with the compensation for impaired function whilst not inhibiting the intact function still available.

Chronic hand impairment commonly occurs following a stroke. Stroke patients often experience unusual stiffness of the hand which is referred to as spasticity. This impairment or spasticity is caused by an imbalance of signals from the brain to the muscles and can result in the development of contractures without intervention. A contracture occurs when connective tissue such as ligaments, tendons, and joint capsules become scarred, or when muscle tissue becomes shortened. This can occur at any joint. Rather than applying an unmaintained quick stretch to the connective tissue involved, which may be very painful for the patient, a low-load (75 - 300g), prolonged stretch (LLPS) evokes a plastic, more permanent and less painful, change in tissue length. Soft, static and dynamic hand splinting is 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. Static and / or dynamic splinting is used under the guidance of qualified professionals 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 [6].

The goal of dynamic splinting is to stress scarred or shortened connective tissue with a LLPS to promote non-traumatic, more permanent tissue remodelling. The lengthened tissue can provide increased range of motion [7]. A study by Chang et al. describe that wearing a dynamic splint for 30 minutes a day for five days a week over three months has shown noticeable improvement in hand function of a patient. The authors also indicate that six months is the minimum time required for rehabilitation [8]. Jeon et al. [9] as well as Frank et al. [10] also showed that the use of dynamic hand splinting is an effective means of rehabilitating hand impairment after a stroke.

An appropriate dynamic hand splint needs to be patient specific due to the complex nature of the hand’s biomechanics. Ideal biomechanical function is essential for clinical rehabilitation as secondary impairments can be established if the movement induced is incorrect. The complex biomechanics of the hand with numerous joints in a small area has traditionally led to dynamic hand splints with complex structures and mechanisms that are bulky, often ineffective and not aesthetically pleasing (Figure 3). Effectively replicating the biomechanical function of the hand will improve functionality, durability and comfort of a dynamic hand splint [11].

![Figure 3: Conventionally manufactured dynamic hand splints [11].](image)

Heo et al. [12] reviewed various exoskeleton structures that facilitate appropriate biomechanical function of the finger (Figure 4). The authors concluded that the direct matching joint center exoskeleton configuration was the most functional. This however results in the necessity for structures to be placed between the fingers which lead to restricted movement and discomfort for the patient.
Figure 4: Mechanisms for matching finger biomechanical function [12].

Yap et al. [13] utilized a moulding process to manufacture patient specific soft pneumatic bending actuators from pour cast elastomer. The structure induced the necessary tension, stability and aesthetic appeal with a slender design. The casting process to produce the actuators was however time consuming and not cost effective.

In order to produce an exoskeleton type dynamic splint with slender finger features, the joints of the device’s fingers need to be moved from the sides to the top of the fingers. Finger joints of the hand rotate through the centers of the joints (Figure 5). With the joint sections of the proposed exoskeleton however placed on top of the fingers, the structures need to lengthen in flexion and contract in extension to counteract the variation of arc length created by rotation away from the neutral axis. Insufficient variation in arc length or misaligned rotation points will cause discomfort for the patient since the joints will be put under pressure. This effect is most noticeable at the MCP joint as the link hinge point needs to be placed on the wrist splint, resulting in a greater arc length. Counteracting the variation in arc length around the finger joints has resulted in dynamic splints with complex linkages that are bulky, or soft expandable pneumatic structures that provide the correct motion but without adequate support [12].

Figure 5: Difference in arc length between center of joint on top of finger [12].

AM has widely been utilized in the physical medicine and rehabilitation sector [14] and has also been specifically useful in manufacturing patient specific foot orthoses, ankle-foot orthoses and prosthetic sockets [15]. Feasibility studies have shown that patient specific foot and ankle orthoses produced through the selective laser sintering (SLS) AM process are as / more effective than currently prescribed orthoses [16], [17]. Paterson et al. [18] investigated various AM processes to directly manufacture upper extremity static splints, concluding that SLS and PolyJet material jetting display unique advantageous characteristics when manufacturing splints, only made feasible by the manufacturing processes. Agarwal et al. [19] and Abdallah et al. [20] utilized AM to produce complex exoskeleton mechanisms that exhibit appropriate biomechanical function, however these mechanisms proved to be bulky and prone to fatigue failure. The patient specific and complex nature of dynamic hand splint manufacturing make it well suited for AM.

Considering the shortcomings of existing dynamic hand splint designs, the aim of this study was to investigate the suitability of AM to produce aesthetically pleasing low cost durable dynamic splints which could be easily customized to fit the needs of different patients and thus addressing the shortfall in delivery to low income patients.

2. METHODOLOGY

Research into various concepts of producing an appropriate dynamic hand splint through AM was performed on an EOS P385 printer using nylon PA2200 as printing material. The SLS printing process and material were selected
because of the durability of parts produced and no need for support structures during the manufacturing process. This paper documents the iterative design process followed to create an AM patient specific dynamic hand splint and the equipment and procedures used to compare different design concepts.

2.1 Exoskeleton design

Two joint concepts were investigated to produce aesthetically pleasing slender finger sections for a biomechanically functional exoskeleton type dynamic hand splint using SLS. These were conical hinge direct joint matching structures and live hinge structures.

2.1.1 Conical hinge concept

The conical hinge concept was investigated by designing in process assembled conical hinges that allow rotation but restrict axial movement (Figure 6). Literature indicates that the direct matching joint center exoskeleton configuration is not effective due to restricted movement of the hand as a result of adding structures on the sides of the fingers [12]. This concept was nonetheless investigated to determine if AM could produce a sufficiently slender structure to reduce the restrictive motion compared to traditional hinge structures. The ability of AM to produce in process assembled structures was leveraged to create a slender hinge design. Samples were produced at various thicknesses (1 mm, 1.4 mm and 1.6 mm) and build orientations (x and y directions) to test the durability and the effectiveness. Printing in the z direction was not investigated because of the excessive costs involved in printing in this direction through SLS.

![Figure 6: CAD of conical hinge joint concept.](image)

2.1.2 Live hinge concept

The live hinge concept was investigated in an attempt to solve the MCP joint design problem and create a slender design that allows for appropriate hand motion. The use of live hinges should result in a simple joint design that should be easy to manipulate to produce patient specific finger sections. Three live hinge designs were produced (Figure 7) to investigate the concept namely solid (a), lattice (b) and geometrical wave (c) live hinges.

![Figure 7: Solid (a), lattice (b) and geometric wave (c) live hinge structure designs.](image)

The solid hinge was produced as a control to determine the properties of such structure without alteration. With the lattice hinge concept, the lattices weaken a section thus creating more flexibility in a required direction. The lattice structure design should also allow for some stretch to overcome the difference in arc length during extension/flexion while restricting side to side movement. The geometric wave structure was used to investigate if a flexible structure that allows extension in arc length can be produced without significantly reducing the strength of the structure. Samples were produced at different thicknesses (1 mm, 1.4 mm and 1.6 mm) and build orientations (x and y directions) to test effectiveness.

2.2 Tendon tension mechanism

Two concepts were considered to replicate the biomechanical function of the extensor tendons of the hand. First was to use a wire and guide system with two 1 mm spring steel wires mounted on top of the finger (Figure 8 a).
Second was a 99% natural rubber strip that attached to pins on top of each joint of the finger through corresponding holes in the strip (Figure 8 b).

![a](image1.png) ![b](image2.png)

**Figure 8:** (a) Steel wire and guide and (b) rubber strip concepts to replicate tendons.

The tension of the rubber tendon can be specifically tailored to each patient’s needs by changing the width of the section. Patient specific rubber tendons are easily manufactured utilizing a CO₂ laser cutter.

### 2.3 Cyclic tester

A finger cyclic tester was designed and manufactured to determine the durability and functionality of the produced concepts (Figure 9). The tester comprised of a crank arm that was driven by a Nema 23 stepper motor. The stepper motor was controlled by a Raspberry Pi and it recorded the number of cycles performed. The result was displayed on a liquid crystal display (LCD) screen.

![image3.png](image3.png)

**Figure 9:** Finger cyclic tester.

A 1 mm stainless steel cable with clear plastic coating was used to connect the front link of the finger to the crank arm of the tester. The connecting hinge point on the crank arm was made adjustable as to vary the stroke length of the finger. A front guide determined the angle at which the cable was pulled. The tester was designed such that the joints of the finger had two ball bearings mounted in each joints to ensure smooth repetitive motion. The three links of the finger were manufactured in nylon PA2200 through SLS.

### 3. RESULTS AND DISCUSSION

#### 3.1 Exoskeleton structure design

It was possible to produce both the concept conical and live hinge exoskeleton structures of a patient specific dynamic hand splint utilizing SolidWorks instant 3D features. In this software, patient specific dimension data is populated in a spreadsheet that interacts with the SolidWorks CAD file, thus presenting an effective means of producing patient specific data that can be used to manufacture parts through AM.

##### 3.1.1 Conical hinge concept results

The conical hinge concept was produced by creating in process assembled conical hinges with thicknesses of 1, 1.4 and 1.6 mm respectively. A clearance of 0.25 mm is required between the sides of the conical wall of the hinge to allow for in process assembly and un-sintered powder to be removed. The 1.6 mm thickness hinge walls and x-axis build direction showed the most promising results amongst the three hinge thicknesses and two built orientations investigated. Even at this hinge thickness, the thin walls of the conical hinges proved to be not practical and easily broke. Adding 1.6 mm to each side of the finger exoskeleton (which had a shell thickness of 1.4 mm) also meant that 3 mm was added on both sides of each finger with resultant restriction of motion of the hand (Figure 10).
A major concern of the conical hinge concept was furthermore producing an effective MCP joint. Due to the MCP joint having to be placed on the wrist splint, there was no effective way of creating a durable linkage that was not bulky.

3.1.2 Live hinge concept results

Solid, lattice and geometric wave structure concepts were considered to improve biomechanical function and durability of the dynamic hand splint finger sections. This was printed at 1, 1.2 and 1.4 mm thicknesses in the x and y print orientations (Figure 11).

All printed concepts were physically tried on a finger and it was found that the 1 mm thickness produced the desired flexibility of the joint sections while the 1.2 and 1.4 mm wall thickness proved to be excessively stiff. It was not possible to perceive any difference between concepts printed in the x and y directions. The geometric wave live hinge concept proved to be impractical since the bottom edge of the wave induce direct pressure onto the knuckles of the finger during flexion. The lattice live hinge allowed for more flexible movement compared to the solid hinge. From these observations, it was decided to produce a complete dynamic hand splint incorporating lattice joints between finger sections (Figure 12 (a) and (b)). To overcome the extensive arc length across the MCP joints, the splint design included linear slide mechanisms for each finger on top of the wrist splint.

Physical testing of the dynamic splint showed that it did not exhibit appropriate biomechanical function. Although the lattice joints were flexible, they did not sufficiently compensate for the increase in arc length between
flexion and extension of the fingers. This resulted in discomfort to the knuckles of the wearer. The sliding mechanism that was incorporated into the dynamic splint design for the MCP joints however proved to be successful and it was therefore decided to also incorporate the same design into the finger joints. A test concept was printed in the x and y directions and the sliding motion of each section of the live hinge slider concept was found to allow for a more comfortable natural hand motion (Figure 13 (a) and (b)).

![Figure 13: (a) Finger section with live sliding hinge during extension and (b) flexion.](image)

Since the 1 mm solid joint was considered to be sufficiently flexible it was decided to move away from the lattice structures in the live hinge slider concept. Although the lattices allow more flexibility, it also results in weakness in the joint structure.

The cost of producing a patient specific dynamic hand splint through SLS in nylon such as shown in Figure 12b was R 3600. This was taking machine time for laser sintering, material cost as well as operator time into consideration. Compared to the R 8000 - R 13000 of a conventionally manufactured patient specific dynamic splint, the AM splint can be considered affordable. The cost of AM is largely dependent on the number of parts that are manufacture together in the same build. If more than one dynamic splint is produced at the same time, the cost can be reduced even further to make these devices available to low income patients at reasonable cost. The design for the additive manufactured splint can also be easily adapted to the unique dimensions of each patient using SolidWorks instant 3D features.

3.3 Tendon tension mechanism results

Prototypes finger exoskeletons were manufactured and tested for both the spring wire and rubber tendon concepts. The spring wires showed insufficient spring effect and friction between the wires and guides proved too high for this concept to be effective. The rubber tendon concept however produced the desired results. Rubber tendons with different designs were produced in an iterative process and tested on the cyclic tester with the slider live hinge joints. A first concept (Figure 14) lasted 1043 cycles while a second concept (Figure 15) lasted 2010 cycles.

![Figure 14: Rubber tendon Concept 1.](image)

![Figure 15: Rubber tendon Concept 2.](image)

The finite element analysis (FEA) module of SolidWorks was used to investigate the stresses that were induced on the second rubber tendon concept (Figure 16). The MCP joint was fixed while a 10 N load was applied to the PIP joint and 8 N to the DIP joint in the simulation. This was the same loading that the rubber tendon experienced...
during cyclic testing. The maximum stress concentration indicated in the simulation corresponded well with the actual point of failure of the second concept.

Taking the stress concentrations indicated in the second concept simulation into consideration, a third concept (Figure 17) was produced.

The third rubber tendon concept was placed on the cyclic tester and at the time of writing this paper was shown to last more than 26 000 cycles without any evidence of failure of the rubber tendon or sliding joints of the finger sections. This was for finger sections printed in both the x and y printing orientations. The finger sections and rubber tendons can therefore be considered sufficiently durable for this application. Since the CAD data of each patient’s dynamic splint will be available, it will also be easy to reproduce a finger section or rubber tendon should failure occur.

4. CONCLUSION

This paper investigated the suitability of AM to produce aesthetically pleasing durable dynamic splints that promotes natural hand movements while restricting / supporting undesired abnormal positions and movements of the finger caused by spasticity. Further requirements were that the device should be easily customizable to fit the needs of different patients and that it should be produced at low cost to address the shortfall in delivery to low income patients.

Different joint concepts were investigated to produce a dynamic hand splint by SLS and it was found that the live hinge structure concept showed the most promise. Physical testing of a dynamic splint incorporating these live hinge features however showed insufficient movement of the MCP joints. An improved live hinge slider mechanism was designed and incorporated into the MCP joints of the dynamic splint. The revised design demonstrated a significant improvement in biomechanical function of the MCP joints compared to the previous design. It was decided to also incorporate the live hinge slider mechanism design into the DIP and PIP joints resulting in slim aesthetically pleasing finger sections. An optimized patient specific laser cut rubber band was proven to be the most effective means of replicating tendon function. The durability of slider live hinge joints and rubber tendons were demonstrated on a cyclic testing device. A cost comparison indicated that a patient specific dynamic hand splint can be produced through SLS in nylon at a lower cost compared to conventionally manufactured patient specific dynamic splints.

Considering the above, the aim of producing aesthetically pleasing low cost durable dynamic splints through AM which can be easily customized according to patient requirements was achieved.

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VALIDATION OF MICROPHONE PLACEMENT FOR ACOUSTIC EMISSION FOR ONLINE DETECTION OF POROSITY FORMING PHENOMENA DURING METAL LASER POWDER BED FUSION

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ABSTRACT

Some concerns which arise during the metal laser-based powder bed fusion (LPBF) process are lack of fusion between tracks following non-optimal input process parameters; scanning and building strategies and/or inhomogeneity in delivered powder layer. The problem is that unstable geometrical characteristics of single tracks cause porosity in 3D parts. Non-contact acoustic emission is one of the methods for online monitoring of LPBF. The purpose of this paper is to validate the placement of the non-contact acoustic emission sensor. This was done by means of mathematical evaluation of the data for symmetrical fusion at different distances from the sensor. Excludible small variants in time domain root mean square values and good correlation of the power spectrum transformations show that the current placement of the sensor was acceptable for acoustic emission and can be used for online detection of porosity forming phenomena during metal LPBF.

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1. INTRODUCTION

Laser powder bed fusion (LPBF) is an additive manufacturing (AM) process which uses energy from a laser beam to fuse selected regions of a powder bed [1]. Online and early detection of unstable geometrical characteristics of single tracks is the most important to prevent porosity in 3D parts. Sensing defects and control during the process is one of the main ways for ensuring repeatability and consistency of LPBF manufacturing. Key process parameters in LPBF are laser and scanning parameters; powder material properties; powder bed properties, recoating parameters and build environment. Process signatures emanating from the melt pools in LPBF are molten/solidified pool, plasma emission/absorption, radiation, reflected light, etc. These parameters need to be controlled and are the basis for stability and repeatability of the LPBF process [2].

Some non-destructive testing (NDT) techniques that can be used for quality control in AM are visual, ultrasonic, Eddy current, radiographic, magnetic methods, liquid penetrant test, shearography, acoustic and thermography [3, 4]. Thermography and acoustic emission testing are applied as inspection methods for in-situ monitoring of AM processes, but the spatial and temporal resolution of in-process monitoring with feedback depends on scanning parameters. LPBF is a rapid process that makes on-line NDT and feedback control extremely difficult. For spatial capability, minimum defect size also have to be determined in order to qualify parts [5, 6]. Available commercial LPBF monitoring systems consists of photodiode melt pool monitoring, CMOS camera for powder bed imaging systems and others that make use of infrared and ultraviolet photo sensors and pyrometers [2].

Yusof et al. [7] investigated the feasibility of using acoustic monitoring of laser power and pulse width during Pulse Mode Laser Welding to indicate depth of penetration. One of the conclusions drawn is that some post processing is needed to eliminate the influence of noise. For metal LPBF, Fisher et al. [8] showed that when attaching a sensor to the substrate a clear difference could be obtained from the acoustic signatures when using different laser powers. It was found that there was a clear shift and missing peaks in spectral analysis at different laser powers. As showed in previous work, a non-contact AE can be used for online monitoring during metal LPBF [9]. Authors have shown that the quality of AE results is dependent on noise; Horvat et al. [10] proposed a new algorithm that eliminates reverberation and background noise during AE monitoring of Gas Metal Arc Welding (GMAW). Similarly Alfaro and Cayo [11] showed that the quality of online AE monitoring was effected more by environmental conditions when compared to online infrared monitoring during GMAW. Thus, factors like the effect of sound reflections, machine environment, noise and the location of the recording device therefore need to be considered as a basis of qualification. This paper shows the analysis of the results of AE sensor placement as sampled in the actual metal LPBF machine. These results include all the environmental factors as well.

2. METHODOLOGY AND RESULTS

2.1 Materials and methods

Maraging steel MS1 from EOS with the chemical composition being Ni 17.6%, Co 8.88%, Mo 4.85, Ti 1.06% was used. Samples were produced by an EOSINT M280 system on the substrate with similar chemical composition. Powder layer thickness was 50 µm. The building chamber was filled with nitrogen atmosphere. 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. AE was measured using an ICP microphone having an optimal frequency range of 3.75-20 000 Hz (±2dB). The microphone was placed inside the building chamber (Fig. 1).

![Fig. 1. Experimental scheme.](image)

To determine if AE differs with respect to the distance from the microphone, the microphone was fixed above the substrate and the laser scanned at 5 different positions, 40 mm apart. Each set containing 3 tracks. Tracks were scanned consecutively from Position 1; Track 1 (P1; T1) on the right, to the left end at Position 5; Track 3 (P5; T3) (Fig. 2).
In Figure 2 the distance from the microphone edge to the midpoint of each position is indicated and their corresponding values are shown in Table 1.

### Table 1: Distance from microphone to different scanning position.

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>240</td>
<td>243.31</td>
<td>252.982</td>
<td>268.328</td>
<td>288.444</td>
</tr>
</tbody>
</table>

The data were acquired at a sampling frequency of 102.4 kHz. Code for post-processing of data was written using LabView and its signal processing algorithm libraries. It was seen experimentally that a 1500 Hz high pass filter could remove the effect of ambient operating noise that does not pertain to the actual laser scanning. Each individual scan track was extracted from the total data scan to ease analysis. The average sound pressure at individual scans was calculated using root mean square (RMS) value. Thereafter evaluation of frequencies at each position were analysed to determine whether certain positions might amplify or absorb some frequencies due to its position in the system. The individual frequency content was analysed using power spectrum and doing correlation with one another. Since all the process parameters are physically the same with the only difference being distance from sensor, good correlation results would indicate the optimal sensor placement (>0.99).

### 2.2 Results

The tracks were visually analysed, and no major irregularities were present. A section of the tracks at Position 1 is shown in Fig 3.

![Fig. 3. Track 1 to 3 of Maraging steel on substrate.](image)

After applying the 1500 Hz high pass filter, the tracks were clearly distinguishable in the time domain. The scanning time of each track is equal to the time that it would take to scan a track at a speed of 1.01 m/s for 200 mm length as shown in Fig 4.
Fig. 4. Signal of first three tracks after applying signal filtering.

The individual RMS values sound pressure level (SPL) showed no large variations in relation to the distance from the microphone. Variations could be attributed to slight differences in powder layer thickness over the platform. Table 2 shows the SPL of each scan. The maximum fluctuations in sound pressure during the process was calculated by taking the max and min value of Track 1, 2 and 3 as shown in Table 3.

Table 2: SPL at each position (dB).

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>83.24898</td>
<td>83.11877</td>
<td>83.16945</td>
<td>82.8472</td>
<td>83.39392</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.656737</td>
<td>0.350508</td>
<td>0.760288</td>
<td>0.471983</td>
<td>0.197635</td>
</tr>
</tbody>
</table>

Table 3: Max and Min track SPL value and corresponding SPL difference.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Δ SPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>83.52422</td>
<td>82.35053</td>
<td>1.17369</td>
</tr>
<tr>
<td>T2</td>
<td>84.00713</td>
<td>83.28985</td>
<td>0.717278</td>
</tr>
<tr>
<td>T3</td>
<td>83.59498</td>
<td>82.4994</td>
<td>1.095574</td>
</tr>
</tbody>
</table>

These results show that the sound levels reaching the sensor is relatively close to each other, but one needs also to indicate if any frequency distortion could have taken place. The individual frequency content for each track was calculated with power spectrum and results correlated with Track 1. Table 4 shows that all the samples showed good correlation.

Table 4: Power spectrum correlation value of Track 1 with other tracks.

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1</td>
<td>0.993</td>
<td>0.999</td>
</tr>
<tr>
<td>T2</td>
<td>0.993</td>
<td>1</td>
<td>0.994</td>
</tr>
<tr>
<td>T3</td>
<td>0.999</td>
<td>0.994</td>
<td>1</td>
</tr>
</tbody>
</table>

Thus, with good correlation and similar RMS values, one can conclude that the current sensor position in this setup is not influenced by the environment or scanning position.

3. CONCLUSION

The purpose of this paper was to validate the microphone placement during acoustic emission for online detection of porosity forming phenomena during metal laser powder bed fusion. Analysis was done inside the EOSINT M280 machine using Maraging steel; placement with chosen distances seem to be adequate, but care should be taken if any variable such as machine, sensor or material is changed. Similar SPL levels and good frequency correlation of the tracks for this environment with this sensor placement indicate that measures and data can be trusted for non-contact acoustic emission during online detection of porosity forming phenomena during metal LPBF. This would pave the way for a
reliable AE detection system for early detection of unstable geometrical characteristics of single tracks or powder layers which can cause porosity in 3D parts.

ACKNOWLEDGMENT

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REFERENCES

DESIGN OF A “LARGE” UNMANNED AERIAL VEHICLE FRAME FOR METAL ADDITIVE MANUFACTURING ON THE AEROSWIFT MACHINE

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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 optimization methodology followed to reach an optimized design solution will be covered in detail.

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INTRODUCTION

An Unmanned Aerial Vehicle (UAV) is an aircraft without a human pilot aboard. The flight is controlled either autonomously by onboard computers or by the remote control of a pilot on the ground or in another vehicle [1].

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 project aims to demonstrate that topology optimization can be used to optimize the design of a large UAV frame and that the Aeroswift system is capable of manufacturing a complex and large scale part.

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

1. FRAME DESIGN

1.1 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 320 x 600 x 560 mm³ build volume
- The UAV should have symmetrical motor placement.
- Flight times of at least 15 minutes should be achieved.
- Components should be included for autonomous flight capability, stabilized 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.
- The 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 maximized.
- Aesthetics should be considered during the design process.

1.2 Component selection

A UAV craft requires a core set of components, i.e. Motors, propellers, electronic speed controllers, a flight controller and a battery in order to be functional [2]. In addition to the core components, additional components such as cameras, camera gimbal and communication are required to satisfy the requirements as described in the previous section.

1.2.1 Motors

The motors are the source of power, to spin the propellers, for the UAV craft. Brushless direct current (DC) motors are most commonly used for this type of application. A brushless motor consists of a core stator and bell with permanent magnets on the inside of the bell. The stator, which is essentially an electric magnet, generates a magnetic field in such a way that the permanent magnets are moved in a sequence to sustain the rotational speed of the motor. Brushless motors are favoured over Brushed DC motors because of their increased torque, reduced noise, reliability, and higher efficiency [2]. Usually, a UAV craft requires multiple motors to supply the total power required for sustained flight.

1.2.2 Propellers

The propellers, which are attached to the motor bell, convert the rotational spin of the motor bell to downward force or thrust. A propeller can be characterized in terms of its diameter and the pitch of the blades. Even though there is a very wide range of propeller sizes and pitches available, the size of the UAV frame and the specifications of the motors limit the range of propellers that can be used on a specific UAV craft. The manufacturer of the motors will also specify the range propeller sizes and pitches to be used to operate a motor safely, achieve maximum performance and efficiency.

1.2.3 Electronic speed controllers

Due to the high current and voltage requirements of the motors, the electrical power to the motors can’t be supplied by the flight controller. Electronic speed controllers are required to handle this task. The electronic speed
controllers control the rotational speed of the motors. These components typically use pulse width modulated signals to vary the voltage and current required by the motor to in turn control the speed. The control signal is connected to the flight controller in order to manage the thrust generated by each motor.

1.2.4 Battery

The battery is the electrical power supply for the entire electrical system and drivetrain. Depending on the power rating of the battery a UAV craft can be operated with a single battery pack or a battery bank, depending on the lifting capacity of the craft and the available space. Lithium-polymer (Li-Po) batteries are the most popular to use in this type of application. Li-Po batteries are light-weight, rechargeable, have a high power density and the ability to provide the high sustained current output required for the motors. A Li-Po battery is characterized by its capacity and the cell count.

1.2.5 Flight controller

The flight controller is the control system of the UAV craft. The basic hardware components on a flight control board are a microcontroller, gyroscope sensor and accelerometer. A number of other sensors can be added to a flight controller to provide feedback about the operating environment, collision avoidance and to aid in autonomous control functions. The control software or firmware that executes on the flight control board constantly reads the sensor data, performs data filtering, processes data in control algorithms and outputs control signals to the motors. The control algorithms constantly make slight changes to the rotational speed of the motors (at high sample rates) to balance out the thrust vectors, perform manoeuvres and ultimately sustain stable flight.

1.2.6 Camera and stabilization gimbal

The usage of cameras on a UAV craft can have two roles, one being to record footage from the UAV and the other to provide the pilot with a first-person video (FPV) view from the UAV craft. There are cameras available on the market that is able to function as a recording camera and as an FPV camera in some applications where 2K or 4K video recording is not a requirement.

Due to the vibrations generated by the spinning motors and propellers, unwanted or blurred lines will be seen in the camera footage. To counteract the vibrations, a gyroscopically controlled gimbal can be used to provide a stable platform for the recording camera to ensure vibration free video recordings.

1.3 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. The flight controller, cameras, camera gimbal/mounts and other control and communication electronics which would satisfy the functional requirements of the UAV craft also had to be specified. 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.

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.

1.3.1 eCalc benchmark tool

To aid in the design and selection process, a comprehensive and specialized calculation tool and component database, namely eCalc [3] 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 eCalc tool is widely known and used for benchmarking non-commercial or custom developed aircraft to estimate performance statistics of the frame and drive train components [1],[4],[5].

With the number of motors and the maximum allowable frame size known an iterative process could be followed to determine the drive train components required to satisfy the flight time and thrust requirements. Due to the vast number of available components in the eCalc database, the focus was placed on reputable component vendors as well as components that are readily available. It was not required to find the optimal drive train setup but only satisfy the flight time and thrust requirements.

1.3.2 eCalc estimation results

The results obtained by the eCalc tool can be shown in Figure 1.
As can be seen from Figure 1, the frame weight and size has been entered as 650 g and 750 mm respectively. The eCalc software only needs the size of the frame to determine if the chosen propeller size will fit the frame. A frame size was of 720 mm (measured between diagonal motors) was chosen in order to fit into the 320 x 600 x 560 mm³ build volume of the Aeroswift machine.

The following components were chosen for the drivetrain:

- Tiger motor MN3110 - 780 Kv motors
- 10000 MAh four cell Li-Po battery
- Dual blade carbon fibre propellers with a diameter of 304.8 mm and a pitch of 101.6 mm.

With this configuration, it was found that a thrust to weight ratio of 2.6 and a flight time of at least 16 minutes can be achieved. This information, together with the component mount positions, were required inputs into the optimization phase of the design.

2. SIMULATION INPUTS

The virtual prototyping that is used to design and evaluate the UAV frame requires various simulation inputs. This section is dedicated to describing those simulation inputs and will commence with a description of the parameters related to the physics of the UAV frame. The parameters relating to the computational solution of the physics are discussed thereafter.

2.1 Physical Parameters

It is necessary to accurately capture the physics of the UAV frame and this is facilitated by defining the following parameters:

- The parameters which characterize the behaviour of the Ti6Al4V titanium alloy to be used for manufacturing. The elastic modulus, poisons ratio and material density are specified as follows: E = 116.5 GPa, Nu = 0.31, Density = 4429 kg/m³, Yield Stress = 827.3 MPa. It is also noted that the benchmark design, which will be discussed later, was simulated using Nylon. The corresponding material properties are: E = 2.91 GPa, Nu = 0.41, Density = 1230 kg/m³, Yield Stress = 75 MPa.
- A definition of the loading that will be impressed on the UAV frame. The identified loads represent worst-case scenarios for the constituent loadings that will, when combined in various combinations, make up any load-case expected to be impressed on the in-flight UAV.

It is noted that in Finite Element Analysis (FEA), in order to analyze structural responses, it is necessary to constrain rigid body motions in the product being analyzed. In reality, however, the UAV experiences an imbalance of forces and torque and this is the mechanism through which motion is achieved. Therefore, it was necessary to perform an equivalent static load (ESL) analysis whereby the analysis reference frame was considered as being fixed to the UAV’s centre of gravity (COG) and fictitious inertial loadings were used to balance out the force and torque imbalances that usually result in UAV motion. In this way, the same structural responses that would be exhibited by the in-flight UAV, are simulated for a particular epoch. This is also referred to as an inertia relief analysis.
There are three equivalent static load-cases to represent the most extreme roll, pitch and yaw motions. These are the names given to rotational motions of the UAV around the three body-fixed orthogonal axes aligned with the frame. These motions, along with an illustration of the constituent loads that cause them are shown in Figure 2. A forth load-case to represent the most extreme vertical accent possible was also defined and is also shown in Figure 2. Lastly, negative variants of the roll, pitch and yaw motions were also analyzed.

It was also necessary to define an additional fictitious load to represent a landing scenario. The primary reason for this was to ensure topology generation in the volumes which encompass the landing gear of the UAV. To ensure appropriate topology generation in these regions a connected mass at the extremities of the landing gear was defined (as shown in Figure 3) which needed to be virtually supported through all the other load cases. This alleviates the difficulty of defining a landing load-case since there are many factors to consider for such a loading scenario (eg. angle of attack, descent speed etc.).

In Section 4, the reader will encounter curves that depend on numerated load-cases that have been described in this section. Therefore, each load-case is numerated below in order to provide context for those descriptions.

1. Vertical Ascent
2. Pitch
3. Roll
4. Yaw
5. Negative Pitch
6. Negative Yaw
7. Negative Roll

2.2 Computational Parameters

There are factors relating to the computation of results for the simulation that affect the accuracy of the simulations, even if it is assumed that the physics of the UAV frame has been accurately represented. In addition, these computation factors can also affect the length of time required for results to be generated. The computational factors considered are as follows:

- **Element Size**: During the course of a finite element analysis, a geometric structure is discretized using a finite number of elements (see Figure 4 for an illustration). Each element is made up of nodes which in turn represent the number of calculation points for which a solution will be generated by the FE solver. The element sizes were varied in each analysis. Initial runs utilized elements in the range of 12mm while final analyses utilized elements in the range of 1.5mm since numerical accuracy was sought in the concluding phases of the design process.
• Element Order: Any single element may be configured by placing nodes at the vertices of the element only, or by placing nodes at the element vertices and the mid-span of the element edges. These are referred to as first order and second order element, respectively, due to the resulting order of the polynomial equations that represent the field quantities across those elements. Equal size second order elements produce a numerically more accurate solution at the cost of computation time. This project has utilized first order elements throughout.

• Number of assigned CPU cores: The FE solver technology that forms the kernel of Altair Inspire (Optistruct) facilitates parallelization of the FE analysis submitted to it. This capability was utilized during this project as four physical cores were used to run all analysis, resulting in shorter wall-times during analyses/optimizations.

• Topology thickness range: The solution space is constrained by the topological thicknesses that are being considered in the solution. By constraining the solution space with a topological thickness specification, computational times can be reduced substantially. It should be noted that there are rules governing the allowable constraints of topological thicknesses based on the size of the elements employed. The topological thickness constraints varied from 9 mm in the first optimization to 4 mm in the last optimization of the design process.

3. TOPOLOGY OPTIMIZATION TECHNOLOGY

Topology optimization (TO) is a mathematical theory which enables the synthesis of structurally optimal products. The basic concepts of the technology will be described below, followed by a description of the components that should make up a TO solution. Lastly, a description of how the technology has been adapted for the Additive Manufacturing (AM) domain specifically will be given.

The layout of material within a volume directly affects the manufacturability, cost, and functional performance of that volume. Designing the material layout for a given volume is therefore complex, and hence best approached in a structured manner. Topology optimization technology is a platform off of which to approach a particular design in such a structured manner. The technology employs an algorithmic approach in which a design concept for material layout within a volume is iteratively modified and gauged for performance in order to inform the modification necessary in the following iteration. The process is repeated until the performance of the design volume has converged within the constraints placed on it [6].

Multiple components should be incorporated into a TO solution. Firstly, the basis of a product designed with TO is a concept design volume which has been created in a Computer Aided Design (CAD) package. The TO solution should, therefore, have open interfaces through which to import these CAD concepts which have been created in other software or it should have native CAD-like capabilities for the generation of a basic concept. Secondly, a TO solution should incorporate FEA capabilities. FEA has traditionally been used for the simulation of the structural behaviour of a designed product. FEA thus provides the mechanism through which to evaluate the performance of each iteration. Lastly, a TO solution should incorporate the appropriate tools for translating the final design concept from the FEA domain into the CAD domain (this is necessary so that the design may be exported from the TO solution and imported into other software in the design/manufacture toolchain). All these components of a TO solution could be found in the Altair Inspire 2018 package which was used during this project for the design of the UAV frame.

Although TO offers designers a tool to synthesize structurally optimal products, the technology does also present its own challenge. The most structurally efficient design is not necessarily the most manufacturable design [7]. To address this challenge, the TO technology can be adapted to account for constraints of the manufacturing process [8]. As an example, and relevant to the additive manufacturing space, a restriction can be added regarding the angle to which consecutive boundary layers of a part are built [9], [10]. This would, in turn, remove the need to create support structures during the build preparation phase.

The angle constraint was only applied during the reduced optimization that is illustrated in Figure 4(g) and not in the other optimizations that were performed. The assumption which drove this decision was that the boundaries created by the reduced optimization (in which subsequent optimizations would search for a final solution) would have been limited to the printable angle ranges, and hence, any topology that would be created within those boundaries would require only minor support within the boundaries themselves. It was found that there still remained the need to support areas in the design but with slight changes in the model, the number of required supports could be reduced greatly.

Figure 4: An illustration of the discretization of the UAV frame.
3.1 Design methodology

Due to specific structural and weight requirements, it was decided to use topology optimization as a tool to optimize the frame design. The design methodology followed is described in the seven steps listed below, whereas the topology optimization technologies themselves are described in Section 3. Where applicable, the outputs of the steps are shown in Figure 5.

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 5(a).
2. The primitive/baseline concept was imported into topology optimization software (Altair Inspire in this case) and a baseline finite element method (FEM) analysis was performed to check that loading conditions are correct.
3. A baseline optimization 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 5(b).
4. A check was performed to verify if the baseline optimization 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 5(c).
5. Topology branch sizes were increased to reduce the computational complexity and the process was repeated to produce the thickest boundaries which encompass the load paths in the material (Figure 5(d)).
6. The design space was reduced and a full-scale optimization was completed where small branch thicknesses were considered. To form a new design space, geometry was created to capture the topology of the baseline optimization from the previous step (Figure 5(e)). Ad-hoc modifications to improve AM manufacturability and aesthetics was done at this step and is shown in Figure 5(f).
7. The final design optimization was completed and the resultant geometry was subsequently recreated with thin, optimized branches (See Figure 5(g)).

3.2 Topology Optimization Results

The methodical process followed in the previous section clearly shows the transformation from a very basic design to a topology optimized 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 5(g)). The estimated weight of the optimized design is ~647g. The eCalc estimation used a frame weight of 650g as input and thus the calculated performance values should be accurate with the tolerance specified by the eCalc tool.

![Figure 5: UAV frame design optimization Process.](image)

4. FRAME EVALUATION

4.1 Strategy and Evaluation Metrics

The UAV frame evaluation focus was to determine if the final frame design adheres to the mechanical specifications described in Section Error! Reference source not found.. Various metrics can be associated with the UAV frame and it is possible to track these metrics through a number of design iterations. Then by comparing these metrics for subsequent iterations with the benchmark (initial concept), it is possible to evaluate whether the design has matured towards an optimal concept or not. The next few paragraphs describe the metrics that were used.
Figure 6: Selected design iterations that are used for evaluation. (a) Benchmark, (b)-(e) Iteration 1 to 4 respectively.

One obvious and valuable metric for evaluating the frame design is its total mass since this metric directly addresses the specification regarding the thrust-to-weight ratio of the UAV. According to the eCalc tool results, the total UAV weight should not exceed 650g. The total mass of the frame must thus be lowered from the baseline concept which has a mass slightly exceeding 1.3kg.

Each frame design iteration has a set of calculable single-values which correspond to the individual load cases and are termed compliances. These compliances describe the strain energy absorption of the frame under the associated load case. Hence, another metric which was used to evaluate the frame designs are the load-case dependent compliances. A single metric i.e. weighted compliance metric, which describes the sum of the individual compliance values for the load cases can be measured during a particular design iteration. It should be noted that the compliance of a structure is an inversed indication of the structure’s stiffness, i.e. it can be concluded that a structure is stiff against a particular load-case if it exhibits a low compliance during that specific load-case.

The second last metric that will be used to evaluate frame performance is the body acceleration of the UAV frame under the given load-cases. These acceleration vectors change as the inertia of the frame is changed from iteration to iteration. By assessing the changes in magnitude and makeup, it is possible to draw conclusions regarding the changes in UAV manoeuvrability through the design process.

For qualitative purposes, the natural frequencies of the frame will be tracked through the various design iterations. This is important to ensure that the possibility of resonance between the frame and motors are considered and mitigated.

4.2 Design Evaluation and Discussion

Table 1 provides the data that will be used to evaluate the frame design in this section. The rest of this subsection will be dedicated to the mining of this data in order to churn it into evaluation information regarding the UAV frame design iterations.

<table>
<thead>
<tr>
<th>Design Iteration</th>
<th>Mass (kg)</th>
<th>Weighted Compliance (m/N)</th>
<th>First 3 Natural Frequencies (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Benchmark)</td>
<td>1.307</td>
<td>4.852974E-03</td>
<td>84.825, 103.963, 122.493</td>
</tr>
<tr>
<td>1</td>
<td>4.3473</td>
<td>6.9578442E-06</td>
<td>75.415, 118.285, 146.338</td>
</tr>
<tr>
<td>2</td>
<td>3.9628</td>
<td>1.0416215e-05</td>
<td>61.603, 105.028, 171.441</td>
</tr>
<tr>
<td>3</td>
<td>0.73926</td>
<td>1.310252E-03</td>
<td>27.916, 50.792, 59.631</td>
</tr>
<tr>
<td>4</td>
<td>0.647</td>
<td>5.902445E-03</td>
<td>28.537, 41.317, 47.003</td>
</tr>
</tbody>
</table>
4.2.1 Mass and Stiffness

Maximizing the frame stiffness was a requirement in the design process, but at the same time, it was necessary to keep the frame mass to a minimum. The former requirement calls for more material utilization while the latter calls for less material utilization in the design volume. The strategy for resolving these conflicting design actions was to maximize the frame stiffness while simultaneously hedging the design with an exact constraint on the mass of the frame. It was thus observed (and expected) that although compliance should have been minimized (equivalent to maximizing stiffness), it was inevitably increased from the benchmark through to the final iteration as a sacrifice for the achievement of the specification relating to the UAV mass. The compliance did, however, increase to a lesser degree than what the frame mass was minimized. This represents a design advantage which outweighs the associated disadvantage and is depicted in Figure 7.

Notice that both metrics have been normalized against the benchmark concept.

Consider the following trends that can be observed in Figure 7.

- Notable changes in mass and stiffness from the benchmark to the first iteration can be seen. The most significant contributing factor is the change in material that has been affected (recall that the benchmark concept is made from Nylon whereas the final product is to be manufactured using Ti6Al4V).
- Iteration 1-2 marks almost no change in magnitude of stiffness, but almost 30% reduction in mass, signalling a significant design advantage gain. However, a significant transfer of stiffness from one load-case to another had taken place during this design iteration, see Section 4.2.2.
- Iteration 2-3 boasts an equally impressive design advantage: 246.6% mass reduction while only increasing compliance by 26.8%.
- Iteration 3-4 does not represent a design advantage since mass decreases by only 7% while compliance increases by 102%. The modifications made between these iterations, however, had been made based on manufacturing considerations.
- Benchmark vs. final design: Mass reduction of 50.5% with a simultaneous compliance increase of 29%. This represents an overall design advantage.

As was shown in Table 1, the frame weight specification has been met. The specification relating to stiffness has also been considered achieved since the frame stiffness has been maximized within the boundaries of the objective mass constraints.

4.2.2 Compliance per load-case

The global view of compliance in terms of its weighted sum which was considered in the previous subsection is further dissected in this subsection. Specifically, the implication of load-case dependent compliance changes are explored and the consequences explained. Consider Figure 7 as an illustration of the observations that follow.
Consider the following trends that can be observed in Figure 8:

- The load cases of positive and negative variants of distinct UAV motions (e.g., pitch, roll, and yaw) create equal magnitudes of compliance in the structure except for pitch. The large difference in pitch/negative pitch compliance is attributed to the geometric asymmetry of the final design in the transverse plane which bisects the front and back halves of the UAV.
- The first load case (vertical ascent) accounts for most of the compliance in all of the iterations, thus influencing the designed topology most heavily of all the load-cases since all of the distinct loads (thrusts and torques) which combine to make up any one load-case are applied during ascent.
- The load-case which bears the lowest influence on the design is the negative pitching of the UAV (in all but the benchmark design).
- The negative pitching, yawing (both positive and negative) and vertical ascent load cases increased in stiffness while all other load cases became slightly more compliant. The effects of the former on the total weighted compliance (and thus the designed topology) of the frame, therefore, decreased while the effects of the latter were increased.
- Iteration 2-3 marked a big difference in compliance with the vertical load case: A large mass reduction was performed during this iteration.
- Iteration 1-2 marked a big increase in pitching compliance with a simultaneous decrease in negative pitching compliance: Aesthetic changes were made during this iteration.

The observations above are further augmented by considering the compliance profile of the benchmark and final design with reference to all seven load-cases. It can be seen in Figure 8 that the compliance profile with regards to the seven load-cases is similar in both the benchmark and the final design.

The most notable difference is that the final design exhibits more stiffness during negative pitching motions while simultaneously providing less stiffness during positive pitching motions. These large changes were realized between iterations 1 and 2, which are also shown in Figure 9.

In conclusion, vertical ascent is the dominant design driver. Furthermore, the disparity in frame compliance during pitching/negative pitching is attributed to the frame’s geometric asymmetry in the relevant plane. Large mass reductions caused large increases in vertical ascent compliance. Lastly, aesthetic changes caused large compliance changes in the pitching motion. Using the evaluation strategies laid out in Section 4.1, the authors consider the frame compliant regarding load-case dependent compliance. This is because, in the first place, the final requirement in Section Error! Reference source not found. called for the consideration of aesthetics during the design process. It was u
ncovered that the functional changes in UAV performance due to aesthetic changes in the UAV design were not adversely detrimental. Secondly, the load-case dependent compliances were tracked through the various iterations and although the changes were noted, they could not be classified as either improvements or deteriorations of the benchmark frame performance.

4.2.3 Linear and Rotational Acceleration

During the inertia relief analysis which supported this UAV design (see Section 2.1) it has been possible to extract the accelerations which are required to balance external forces from the analysis results. It is possible to draw conclusions about the changes in UAV manoeuvrability/dynamics by comparing these externally applied accelerations for the final and benchmarked models. The observations which follow are also coupled with the ones in Section 4.2.2, but it is much more intuitive to understand manoeuvrability changes from the perspective of balancing accelerations as opposed to weighted compliances. Consider Figure 10.

![UAV Linear Acceleration per Loadcase](image1)

**Figure 1: UAV accelerations per load-case for selected design iterations.**

Consider the following observations that can be seen in Error! Reference source not found.

- The final design exhibits larger magnitudes in its linear and rotational accelerations. This can be attributed to the increased thrust-to-weight ratio relative to the benchmark.
- The vertical load-case causes the largest linear acceleration while simultaneously causing the smallest rotational acceleration in the benchmark.
- The yawing (positive and negative) load-cases cause linear accelerations similar in magnitude to the vertical load-case in the final design. The load-cases simultaneously cause large rotational accelerations, but this second part of this observation applies to the yawing load-cases in the benchmark case as well. The explanation for this is that in the final design, the COG has been shifted further from the intersection of the diagonals that connect the motors. Thus, thrust forces translate more efficiently into vertical ascent when applied across a single diagonal. However, during vertical ascent, since the motor positions are still not square, the combined thrust of all four motors translates into vertical ascent as well as a component of rotational acceleration which effectively dilutes the vertical ascent magnitude.
- The negative pitching load-case causes the lowest linear acceleration in both the benchmark and final design, although, in the case of the final design, the relative margin is higher between the magnitude of linear acceleration in the negative pitching load-case and all other load-cases.

In conclusion, the main inferences from these observations are that the UAV has become, on average, more manoeuvrable due to the increased thrust-to-weight ratio. Furthermore, the frame has become, relative to its other motions, more manoeuvrable in its yawing motions and less manoeuvrable in the negative pitching motion. The second of these conclusions will be influenced by the battery placement during assembly of the UAV. Thus, the two evaluation strategies laid out in Section 4.1 have been completed regarding frame acceleration since this subsection has successfully compared the various iterations and associated the comparisons with the thrust-to-weight ratio requirement given in Section 1.1.
4.2.4 Natural Frequencies

The change in natural frequencies for the first three natural modes of the structure is shown in Figure 11. Notice that the natural frequencies have been normalized by the baseline concept. Whereas the second and third modes increased slightly in the interim, they ultimately decreased. Comparing the benchmark and final design, it can be seen that all natural frequencies have been reduced in the range of 60-70%. This observation is of no consequence, however, since the excitation produced by the motors is to occur at frequencies far in excess of these natural modes and it is concluded that this metric has been successfully evaluated in terms of the strategy provided in Section 4.1.

![Evolution of Natural Frequencies](image)

**Figure 2: Evolution of the first three UAV frame natural frequencies.**

5. CONCLUSION

A methodology for the mechanical design of a topologically optimized UAV frame was provided. The unique feature of the methodology which was developed is that it utilizes a two-step optimization process in which the first optimization serves to reduce the size of the computational problem while the second optimization becomes responsible for the generation of the final form of the UAV frame. The methodology was also injected with modifications to accommodate both aesthetic and manufacturability considerations. Since the design process was largely driven by simulation or virtual prototyping, the paper has provided details regarding the simulation technology and the inputs that have been submitted through the technology. These inputs included physical parameters such as material specifications and load definitions. The inputs also included considerations which affect the computation of the solution.

It was argued that in many of the simulations, trade-offs needed to be considered between accuracy and computation time. Lastly, the final frame design was evaluated utilizing a two-phase evaluation strategy. In the first phase, some evaluation metrics which can be determined, for each iteration of the UAV frame, during the design process. The metrics were then used to track changes through the design process and the final design was ultimately compared with the benchmark to conclude whether the design process had produced a result which was better than the benchmark. This was indeed the case. In the second phase, the metrics which could be associated with any of the UAV frame requirements set out in Section Error! Reference source not found. were used to settle those requirements.

It was concluded that the UAV frame requirements were met, including frame weight, thrust to weight ratio and flight time all while maintaining frame stiffness. The optimized design solution, for the most part, minimizes features that will prevent the design from being printable with the powder bed fusion process on the Aeroswift machine. Topology optimization allowed for the development of a non-conventional frame while AM ensures manufacturability of this shape.
REFERENCES


PRODUCTION OF SPHERICAL TITANIUM BASED POWDERS FROM POWDER METALLURGY BARS

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ABSTRACT

This article describes the results of preliminary investigations into the production of spherical titanium-based powders via powder metallurgy routes. The investigations seek to support the localization initiatives through the manufacture of high-quality low-cost spherical powders. Feedstocks for atomization (in billet and bar forms) were prepared using low capital-intensive equipment and atomized via the vacuum induction melting (VIM) or electrode induction gas atomization (EIGA) systems. The atomized powders were characterized for both properties and application using the Laser Engineered Net Shaping (LENS) Additive Manufacturing (AM) system. The investigated feedstock production routes were both found to be feasible and cost effective. The produced powders were spherical and suitable for application in the LENS AM system.

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\textsuperscript{2,3,4,5} CSIR-MSM, Light Metals, Republic of South Africa
1. INTRODUCTION

The Republic of South Africa is pursuing 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, in that order). Research efforts led by the Department of Science and Technology through the Titanium Centre of Competence (TiCoC), are currently underway to develop a suite of complementary technologies to help South Africa add value to its vast body of titanium ores. Key to these efforts is the development and commercialisation of a novel process for converting the titanium ores to titanium metal granules/powders, at low cost, and to further convert the metal powders to intermediate and finished products. Alongside the beneficiation strategy, the additive manufacturing (AM) strategy was recently commissioned [2]. The latter seeks to position and support AM as the next chapter in the industrial revolution [2]. Together 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 has developed swiftly in the last decade. It has demonstrated significant potential and gained popularity; the reader is therefore referred elsewhere for discussions on its fundamentals and merits [2,3,4]. It is a generally accepted opinion that AM is a disruptive technology with the potential to significantly improve competitiveness and boost productivity across industry sectors. While the manufacture of Ti-based components by AM is currently well established [5], its uptake has been uncharacteristically underwhelming, caused by among other, things expensive feedstock powder materials [6,7]. In the case of South Africa, AM users bear exorbitantly high transport and import costs of the titanium-based feedstock powder due to the fact that such materials are considered hazardous under the OSHA Standard (in addition to the already high international commodity prices). There is a case therefore for localization of production of these AM powders.

Commercial Ti-based AM feedstock powder is currently produced via a number of processes, including atomization and spheroidization techniques. Atomization techniques, such as electrode inert gas atomization (EIGA), plasma rotating electrode process (PREP), plasma atomization (PA) [7] and lately vacuum induction melting (VIM) [8] have gained prominence. Currently, the most used methods of making AM Ti-based feedstock spherical powder start with Ti-based feedstock bars/billets or wires made by the ingot metallurgy technique of vacuum arc re-melting (VAR) [9] 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), it is not surprising that methods such as plasma spheroidization have demonstrated cost-effective alternatives [10]. In this study, the feasibility of producing Ti6Al4V feedstocks for atomization (in the form of bars/billet) via powder metallurgy techniques was investigated. Powder metallurgy bars/billets were produced and atomized using the EIGA and VIM systems. Subsequently, the atomized powders have been characterised and components built using a LENS system.

2. METHODOLOGY AND RESULTS

2.1 Methodology

The starting titanium materials used in this preliminary study were the -325 mesh Ti HDH powder and the -100 mesh Ti HDH powder both supplied by Baoji Lihua Non-Ferrous Metals Co., Ltd of PR China. Two Ti6Al4V bars/billets used in this study were manufactured via blended elemental powder metallurgy starting with -325 and -100 mesh Ti HDH and a -325 mesh 60Al40V master alloy supplied by Reading Alloys, USA. The starting powders were weighed in the right proportion for the starting powders, by using an Eltra ONH 2000 gas analyser. The morphology was determined using a JEOL JSM-6510 SEM. The porosity and microstructures of the powders were both determined from polished cross-sections using the JEOL JSM-6510 SEM. The ultimate suitability of the powders for AM application was determined using a Hall Flowmeter, in accordance with standard ASTM B213-13. The oxygen content was determined as follows: Powder flowability, oxygen content, and microstructure.

For the purposes of comparison and benchmarking the processes, a commercial Ti6Al4V billet (meeting Ti Grade 5 AMS 4928R composition specifications) was also atomized via the EIGA system.

The atomized powder was classified for size distribution by sieving the as-received powder into different size fractions. Characterization powders were focused only on the size fraction suitable for the Laser Engineered Net Shaping (LENS) AM system. The LENS AM systems generally use powder within a 75 - 250µm particle size distribution range (Frazier, [4]). The atomized powders were characterised for particle size distribution, porosity and morphology, powder flowability, oxygen content, and microstructure.

In this study, powders with particle size in the 40 - 100 µm targeted range were used. The powder flowability was determined using a Hall Flowmeter, in accordance with standard ASTM B213-13. The oxygen content was determined as for the starting powders, by using an Eltra ONH 2000 gas analyser. The morphology was determined using a JEOL JSM-6510 Scanning Electron Microscope (SEM). The porosity and microstructures of the powders were both determined from polished cross-sections using the JEOL JSM-6510 SEM. The ultimate suitability of the powders for AM application was...
tested on a directed energy deposition (DED) technique Laser Engineered Net Shaping (LENS) 850-R system at the National Laser Centre, CSIR.

2.2 Results and Discussion

2.2.1 Starting materials

Figure 1 shows that the morphology of the starting powders was angular, and typical of the production process which includes crushing hydrogenated Ti powder to reduce particle size. Angular powder particles are easier to process using the conventional press and sinter powder metallurgy technique. The oxygen content of the powders was determined to be 0.18wt.% for 100 mesh TiHDH, 0.32 wt.% for the TiHDH 325 mesh and 0.03 wt.% for the 60Al40V master alloy. Oxygen content of titanium powders is a function of the particle size, being higher for finer than coarser particles, as in the current case.

![Figure 1: Particle morphology of starting powders: (a) 100 mesh TiHDH, (b) 325 mesh TiHDH, (c) 325 mesh 60Al40V master alloy.](image)

2.2.2 Sintered PM Bars/Billets

Figure 2 (a & c) show the Ti-6Al-4V long and short bars/billets produced via PM techniques at the CSIR; the bars/billets had theoretical sintered densities of 65 and 87% respectively. The difference in the sintered density was caused by the difference in the green densities and powder particle size; the higher green density of the short billets, and also the fineness of the powders used to make them, accelerated densification. Oxygen analysis by ICP-OES found the sintered long bars/billets had 0.27wt.% oxygen while the short bars/billets contained 0.48wt.% oxygen. These oxygen contents were influenced by the oxygen contents in the starting powders, which were lower for the powders used to produce the long billets, and by the powder particle size, where finer particles, due to their higher surface area adsorb more gas at the surface which then diffuses into the powders during sintering. Apart from the powder characteristics, the environment in the furnace used to sinter the billets could also have been contaminated with air. Future work will endeavour to sinter billets in a vacuum furnace. An analysis of the microstructures of the bars/billets showed that they had the typical alpha-beta microstructure characteristic of the Ti-6Al-4V alloy, indicating that the sintering conditions had been sufficient to allow for elemental diffusion and chemical homogenization.

![Figure 2: Sintered PM bars and billets](image)
Figure 2: PM Ti-6Al-4V bars/billets and their characteristic alpha-beta two-phase microstructures.

2.2.3 Characteristics of atomized powders: Powder morphologies

Figure 3 shows the typical morphology of the powders atomized by EIGA and VIM. Regardless of the starting billets and the atomization route, all the atomized powders were mostly spherical with either smooth or textured surfaces. This was an important observation, and indicated that the atomization processes were not sensitive to the densities of the billet feedstock. Spherical powders, in theory, have an enhanced flowability, and a high flowability is required by all AM technologies (Anderson, [11]). By observation, the EIGA system produced powders from both the commercial and the long PM billets had a significant amount of ‘satellite particles’ compared to the VIM system produced powders. Satellites particles are the fine particles attached to larger particles and, according to Sun et al [7] form when fine particles are blown onto semi-solidified particles. The fact that more satellites appeared to have formed on the EIGA powders tallied with the known fact that the EIGA process produces more fine particles than the VIM process (Sun et al [7]). The presence of satellites introduces obstacles to smooth continuous flow.

Figure 3: Morphology of EIGA (a) commercial (b) PM Long bar and VIM (c) PM short bar derived atomized powders.

2.2.4 Characteristics of atomized powders: Microstructures of powders

The polished cross-sections of all the powders indicated that some larger particles had pores in addition to the satellite particles attached to them (Figure 4). However, the volume of the porous particles constituted a small percentage
According to Rabin [12], pores in atomized powders are caused by the entrapment of the atomizing gas. Chen [8] recently determined that the amount of entrapped gas increased with powder particle size, which explains the reason why only larger particles in the current study had porosity. According to Anderson [11], the powder particle porosity is generally difficult to eliminate and is therefore detrimental to AM builds.

![Figure 4: Polished sections of powders showing pores in some particles.](image)

The microstructure of the polished cross-sections of the powder particles (Figure 5) showed the occurrence of martensitic laths, typical of fast cooled Ti6Al4V alloy for the EIGA-PM long bar derived powder. The corresponding energy dispersive spectroscopy (EDS) EDS analysis (Figure 5 and Table 1) indicated that the elemental composition of the powders was characteristic of Ti6Al4V alloy. Similar microstructures and compositions were observed for the VIM-PM short billet derived powder and the EIGA-commercial bar derived powder.

![Figure 5: Microstructure and EDS analysis of powder particles.](image)

### Table 1: Characteristic chemical composition of powders from SEM-EDS.

<table>
<thead>
<tr>
<th>Element (Line)</th>
<th>Weight %</th>
<th>Atom %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al K</td>
<td>5.3 ± 0.06</td>
<td>9.03 ± 0.11</td>
</tr>
<tr>
<td>Si K</td>
<td>0.43 ± 0.03</td>
<td>0.71 ± 0.04</td>
</tr>
<tr>
<td>Ti K</td>
<td>90.77 ± 0.29</td>
<td>86.11 ± 0.27</td>
</tr>
<tr>
<td>V K</td>
<td>3.49 ± 0.09</td>
<td>3.15 ± 0.09</td>
</tr>
<tr>
<td>Cr K</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>
2.2.5 Characteristics of atomized powders: Powder oxygen content and flowability

Table 2 below shows the oxygen content and the flowabilities of the atomized powders. The oxygen contents, which ranged between 0.21 and 0.47 wt.% were generally a reflection of the oxygen contents of the billets. The oxygen content of the powder from the EIGA atomization of the commercial billet was only marginally higher than that of the starting billet. For the experimental PM billets, the EIGA atomization of the long billet also resulted in oxygen content pick-up compared to the starting powder. In contrast, the VIM atomization of the PM short billet did not cause a pick-up of oxygen: the oxygen content of the atomized powders marginally decreased. This observation for the VIM process was in line with literature: Takaki and Abiko [13] showed that the oxygen content of titanium bars did not change after VIM. The indication therefore is that the oxygen content of the powders from the short PM billets could have been lower had the billet manufacture used lower oxygen content powders. In comparison to the ASTM F2924 [14], the standard for Ti Grade 5 powders for AM powder bed fusion, neither the EIGA nor VIM atomized experimental powder met the standard while the commercial billets also missed the standard for AM applications, but marginally. However, meeting the specifications of the ASTM F2924 standard was not the aim of the study, which was to investigate the feasibility of atomizing PM billets.

The flowability of the powders exhibited considerable dependence on the atomization technique. While all the EIGA atomized powders did not flow through the hall flowmeter, VIM atomized powders exhibited very good flowability through the hall flowmeter. The non-flowability of the EIGA powders was attributed to the occurrence of satellites on the powders. However, it is worth noting that the current standard for Ti Grade 5 powders for AM powder bed fusion fails to specify the minimum accepted flowability. While this flowability test was a comparative test, Spierings et al [15] advises that that the non-flowability of a powder in a Hall Flowmeter is not necessarily an indication of performance during use for building AM components.


<table>
<thead>
<tr>
<th>Specimen</th>
<th>Oxygen content (wt.%)</th>
<th>Flowability (s/50g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Starting powder or</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(billet)</td>
<td></td>
</tr>
<tr>
<td>EIGA powder from commercial bars/billets</td>
<td>0.18</td>
<td>0.21</td>
</tr>
<tr>
<td>EIGA powder from PM bars/billets</td>
<td>0.20</td>
<td>0.27</td>
</tr>
<tr>
<td>VIM powder</td>
<td>0.32(0.48)</td>
<td>0.47</td>
</tr>
<tr>
<td>ASTM F2924 - Grade 5 Ti AM powders</td>
<td>--</td>
<td>0.20</td>
</tr>
</tbody>
</table>

2.3 AM directed energy deposition - LENS Build

Figure 6 shows a component built by the LENS AM system using the atomized powders. In general, the relative ease of building varied between the powders. Generally, built components were difficult to grow using both the EIGA powders, and easier with the VIM powders- components from the EIGA powders suffered burns, and loss of defined fine edge and features, all caused tentatively by poor flowability. On the other hand, the good flowability of the VIM powders allowed for ease of material processing to the desired components.

Figure 6: AM product of VIM atomized powders.
3. CONCLUSION

The production of spherical Ti-based powders from powder metallurgy produced bars/billets was demonstrated. The density of the PM billets was shown to not affect the atomization process. The demonstration has the potential to lower the cost of Ti-based AM powders because PM billets are cheaper than wrought billets. Low cost AM powders have the potential to exponential increase the uptake of Ti AM by industry. The EIGA atomization of PM bars/billets produced powders with similar characteristics to those from commercial bars/billets. Atomization by EIGA and VIM produced powders that differed in flowability, and ease of processing using the LENS system. Both the powders from the PM bars/billets failed to meet oxygen contents stipulated in ASTM standards for powders for Ti Grade 5 AM applications: this was caused by the already high oxygen content of the starting Ti HDH powders. Work is continuing aimed at producing powders that meet the specifications of international standards. Emphasis will be placed on using Ti powder that has as low oxygen as possible.

ACKNOWLEDGMENTS

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REFERENCES

INVESTIGATION OF MICROSTRUCTURAL CHARACTERISTICS OF HEAT TREATED HIGH SPEED SELECTIVE LASER MELTING FABRICATED Ti6Al4V COMPONENTS

P. Lekodi¹, ², N. Maledi², M. Tlotleng¹, ³ and B.N. Masina¹

ABSTRACT

This study presents an investigation of the effect of different heat treatments on the microstructure of Ti6Al4V fabricated components produced by high speed selective laser melting. 10 mm x 10 mm x 10 mm cubes were heat treated in an inert oven at temperatures of 700 °C and 950 °C. 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 sample showed a martensitic alpha phase which was also observed on the 700 °C sample. Elongated columnar grains were observed on the as-built and the 700 °C heat treated sample. Furthermore, a fully transformed lamella α+β microstructure was observed for the 950 °C heat treated sample.

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1. INTRODUCTION

Additive manufacturing (AM) is currently a topic of interest in the aerospace industry due to its various advantages over conventional methods. These advantages include possibility of manufacturing parts of any geometric complexity, great design freedom and reduced production time, Galti et.al [1]. There are various types of AM techniques/platforms which are currently being used. These platforms include powder beds, direct energy deposition, material extraction and sheet lamination, Gockel et.al [2]. This study focuses on selective laser melting (SLM), a powder bed AM technique which builds components by selectively melting powder layer-by-layer with focused laser beam, Vrancken et.al [3]. The advantages of SLM include high level of flexibility (able to change easily according to situation), material efficiency, near net shape production and the build-up of complex geometries in a very short period of time, Vrancken et.al & Eylon et.al [3-4]. Various materials can be used in AM processes including Titanium alloys [2].

Titanium alloy grade 5 (Ti6Al4V) is an attractive material for aerospace industry because of its light weight, high strength properties and excellent corrosion resistance at high temperatures, Eylon et.al & Wanying et.al [4-5]. Ti6Al4V was developed in early 1950s for aerospace application and it is now qualified and widely used. Ti6Al4V is widely used in the aerospace industry because it possesses high specific strength and high corrosion resistance at temperatures up to 500°C, Yaidroitsev et.al & Vilaro et.al [6-7]. It has a crystal structure of α+β, which allows full transformation to beta phase during heat treatment and transform back to α+β when cooling [5]. Another interesting feature of Ti6Al4V powder is that it has an excellent combination of ductility and low weight ratio which makes it a suitable alloy for aerospace industry, He et.al [8]. Ti6Al4V is used for high performance engineering solutions in aerospace motor cases, aircraft turbines, pressure vessels and marine components, Imam et.al [9-10].

Ti6Al4V component produced from SLM, in the as-built state, are unable to achieve high material performance to wrought counterparts (Ter-Haar et.al [11]) for aerospace application. This is because Ti6Al4V component produced from SLM exhibit α’ phase which is associated with residual stresses that are generated during processing, Zaeh et.al [12]. These stresses are as a result of high temperature gradients which form during fabrication. Kong et.al [13] investigated the microstructure of Ti6Al4V samples produced by SLM and found that it exhibited fine martensitic α’ phase with tensile strength of about 1.45 GPa and elongation of 4.4%. Thijs et.al [14] found that Ti6Al4V materials processed by SLM shows a very fine, non-equilibrium microstructure due to high temperature gradients. Post production heat treatment is one of the methods that can be used to relieve these residual stresses that result in a part post production.

Several studies [3, 5, 7, 11, 15] showed that heat treatment can improve the microstructure and mechanical properties of SLM Ti6Al4V components. The Ti6Al4V microstructures of the produced components were complex and differed within a built. The types of microstructures depend largely on the heat treatment temperature and the cooling rate. It is possible to achieve a highly desirable microstructural features such as a highly refined precipitate, Collins et.al [16]. The aim of this paper was to investigate the effect of heat treatment on the microstructure of Ti6Al4V produced by a high speed SLM system.

2. METHODOLOGY AND RESULTS

2.1 Methodology

Gas atomized Ti6Al4V powder with a particle distribution of 20-60 μm was used in this study. The powder was supplied by TLS and used as received. Ti6Al4V samples were produced with energy densities of 42.41 J/mm³ and 78.46 J/mm³ using the high speed SLM system available at CSIR (NLC). The energy densities were calculated using this formula $E = \frac{P \cdot h}{v \cdot t}$ where $P$ is the laser power, $h$ is the hatch spacing, $v$ is the speed and $t$ is the layer thickness. A schematic diagram of the SLM process is shown in Figure 1. During processing, a CAD model of the part is loaded onto the machine working station where a pre-processing software slices the model into layers of finite thickness. A powder is deposited onto a plate above the built platform then a focused laser beam scans over the powder bed based on the sliced CAD data. The scanning results in localised melting and solidification of the powder form layer of the part. Subsequent layers are built one over the other by lowering the platform equivalent to the layer thickness until a part is completed.
During the printing process 10 mm x 10 mm x 10 mm cubes of Ti6Al4V samples were produced by scanning very fast the focused high power fibre laser beam with wavelength of 1073 nm over the pre-placed powder bed. Post manufacturing, the produced samples were then heat treated in an air rich oven at temperatures of 700 °C and 950 °C, respectively. The temperatures were chosen on the context that 700 °C is a stress relieving temperature and 950 °C is the β-transus temperature, Vracken et.al & Dong et.al [3, 17]. During heat treatment the condition was such that the set temperature was held for 2 hours. The samples were allowed to air cool to room temperature.

The as-built and heat treated samples were mechanically prepared and polished for microstructural analyses. The samples were cross sectioned in direction perpendicular to the built direction. The samples were then etched with Kroll's reagent before metallographic examination. Metallurgical samples (as-built and heat treated) were analysed for microstructural evolution using Joel JSM-6010PLUS/LA Scanning Electron Microscope (SEM) with an accelerating voltage of 20 kV.
2.2 Results
2.2.1 Microstructures

Figure 2 below shows microstructures of the as-built samples.

Figure 2: Microstructures of the as-built samples: (a) 42.41 J/mm³ and (b) 78.46 J/mm³.

Both samples show large columnar grains as highlighted on the optical images. These grains are orientated along the build direction. Additionally, both samples show an acicular martensitic α' phase which forms as a result of high cooling rates. Figure 2a shows regions where there are sharp crack-like pores which are attributed to the low energy density that was used. The crack-like pores are not observed on the microstructure sample in Figure 2b which was manufactured a high energy density. Both of the samples show the presence of three phases (α, β and α’), but β phase is present in small quantity. These observations are detailed in the high magnification SEM microstructures that are presented in Figure 3.

Figure 3: EDS graphs (a) 42.41 J/mm³ and 78.46 J/mm³.

From Figure 3, α’ martensitic structure are rods or needle like structures that are seen on the image. This phase is somewhat precipitated with higher energy density (Figure 3b). The bright-white particles on the image are β-phase while α is the overall darker matrix of the sample. The microstructures of the heat treated samples are given in Figures 4 and 5 for 700 °C and 950 °C, respectively.
The microstructures of the samples that were heat treated at 700 °C.

Figure 4: Micrographs of the samples after heat treated at 700 °C: (a and b) 42.41 J/mm$^3$ and (c and d) 78.46 J/mm$^3$.

Heat treatment at 700 °C, for 2 hours followed by air cooling, resulted in no phase transformation, however the grain sizes of the sample that was manufactured with energy density of 42.41 J/mm$^3$ (Figure 4a) were refined to smaller size and became more equiaxed as compared to the as-built (Figure 2a). This is due to nucleation when $\beta$ columnar grain changed to $\beta$ equiaxed grains. The sample that was built at 78.46 J/mm$^3$ and heat treated to 700 °C seem to remain the same since no grain growth or nucleation can be reported, however, the SEM microstructure clearly depict that at this heat treatment temperature $\beta$ phase was highly precipitated and the $\alpha'$ martensitic phase grew longer in the rich $\beta$-precipitated columnar grain (top of the b-image) and shorter on the $\alpha$ grain (bottom part of image b). In both samples all three phases can still be identified. The microstructures of the sample after heat treatment at 950 °C are shown in Figure 5.

Figure 5 below shows the microstructures samples after heat treatment at 950 °C.
Heat treatment at 950°C altered the grain sizes and phases for both samples. Full phase transformation was observed on the microstructures of the two samples. α’ martensitic phase present in both the as-built samples (Figure 2a & 2b) and samples that were heat treated at 700 °C (Figure 4a & 4c) can no longer be observed after heat treatment at 950 °C as shown on Figures 5a & 5c. It has been cited that when Ti64 is heat treated at β-transus temp or above α’ martensitic phase will fully transform to β phase. This transformation leads to a lamellar α+β structure being formed (Vracken et.al & Vilaro et.al [3, 7]) as seen on Figures 5 (a and b). Study by Vrancken et. al [3] has shown that when Ti6Al4V is heat treated above the β-transus temperature, it would homogenise, and all the beta phase present will transform to lamella α+β during furnace cooling. They also observed grain growth with increase in heat treat temperature. Similar results [Figure 4d (700 °C) and Figure 5d (950 °C)] were observed in this study when temperature was increased.

2.2.2 Hardness

Hardness is the measure of strength of material and is influence main by material consolidation and homogeneity. Meanwhile a sample that underwent heat treatment will have its hardness influence by formed grains, precipitates and the resulting phases. The Hall-Petch relationship is the accepted relationship that explains the influence of mechanical properties to the grains of the alloy (Malheiros et.al & Ruan [18-19]). This background is necessary for the interpretation of the hardness results presented in this study. Figures 6 and 7 show the hardness profiles of the samples in both as-built and heat treated conditions.
Figure 6 presents the micro-hardness profile of the as-built sample and its corresponding heat treated samples. The sample was built using 42.41 J/mm³ energy density, and heat treated at 700 °C and 950 °C followed by air cooling, respectively. Hardness was measured across the sample perpendicular to the build direction. The hardness profile of the as-built sample is wavy. This observation can be attributed to the microstructural inhomogeneity, defects, and also might be due to the observed α' martensitic phase. The hardness profile of the heat treated samples remained constant. This might be due to a homogenised microstructure, and the refinement α' martensitic and its partial transformation to β-precipitate. It should be noted that the hardness profile of the sample that was heat treated at 950 °C is a bit lower than the sample that was heat treated at 700 °C. This can be attributed to the over refinement in the microstructure and full transformation of α' to β leading to a lamellar α+β microstructure.

The micro-hardness profiles of the sample that was built at 78.46 J/mm³ energy density and its corresponding heat treated samples are reported in Figure 7.

Figure 7: Average hardness profile of 78.46 J/mm³ sample.

It can be said from Figure 7 that the hardness profile of the as-built sample and its heat treated sample (700 °C) are the same. Both samples had similar microstructure. The hardness profile of the sample that was heat treated at 950 °C is wavy and significantly increased when compared to the hardness of the as-built sample and the sample that was heat treated at 700 °C. The increase in hardness cannot be attributed to the presence of α' phase as it was fully transformed. Dong et. al [17] reported a similar jump in hardness and attributed it to the thermal oxidation. This study would investigate the effects of thermal oxidation and its impact on the hardness of the Ti64 alloy as a future study. The overall hardness values of the samples are summarised in Table 1 with the error.
Table 1: Overall hardness (HV0.3) values.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>As-built</th>
<th>700 °C</th>
<th>950 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.41 J/mm³</td>
<td>367±30</td>
<td>365 ±30</td>
<td>363±30</td>
</tr>
<tr>
<td>78.21 J/mm³</td>
<td>377±30</td>
<td>375 ±30</td>
<td>547±30</td>
</tr>
</tbody>
</table>

Table 1 summarises that there was no significant difference in the as-built and heat treated sample for the sample that was built at 42.41 J/mm³, but a significant jump was observed in the sample that was heat treated at 950 °C for the sample that was built at 78.21 J/mm³.

3. CONCLUSION

High Speed SLM process was used to produce 10 mm x 10 mm x 10 mm cubes Ti6Al4V samples. The effect of heat treatment on Ti6Al4V microstructure was investigated. It was observed that the resulting Ti6Al4V microstructure after annealing depend mainly on the heat treatment temperature. It was also observed that grain size increases with heat treatment temperature for the same cooling method. It was also observed that heat treatment at 700 °C does not allow full α' transformation but 950 °C allow full phase transformation to lamella α+β.

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REFERENCES


A LITERATURE REVIEW OF LASER POWDER BED FUSION OF 55NI-TI SHAPE MEMORY ALLOY FOR BIOMEDICAL APPLICATIONS

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ABSTRACT

The binary near equiatomic nickel-titanium alloy 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 superelasticity. 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 superelastic behaviour. The current review will focus on the emerging additive manufacturing methods such as laser powder bed fusion that will 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 geometrics which would enhance the biomechanical and biofunctional properties of the material and translate into quality life for implant patients.

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1. INTRODUCTION

Titanium was discovered by William Gregor in 1791 [1], and it has been widely used in many engineering application due to its outstanding mechanical properties, which are resistance to corrosion and a high strength to weight ratio. The use of titanium and its alloys was found to be applicable in constructing aircraft, jet engines, and biomedical objects since the 1950s [2]. Despite the celebrated mechanical properties of Ti alloys, especially for biomedical applications, there were obvious limitations due to its high elastic modulus. The shortcomings of Ti alloys have prompted material scientists to search for a material with thermomechanical behaviour [3].

A shape memory alloy (SMA) are alloys with large plastic deformation and when heated they "remember" their original shape [2]. It is an unusual thermomechanical behavior due to their reversible crystal structure characteristics induced by stress or temperature. The material’s ability to remember its original shape is termed as shape memory effect. Superelasticity which is also known as pseudoelasticity is another thermomechanical characteristic of SMAs, and is the ability of the material to sustain elongation or strain (3-8%) after being deformed [4]. The discovery of the shape-memory effect was reported in the 1930s, according to Otsuka and Wayman, Arne Olander discovered the superelasticity behavior of the Au-Cd alloy in 1932. Greninger and Mooradian (1938) observed the allotrophic behaviour of Cu-Zn alloy when temperature is applied in the material [5]. Then basic phenomenon of the memory effect governed by the thermelastic behavior of the martensite phase was widely reported a decade later by Chang and Read (1951), [4,5].

There are many known shape memory alloys; namely, NiTi, Cu-Al-Ni, Cu-Zn-Al, Cu-Sn, Nb-Ti, Cu-Al-Be and Ti-Nb [2,3,5]. All have found application in actuators such as hydraulic, pneumatic, and motor-based systems. They are also used in the robotics, automotive, aerospace and biomedical industries. Nickel-titanium alloys (Ni-Ti) has taken the center stage among the SMAs for many engineering applications due to it being able to exhibit temperature dependent acoustic damping properties, surface relief, unusual micro-hardness indentation behaviour, substantial ductility combined with good strength, good corrosion resistance and low density [6]. It is also reported to have superior biocompatibility as compared to other SMAs. Its biocompatibility and superelasticity make NiTi a suitable material for biomedical applications while the shape memory (SM) and the damping characteristics are used for other engineering applications such as innovative actuating systems [7, 8].

Nickel-titanium alloys (Ni-Ti) was first developed in 1962-1963 by the United States Naval Ordnance Laboratory and commercialized under the trade name Nitinol (an acronym for Nickel Titanium Naval Ordnance Laboratories). Their remarkable properties were discovered accidentally. A sample that was bent out of shape many times was presented at a laboratory management meeting. One of the associate technical directors, Beuhler, decided to see what would happen if the sample was subjected to heat and held his pipe lighter underneath it. To everyone’s amazement, the sample went to its original shape [9]. Further research revealed that the TiNi alloy has unique properties of shape memory and superelasticity as a result of phase transformation within its crystal structure as a response to change in temperature and stress [6, 7, 10, 11, 12, 13]. At lower temperatures, or when deformed the NiTi structure is in the martensite phase, meaning a weaker form of the structure and at a higher temperature is in the austenite phase, which is the stronger crystal structure [14]. In Nitinol, the change is from an ordered cubic crystal structure (austenite) to a monoclinic crystal phase (martensite) [15]. This behaviour is known as the martensitic transformation. The temperatures at which the formation of martensite starts and ends are called martensitic start temperature (Ms) and martensitic finish temperature (Mf). Austenite formation starts and ends at austenite start (A•) temperature and austenite finish (A•) temperature [16, 17]. There are 24 habit plane martensite variants for stress-induced martensitic transformation (Fig.1). This temperature or stress-induced phase transformation (as opposed to conventional diffusion induced transformations) is the basis for the unique properties in these alloys, namely shape memory effect, superelasticity (pseudoelasticity) and damping.
Fig. 1: When NiTi cools below austenite start (As) temperature the material deforms until the Martensitic finish (Mf) temperature is reached. Then material would only retain its parent shape when heated above the austenite finish temperature (Af). [6].

Nitinol has three crystallographic phases, i.e. austenite, R phase and martensite when induced by temperature or stress [6]. Martensite is only stable at low temperatures. The atoms within the material move through a process called diffusionless transformations from the austenite in the super B lattice B2 structure, to the martensite which is in the monoclinic B19’ weaker lattice structure (Fig. 1), while the phase during transition is known as the rhombohedral structure, or the R phase [19]. The reverse thermo-mechanical process, martensite to austenite the process happens through a diffusionless process [20]. The strains that nitinol (3-8%) can recover is based on the post-processing of the material. While the hysteresis (transformation temperature) is associated with the change of nickel or titanium content, where it was found a change of 1% in alloy content will shift the transformation temperature of this material with 100°C [18, 20]. This will then affect the superelasticity strain which will then affect the biocompatibility of NiTi used in biomedical application [20].

Fig. 2: The temperature transformation curve of a NiTi alloy, Ms: martensite start temperature upon cooling; Mf: martensite finish temperature upon cooling. The graph depicts the reverse transformation start temperature (As), upon heating; and the reverse transformation finish upon heating (Af). T is the transformation hysteresis. [8]

Post-processing treatments (e.g. heat treatment, cold working etc.) are generally required for NiTi manufactured parts to enhance the superelasticity and help improve biocompatibility [9-10]. Besides its superelasticity and unique properties for biomedical application the high nickel (Ni) content of the alloy (55 wt. % Ni) and its influence on the biocompatibility is a major concern [21]. However, the experimental results of Ryhanen et al. [13] with a fibroblast and osteoblast cell culture revealed that the high Ni content posed no threat of cytotoxicity. This is due to the fact that NiTi is a passive alloy, like titanium and stainless steel. A stable surface oxide protects
the base material from general corrosion. Titanium is not toxic when used in the human body, although nickel could be toxic when used in large amounts. Human tissue contains approximately 0.1 ppm of nickel, which is essential nutrition for the biological functionality of the human body [22, 23]. Fortunately, nitinol forms a passive titanium oxide layer (TiO₂) which acts as a physical barrier to nickel oxidation and protects the bulk material from corrosion. This layer is responsible for protecting nickel ions from leaking into the human bloodstream. It has been shown that the cytotoxicity of nitinol is comparable with other implantable alloys [24], such as 316 stainless steel and Ti6Al4V titanium alloy. Literature shows that that nitinol has no toxic effects on human tissue [25].

Nitinol could be confidently used for biomedical applications since it remains biologically innocuous inside living tissues [26]. It has also met the stringent requirement of the ASTM F86 [27] standards, which specifies that the various chemical and electrochemical surface treatments specified in this practice are intended to remove objectionable surface contaminants and to restore maximum corrosion resistance to the passive oxide film. Also the implant must not produce allergic reactions inside the host or release ions into the bloodstream. The biomechanical and biofunctional properties of nitinol have made it favoured in medical devices, e.g. surgical instruments, orthopaedic implants and cardiovascular devices [24], discussed below.

1.2 Surgical instruments

In recent years, the medical industry has focused on the concept of less invasive surgical procedures [28]. Following this tendency, nitinol shape memory surgical instruments have been developed (Fig. 3). Since nitinol has strains of (3% to 8%) they are preferably used in surgical endoscopic procedures, the recoverable deformation is primarily the key characteristic sought in these types of applications [4]. Instruments that are steer able, hingeless, kink resistant, and highly flexible and that provide constant force have all been developed [29].

![Fig 3. Laparoscopic instruments for minially invasive surgeries [24].](image)

1.3 Orthopedic applications

NiTi has been used extensively for orthopedics and a lot of research has gone into various correction rods, compression staples and fracture fixators (Fig. 4). Orthopedic applications tend to be concerned with shape memory thermal recovery and the associated forces generated during recovery. SMA has a large number of orthopedic applications. The spinal vertebra spacer is one of them. The insertion of this spacer between two vertebrae assures the local reinforcement of the spinal vertebrae, preventing any traumatic motion during the healing process. The use of a shape memory vertebra spacer allows the application of a constant load regardless of the position of the patient, with some degree of motion. This device is used in the treatment of scoliosis [19].

![Fig 4. Spinal vertebra spacers [24].](image)

Another application in the orthopaedic area is related to the healing process of broken and fractured bones. Several types of shape memory orthopedic staples (Fig. 5) are used to accelerate the healing process of bone fractures, exploiting the shape memory effect. The shape memory staple, in its opened shape, is placed at the site where one desires to rebuild the fractured bone. Through heating, this staple tends to close, compressing the separated part of bones. It should be pointed out that an external device performs this heating and not the temperature of the body. The force generated by this process accelerates healing, reducing the time of recovery.
1.4 Cardiovascular applications

The passing of catheters into arteries and veins has developed into a form of minimally invasive therapy known as interventional radiology. This therapy employs X-ray imaging techniques and magnetic resonance imaging (MRI) to guide different instruments and carry out advanced medical procedures. The atrial septal occlusion device (Fig. 6) is an alternative to the traditional surgery that is extremely invasive and dangerous because the thorax of the patient is opened and the atrial hole is sewn. This device is composed of SMA wires and a waterproof film of polyurethane. First, one half of the device is inserted through a catheter by the vena cava up to the heart, in its closed form. Then, it is placed on the atrial hole and opened, recovering its original shape. Next, the second half of the device is placed by the same route as the first one, and then both halves are connected. This procedure seals the hole, avoiding blood flow from one atrium to the other. A schematic diagram of the heart with the device in place is presented in Figure 6. [24]

Angioplasty is a technique for treating occlusion of a blood vessel or heart valve. It is used extensively for the treatment of peripheral vascular disease to restore the correct blood flow and for the treatment of coronary heart disease. The procedure involves guiding a thin guide wire through the femoral artery until it is just past the blockage. Permanently implantable metal cylinders named stents made from nitinol are often used to support the walls of the vessel and maintain arterial lumen. The stent is shape set into the open condition, then compressed, and inserted into the delivery catheter. The deployed stent is prevented to completely recover its original shape and exerts a very gentle outside pressure against the vessel wall to keep it open and minimize its recoil [24] (Fig. 7).
2. CONVENTIONAL METHOD OF MANUFACTURING NITINOL

The thermo-mechanical properties of NiTi are extremely sensitive to the alloy composition and the method of manufacturing [30]. Conventionally, NiTi is produced in ingots by self-propagating high-temperature synthesis (SHS), vacuum induction melting (VIM) or vacuum arc remelting (VAR) processes, which is followed by hot working and tooling until the required shape of the object is obtained. However, the arc melting requires multiple re-melting in a vacuum to obtain a near-homogeneous alloy. The induction melting can lead to carbon, and or oxygen contamination of the product [31]. The manufacturing and processing complications encountered when using the conventional methods to manufacture the NiTi alloy have the shortcoming of homogeneity in the microstructure, which affects the material’s shape memory and superelastic behaviour. The method used to manufacture the NiTi alloy is crucial in that the manner in which the metallic powder is melted determined the quality, functionality, and behaviour of the NiTi alloy when in service [7]. The conventional methods which are normally used to manufacture Nitinol have obvious limitations, which affect the material’s microstructure and mechanical properties adversely.

It is also reported that NiTi material’s processing history and surface conditions are generally not well documented [7, 12, 21, 32]. Nickle-Titanium requires controlled processing to achieve optimal mechanical and thermal properties. Optimization of the thermo-mechanical processing provides good fatigue life and general mechanical properties to meet the stringent structural requirements of medical implants. Similarly, surface processing is required in order to promote optimal corrosion resistance and biocompatibility of the material [18,33]. The ASTM F86 [33] standard recommends surface improvements to improve the corrosion resistance of metallic surgical implants and also various chemical and electrochemical surface treatments are intended to remove objectionable surface contaminants. NiTi is a passive alloy like titanium and stainless steel and a stable surface oxide protects the base material from general corrosion. The surface is predominantly composed of titanium oxide and thus its passivity may be further enhanced by modifying the thickness, topography and chemical composition of the surface by selective treatments which cannot be conducted by the conventional methods [12, 21, 32]. The employed technologies need to be improved in order to produce parts with homogenous microstructures in cost-effective manners.

To further understand the fabrication of nitinol, its binary phase diagram needs to be studied. The phase diagram gives clarity on different phases of the alloy, especially if the material properties have to be adjusted during heat treatment processes. NiTi SMA is a near equiatomic (i.e. ~Ni 50.0 at. % Ti) with intermetallic compound TiNi that forms eutectic during solidification, together with the Ni-rich solid solution. There are other compounds that are brittle in the system, Ti3Ni, Ni3Ti and Ti3Ni, as shown in the Ni-Ti binary phase diagram (Fig.8) [34].

The intermetallic compounds which are detrimental to the mechanical properties of NiTi exist with other phases that form during ingot casting including titanium carbide (TiC), which form due to eutectic reaction with the graphite crucibles used in vacuum induction melting (VIM). During the reaction of NiTi the alloy undergo a peritectic reaction with oxygen due to higher reactivity of these metals. Even though the reaction happens in a vacuum atmosphere, peritectic reaction forms Ni2TiO4, TiO2 oxides [35]. During the casting process, it was discovered that there were more carbides that form than oxides due to faster formation of eutectic reactions than peritectic reactions [34, 36]. These have a negative impact on the product formed, by causing the material to fracture and form particle void assemblies (PVA), which serve as a points of fracture after casting process [36, 37, 38, 39, 40, 41].

These limitations of conventional methods of producing NiTi have put materials scientists on the urge of using additive manufacturing (AM) technologies for better outcome.
3. ADDITIVE MANUFACTURING OF NITINOL

Additive manufacturing (AM) is a process which is applied to build up objects in layer-by-layer from 3D CAD model [43]. The first patent of Laser Powder Bed Fusion (LPBF) concept was done by Pierre Cirauds in 1973, he described the creation of solid parts using a beam of energy to solidify powdered material (e.g., plastic or metal powder) onto a substrate [50]. Then in the 1980s, the LPBF concept was brought into practice by Dr. Carl Deckard and academic adviser, Dr. Joe Beaman at the University of Texas at Austin in the 1980s. The program was sponsored by the Defense Advanced Research Projects Agency (DARPA) [51]. Though similar process was patented by R.F Housholder in 1979, but never commercialized [51, 52]. Deckard, CR, thought the process will be better and will allow the manufacturing of complex parts from CAD models. He spent two and a half years thinking about how he would develop such a method. By the end of 1984, Deckard came up with an idea of using a direct energy beam (such as a laser or electron beam) to melt particles of powder together to produce a three-dimensional object. The first machine Deckard built was called “Betsy”, used a 100 W YAG laser (synthetic crystal yttrium aluminum garnet laser) to increase the power of the light emitted. Deckard filled a small box with powder by hand using a device similar to a salt shaker while a computer ran the scanner on the table. “Betsy”, was a success in additive manufacturing that which led to the development of other processes.

By contrast to the conventional methods of fabrications, AM technology provides an almost unchallenged freedom of design without the need for part-specific tooling. AM is an Eco-Design topology optimization technology that allows very complex parts to be created monolithically [44] [45]. The high degree of freedom offered by AM technology of building complex geometries that would otherwise be difficult or impossible to produce using the conventional manufacturing process (casting, drilling, milling, vacuum induction melting, and vacuum arc re-
Laser Powder Bed Fusion (LPBF) is a process capable of making metal alloy components that have mechanical properties comparable to wrought material. It is possible with LPBF to produce fully dense parts (up to 99.9%). The advantage of this process is that metal parts of complex geometric topology can be produced, which enables the production of customized components such as biomedical implants [49]. The efficiency of the process can also be attributed to the fact that there is no wastage of material. LPBF has opened a whole new world to the manufacturing industry; previously impossible designs and manufacturing concepts are now made possible with LPBF. Complex shapes and objects could be manufactured by utilizing the layer by layer scanning process of LPBF. Currently, much research and development are in progress to ensure optimal process parameters for a number of metal powders such as Nitinol. The new and innovative manufacturing technique (Fig. 10) of AM has seen massive sales growth in the past years.

Figure 10: Schematic diagram of the laser powder bed fusion [53].

Cutting NiTi into desired size and shapes also posed a serious challenge due to the superelastic effect nature of the NiTi materials [54]. Using the versatility of AM technology such as laser powder bed fusion (LPBF) to produce biomedical objects of near-net shapes that would enhance the geometrical, technical and functional properties of the NiTi. The mechanical properties of a material are not the only determining factors for qualifying it for a specific application, but also the geometrical characterisation. This functional requirements of near-net shapes of complex geometries make additive manufacturing an attractive manufacturing technology to be exploited for manufacturing NiTi alloys with specific geometrical characteristics for biomedical applications. In addition, the AM processing routes are more promising to get more isotropic microstructures, since the building process takes place in an enclosed chamber it would eliminate any issues of contamination. It is a very cost-effective, energy efficient, and environmentally friendly manufacturing process [7].

AM, process parameters can be categorised into three categories:

1. Machine based input parameters (laser, atmosphere, substrate etc.),
2. Powder-related parameters (particle shape, size, density, distribution, layer thickness, etc.), and
3. Process input parameters (laser, powder, design and strategy, and control unit) (Fig.11)
The product quality requires the development of a set of optimized processing conditions or parameters, which assure uniformity and control of microstructure in the associated mechanical properties and performance [56].

4. METHODOLOGY

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 [57], according to well-known procedures [43, 58]. The optimum process parameters will be used to produce as-built samples for microstructural and mechanical properties investigations. The microstructural analysis would be conducted with optical and scanning electron microscopes. The mechanical property results obtained using LPBF will be compared to the properties of NiTi already found in literature. Based on the outcome of the comparison, conclusions will be drawn on the feasibility of using LPBF for producing NiTi samples for biomedical applications. More than one tensile test would be performed using a MTS Criterion model 43 Universal Test machine. The surface roughness of the samples will 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.
5. CONCLUSION

From the literature review, it was revealed that the conventional methods have been used to manufacture NiTi for biomedical applications. However, the thermomechanical behaviour that gives Nitinol its superelastic 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 will be employed in an anticipation of producing biomedical objects with excellent biomechanical and biofunctional properties with complex shapes without contaminants.

The study intends 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 mechanical properties and superelasticity. Literature shows that the elastic young modulus obtained from nitinol will be far less than that found in other biomedical titanium alloys, meaning nitinol will in the future help produce implants with appreciable mechanical properties to improve life of implant patients.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the South African Department of Science and Technology through the Collaborative Programme in Additive Manufacturing, for financial support (Contract No CSIR-NLC-CRPM-15-MOA-CUT-01).
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LASER POWDER BED FUSION PROCESS DEFECTS AND MECHANICAL PROPERTIES OF T16AL4V ELI MANDIBLE IMPLANTS


ABSTRACT

Ensuring additive manufactured metal based components are free of major defects is crucial to fulfil medical requirements for clinical applications. Random porosity, high surface roughness and deformation during processing are the main current drawbacks in laser powder bed fusion parts. The prediction of defective samples’ mechanical properties with numerical simulations is highly important to understand the effect of these defects. A step-by-step systematic approach of determining defects in laser powder bed fusion (LPBF) and their influence on mechanical properties will be used for the current research. This paper presents the first successful steps in this project.
1. INTRODUCTION

The need for new implant, treatments and prosthesis as well as prolonging the life span of current implants has increased, and has brought a robust change in people’s quality of life [Khan, 2014]. Additive manufacturing of metals is growing steadily, and offers exciting possibilities for future development - producing parts with higher complexity with many applications including medical and aerospace [du Plessis, 2016a; Dunbar, 2016]. The endoprosthesis replacement of the lower jaw with an artificial implant is typically performed in the case of traumatic gunshot injuries, or when a large section of bone was destroyed by a chronic infection, when malignant neoplasms developed, and also in connection with osteomyelitis lesions. The clinical goal for mandibular implants is to serve as a replacement or anchor for muscle and mastication loading, which recreates the skeleton’s original stress-strain trajectories. The mandible is the only movable stress bearing bone in the face and reconstruction of mandibular defects should restore the anatomical height and contour of the resected mandible. Ti6Al4V alloy is one of the most suitable materials of choice for such implants, due to its incredible strength, low weight ratio, outstanding corrosion resistance and biocompatibility.

Quality control in metal based additive manufacturing is extremely important for effective control of dimensional inaccuracy, porosity and other defects that arise during the process [du Plessis, 2016b]. Grain morphology and texture of any part produced in laser powder bed fusion (LPBF) are strongly affected by the solidification rate, rapid cooling, and cyclic re-heating and cooling from adjacent tracks and subsequent layers. The inconsistency of the thermal processing throughout the part arises imprecisions from a variety of factors, including scan strategies, processing conditions, and geometric effects such as the reduced ability to conduct heat away from the melt pool when creating overhangs [Dunbar, 2016; Zhao, 2017; Yadroitsev, 2018]. Special microstructure and high residual stress are peculiarities of LPBF material that influence its mechanical properties. Also consecutive layer by layer delivering of powder particles sometimes tends to clump together causing inhomogeneous powder layers, which result in unmelted areas and pores in the final product. Inappropriate selection of LPBF process parameters, scanning and manufacturing strategies of complex objects can lead to fractures, warps, and pores. CT scanning has previously been used for defect analysis of LPBF parts and it is clear that imperfections such as pores, etc, are prevalent in this process. [du Plessis, 2018; du Plessis, 2016b].

1.1 Biomechanics of mandible

During mastication the following muscles serve in the movement of the mandible: masseter muscle, temporal muscle, medial pterygoid muscle, lateral pterygoid muscle, and buccinator muscle (Fig.1) [Emin, 2018; Kober, 2004; Ingawale, 2012]. The mandible is the only movable stress bearing bone of the face, and disregarding the forces acting on the mandible can lead to reconstruction failure [Wong, 2011]. Loadings and bone properties are factors that have to be taken into account for modelling of mastication. For numerical simulations, during a mastication cycle the directions of the forces exerted by the jaw closing muscle can be assumed as uniform, due to the fibres running approximately parallel close to the insertion to the mandible; constant through the cycle, according to the small amplitude motion of their insertion points (Fig. 1) [Commisson, 2015].

(a) (b) (c)
Fig. 1: Mandibular bone with respective muscle attachment (Posterolateral view) (a); typical loading forces, boundary conditions, and force vectors during mastication [Faulkner, 1987] (b) and forces working on the temporomandibular joint during mastication [Commission, 2015] (c).

For numerical simulations, cortical bone material properties can be considered orthotropic in different anatomic regions of the mandibular bone, cancellous bone and reconstruction plates and screw can be defined as isentropic independent of directions. Loads can be applied to the five principal muscles (Table 1). Material properties of different bones found in the human mandible are shown in Table 2. Thus, typical mechanical properties of different areas of mandible and response of human mandible (strains and loadings) can be found in the literature.

<table>
<thead>
<tr>
<th>Table 1: Muscular load action [Ramos, 2011].</th>
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<tr>
<td>Muscle action</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Deep masseter</td>
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<tr>
<td>Superficial masseter</td>
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<tr>
<td>Medial pterygoid</td>
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<tr>
<td>Temporalis</td>
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<td>Medial temporal</td>
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<table>
<thead>
<tr>
<th>Table 2: Material properties of different bone found in the human mandible [Vajgel, 2013].</th>
</tr>
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<tbody>
<tr>
<td>Material property</td>
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<tr>
<td>Symphysis</td>
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<tr>
<td>Elastic Modulus, $E_x$ (MPa)</td>
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<tr>
<td>Elastic Modulus, $E_y$ (MPa)</td>
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<tr>
<td>Elastic Modulus, $E_z$ (MPa)</td>
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<tr>
<td>Poisson’s ratio, $\nu_{xy}$</td>
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<td>Poisson’s ratio, $\nu_{yz}$</td>
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<tr>
<td>Poisson’s ratio, $\nu_{xz}$</td>
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</table>

1.2 Mandible reconstruction by LPBF

Additive Manufacturing (AM) makes the manufacturing of any given design possible regardless the geometric complexity and allows the production of integrated components. This is extremely important towards the design of revolutionary shapes and lighter parts without the need to consider manufacturing constrains related to machining, moulding, etc. The production in AM does not need any special tooling, thus, making it easy and immediate to manufacture complex objects with various changes in geometry such as customised implants (Fig. 2).

AM mandible reconstructions begins from a CT scan of the patient of the diagnosed area; the CT scan is then converted to a 3D virtual and physical model (Fig. 2a, c and e). The result of this 3D model is used as an input to plan the resection planes and design of a cutting guide that allows surgeons to precisely cut around the tumor/affected area without fault. A titanium alloy implant is designed to replace the affected area of the mandible (Fig. 2 b, d and f) to fit the required geometry in order to restore facial symmetry and to allow quick recovery.

In some author’s expert opinion, a single screw in the anterior segment (Fig. 1a) may not prevent rotation, leading to implant failure (Mommaerts, 2016). Loading and contact boundary conditions are described by three main muscular forces during chewing operation; masseter, medial pterygoid, and temporalis. Each person’s physique and bone structure differ from others which means the chewing load can vary in both magnitude and direction. Parameters to evaluate the design is the flexibility of the reconstructive implant, that is, the capability to absorb the chewing load, and the stress and strain distribution, ensuring the maximum stresses developed are lower when compared to the yield strength of Ti6Al4V ELI (Al-Ahmari, A, et al. 2015). Thus, at present implants are designed to withstand forces of 700N with a safety factor of two.

A scaffolding is useful where there is bony contact, the friction provides primary stability as with any screw-fixed plate (Cordey, J, et al. 2000). Scaffolding (Fig. 2b, d, f) increases the overall elasticity to more closely approximate that of bone (Lin, C.Y, et al. 2004) and therefore reduce stress shielding and permanent loosening of an implant fixed to the weight-bearing mandible, and allows an easy method for weight reduction (Mommaerts, M.Y. 2016). In the present cases, implant thickness was 2 mm.
2. METHODOLOGY AND RESULTS

2.1 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 (du Plessis et al., 2017; Weiler et al., 2005). Vanderesse et al. (2011) and Nicoletto et al. (2010) used microCT in combination with FEA to highlight stress regions and correlate fatigue cracks with pores and their stress regions in aluminium castings. du Plessis et al. (2017) simulated static loads directly on CT scans voxel data. It was shown that combination of spatial data of pore’s geometry and their locations is very suitable to predict the effect of the pores on the performance 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 for quality control of produced implants having some porosity or other differences from the CAD model.

Main stages of the present study have to be mentioned:
- investigation of biomechanics and numerical simulations on human mandible functioning;
- analysis of stresses and critical points for different types of mandibular reconstruction;
- analysis of porosity in LPBF parts on the basis of CRPM’s experience and literature sources;
- production and testing AM Ti6Al4V ELI samples with prescribed sizes, loadings, directions and porosity;
- numerical simulations and validation data compiled from numerical simulation with mechanical testing of LPBF samples after heat treatment.

Fig. 2: Design steps followed for reconstructing mandibular implants: 3D reconstructed CT scan of mandibular effected area (a, c and e); 3D rendering of designed titanium implant, (b, d and f).
Thus, test samples with defects and without defects will be manufactured by LPBF. The test samples will have geometrical characteristics similar to the mandible and mechanical testing will be done according mastication loadings.

2.2 Porosity in LPBF parts

In [Yadroitsev, 2018] LPBF Ti6Al4V ELI tensile samples were analysed by CT scans in as-built condition. It was found that maximum pore size was 132 µm for horizontal sample and 96 µm for vertical one (Fig. 3). The pores were randomly distributed throughout the volume. Although a statistically significant difference was found in the pore sizes for these samples, it can be stated that the porosity of the objects was insignificant: the estimated porosities were 0.0004% for vertical samples and 0.0018% for horizontal ones. The mechanical properties of the horizontal and vertical samples did not differ significantly. It should be mentioned how these samples were produced and analysed: 1) rectangular bars 10×10×60 mm were manufactured in horizontal and vertical directions; 2) round specimens with threaded ends were machined from bars accordingly to the geometry recommended by ASTM E8M standard (gage length four times the diameter); 3) microCT scans were made for gages 4 mm in diameter and 20 mm in length.

Fig. 3: Diameter of the pores measured by microCT scans in tensile samples.

In the presented study, for Ti6Al4V (ELI) samples density measured by microCT scans, was more than 99.99% (for pores >30 µm). It was found that the biggest pores were predominantly elongated in shape and can be considered as interlayer pores. Defects in LPBF are caused due to melt pool discontinuities and lack of melt pool overlapping. If the laser output is stable with prescribed scanning speed and power, with prescribed optimal scanning strategy, all voids are likely resulting from inhomogeneity in the powder layer. This inhomogeneity can be caused, in turn, by poor powder flowability, violation of loose powder layers during processing and deformation of the part during processing. Thus by LPBF, high density can be achieved at optimal process-parameters and scanning strategy.

Fig. 4 shows the graphic steps followed to produce a complete approved Ti6Al4V metal facial implant of an adult human produced in CRPM, at Central University of Technology with an EOSINT M280. Biomaterials are used to engineer functional restoration of different tissues to improve human health and the quality of life. A key issue in the designing of a new implant of any given product through AM is the prediction of the mechanical properties of the material. Several experimental results show AM-based products are often affected by widespread porosity, low density regions within their volume and anisotropy. These factors are due to manufacturing process, despite efforts of improving the process parameters. AM offers a product development for rapid iteration between designs, assembly and functional tests, (Fig. 4c) bringing about a remarkable decrease in both time and product development costs.
Maxillofacial Ti6Al4V ELI implants produced by LPBF were analysed in terms of porosity by CT scans by General Electric VTomex L240kV CT as described by du Plessis et al. in [du Plessis, 2016a-b]. First scans were done at 100 µm resolution and second time, when main porosity was identified, with 50 µm resolution to provide porosity details in the region of interest. In the first implant, two places were identified with serious defects, which run across the entire width of the sample (Fig. 4d). Under higher resolution, these type of porosity was recognised as layered defects. Analysis of the sample shows that layer pores were arisen due to problems with the powder delivering. When the synthesis of the overhanging parts of the implant began, high residual stress led to the deformation of this part. That, in turn, caused the contact of the recoater with the deformed part and its vibration. The deformation confirmed by the high deviation of this part of the implant from prescribed sizes (Fig. 4e). After vibration, loose powder was compacted and settled, which led to a non-uniform delivering of the next powder layer and, subsequently, to the porosity of the part. For quality control of layered defects du Plessis et al. (2018) proposed to use witness specimens to ensure lack of layered or other unwanted types of defects, as this allows higher resolution to ensure these defects are not missed in a large-part scan [du Plessis, 2018].

In the other sample, the pores also were in a layer and form a porous plane through the samples tip which is up to 17.6 mm in length and the maximum pore's width in that region was 355 µm (Fig. 5). The recommendation was that the pores located in a load bearing section of the implants can influence on mechanical response of the implant and it was decided that this implant could not be suitable for the implant procedure. New implants with additional supports were produced and no internal defects more than 300 µm were identified by CT scans.
The new part with supports removed was then scanned and found defect free as mentioned above. This new part was subjected to microCT-based load simulation using the structural mechanics simulation module of VGStudioMax 3.2. This is an immersed-boundary finite element method which allows calculation of displacements and stresses in voxel data using solid mesh elements, but not requiring a conformal mesh as in typical finite element softwares. This is computationally efficient and allows to evaluate the effect of real part geometries including defects, warping, internal porosity, etc. In this simulation, the inputs were linear isotropic material properties for Ti6Al4V: elastic modulus 115 GPa and Poisson’s ratio 0.3, with loading direction selected as shown in Figure 6, with load 10 N. The stress distribution shows two major stress areas as shown where the stress reaches 100 MPa. This value is significantly lower than the yield stress of the material and hence, in this case, sufficiently safe for typical loads. However, much work remains in determining a suitable safety factor, validating this workflow, and assessing also the effect of such defects on fatigue life.

Figure 6: Mechanical simulation highlighting high stress areas in real part, using microCT data.

Quality control for complex shape objects such medical implants are of great interest; non-destructive quality control has to be performed on parts before implantation. ASTM had 21 standards for Ti alloys concerned medical device standards and implant standards to inspect and assess such instruments to ensure proper quality and workmanship [ASTM international]. But additionally, standard similar to “Standard practice for Computed Tomographic (CT) examination of castings”, “Standard practice for radiographic examination of advanced aero and turbine materials and components”, “New guide for non-destructive testing of Additive Manufactured metal parts used in aerospace applications” and “Standard guide for micro-computed tomography of tissue engineered scaffolds” should be developed for systematic CT scans non-destructive testing of AM Ti implants. It is very important that an implant does not contain critical pores. Understanding of critical porosity in general and maximum critical size of the pores permissible for different type of AM Ti implants are vital task for the new AM technology.

Detailed analysis of manufacturing strategy, build orientation and supports and its influence on porosity can be performed based on X-ray micro-computed tomography. Revealing of the typical shape of the pores and its size permit to produced samples with artificial defects and without it by LPBF. Analysis of porosity and mechanical properties of samples with defects will be compared against standard specimen samples and numerical simulations. Numerical simulation of various loading on test parts with defects and its evaluation by experimental data on loading permit to establish mechanical consequences of defects on manufactured customised mandible implants.

3. CONCLUSION AND FURTHER RESEARCH

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 purpose of validation of the numerical simulations, all joint and forces during mastication must be tracked and included in both experiments and simulations, to assume ideal conditions for both cases boundary conditions has to be taken into consideration.
- Defects are included in the design of mandibular Ti6Al4V test samples with different design geometries, thus to indicate which size and direction of porosity will cause any significant defect in the geometry of a human mandible. An example of different test subjects will be subjected to porosity during LPBF with the aid of microCT-based simulations to validate experimental and simulated data.
- We believe that with the aid of mechanical testing in collaboration with numerical simulation and data analysis of different loaded porous implants could open a new chapter in the development of reliable AM medical implants.
ACKNOWLEDGMENTS

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REFERENCES


DESIGN CONSIDERATIONS FOR DEVELOPING AN ADDITIVE MANUFACTURED TI-6AL-4V COMPACT COUNTER-FLOW HEAT EXCHANGER FOR APPLICATION IN ORGANIC RANKINE CYCLES

S.C. Venter¹, G.G. Jacobs² and J. du Preez³

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 The author is enrolled for an M Eng (Mechanical) degree in the Department of Mechanical and Mechatronics Engineering, Central University of Technology, Free State
1. **INTRODUCTION**

With the current high demand for energy, engineers all over the world are aiming to increase the efficiency of energy producing equipment [1]. Increasing the efficiency will reduce the production of greenhouse gasses, lessening the effect of global warming. Various methods exist to accomplish this. The method of interest in this study is the Organic Rankine Cycle (ORC). An ORC operates on a similar base as a conventional steam cycle for energy conversion, this cycle however uses organic fluid instead of water. It is implemented to improve the efficiency by utilising waste heat, captured by means of a heat exchanger (evaporator) and used to produce additional power via a generator [2,3].

Large scale ORCs are already implemented in numerous power plants over the world [4]. Micro ORCs are more compact systems that can be utilised by domestic users (1-10kW) [5]. Miniaturising such system would be possible by using additive manufacturing (AM) processes.

The AM process involves material being joined layer upon layer to produce the desired part [6]. This technology opens a world of opportunities to develop intricate parts as one solid, which was not previously possible with traditional manufacturing methods [7,8]. One technology that could substantially benefit from additive manufacturing is micro-channel heat exchangers. These devices achieve a very high surface area per unit volume due to small channel sizes.

Traditional methods for producing micro-channel heat exchangers is time consuming and are limited to basic designs [9]. With the ability to produce walls with thicknesses of less than 200 \( \mu m \) these devices can evolve from its former conventional manufactured designs to increase its effectiveness [10].

Implementing high effectiveness micro-channel heat exchangers in ORC allows a reduction in size of these cycles to implement on systems producing low grade waste heat such as flue gas. The main focus of the study is the development and characterisation of Ti-6Al-4V compact counter-flow heat exchangers for production with AM with application in ORC’s.

Although additive manufacturing is a versatile technology, there still remain limitations to which a design should adhere to. This paper outlines the design considerations that were considered during the design of a Ti-6Al-4V compact heat exchanger.

2. **LITERATURE REVIEW**

2.1 **Heat exchangers**

Heat exchangers are devices used to transfer heat between two or more fluids, either to capture or reject excess heat. This study focused on compact counter-flow heat exchangers. The above-mentioned heat exchangers have a high effectiveness due to its ability to operate with close approach temperatures [11]. The ratio of the actual heat transferred to the maximum possible heat transfer is known as the effectiveness of a heat exchanger. High effectiveness is particularly beneficial in power-producing systems [12].

A simple heat exchanger design was considered for this study to minimise the effects of uncertainty and simplify the characterisation process. The characterisation of these heat exchangers would allow better understanding of the possibilities and limitations of additive manufactured compact heat exchangers.

2.2 **Production methods**

X-ray lithography (LIGA), chemical and silicon etching and diamond or wire machining are traditionally used to produce compact heat exchangers. These methods either limit the design complexity or require more than one process to produce a heat exchanger [9,10].

Additive manufacturing is a well suited method to create complex parts with great accuracy (± 50 \( \mu m \)) [13]. A well suited AM technology for creating metallic parts is selective laser sintering (SLS). Therefore, SLS is considered to be a viable method to produce intricate parts such as compact heat exchangers in a variety of metallic materials.

2.3 **Material selection**

Additive manufacturing possess the ability to produce parts in a variety of materials [6], with Titanium (Ti-6Al-4V) being the material of interest in this study. Ti-6Al-4V is a well suited material for producing compact heat exchangers, with its high specific strength (± 930 MPa) the heat exchangers’ channel walls can be thinned down significantly to reduce heat transfer resistance. Furthermore, Ti-6Al-4V has exceptional corrosion and good fluid erosion resistance and with its low thermal expansion coefficient (± 8.6 \( \mu m/m. {^\circ}C \), 0 – 100\(^\circ\)C ), warpage and fatigue effects are minimised during thermal cycling [14].
3. METHODOLOGY AND DESIGN CONSIDERATIONS

Table 1: List of symbols.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$\varepsilon$</td>
<td>Heat exchanger effectiveness</td>
</tr>
<tr>
<td>$q$</td>
<td>Heat transfer</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass flow rate</td>
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<tr>
<td>$c$</td>
<td>Specific heat</td>
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<tr>
<td>$T$</td>
<td>Temperature</td>
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<tr>
<td>$P$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$G$</td>
<td>Mass velocity</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Fluid density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Ratio of free-flow area to frontal area</td>
</tr>
<tr>
<td>$K_{c/e}$</td>
<td>Entrance/Exit loss coefficient</td>
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<tr>
<td>$f_F$</td>
<td>Fanning’s friction factor</td>
</tr>
<tr>
<td>$L$</td>
<td>Length</td>
</tr>
<tr>
<td>$D_h$</td>
<td>Hydraulic diameter</td>
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3.1 Theoretical Design

A mathematical model for the preliminary design was developed with the effectiveness-NTU method. This method is generally preferred for analysis and design of heat exchangers [15].

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

$$\text{Effectiveness} = \varepsilon = \frac{\text{Actual Heat Transfer}}{\text{Maximum Heat Transfer}}$$  (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 [15].

$$q = m_h c_h (T_{h_i} - T_{h_o}) = m_c c_c (T_{c_o} - T_{c_i})$$  (2)

$$q_{\text{max}} = (\dot{m}c)_{\text{min}} (T_{h_i} - T_{c_i})$$  (3)

The core pressure drop across the heat exchanger is calculated by Equation 4. This equation includes entrance-, core friction-, flow acceleration- and exit- losses [16].

$$\Delta P = \frac{G^2}{2\rho_1} \left[ (1 - \sigma_1^2 + K_c) + f_F \frac{4L}{D_h} \left( \frac{\rho_1}{\rho_m} \right) + 2 \left( \frac{\rho_1}{\rho_e} - 1 \right) - (1 - \sigma_2^2 - K_c) \left( \frac{\rho_1}{\rho_e} \right) \right]$$  (4)

With these equations a theoretical outcome can be predicted for a specific heat exchanger design. The aim of this study is to produce and characterise heat exchangers with three different channel sizes, 0.5, 1 and 2 mm which can transfer 3 kW of heat.

Mathematical models of the heat exchangers were created using Engineering Equation Solver (EES), using the above-mentioned equations. These models were then used as a guide line for the CAD models shown in Figures 1 to 9. The CAD models of the heat exchangers were sent to the Centre of Rapid Prototyping and Manufacturing (CPRM) at Central University of Technology, Free State for review.
3.1.1 Design 1

Details:

- Heat exchanger width: 18.65 mm
- Heat exchanger height: 11.00 mm
- Channel length: 30.00 mm
- Channel size: 0.50 mm
- Number of channels: 20
- Number of rows: 11
- Estimated heat transfer: 3012 W

![Figure 1: 3-D CAD model of design 1.](image)

![Figure 2: Side view of design 1.](image)

![Figure 3: Top cross-section view of design 1.](image)

3.1.2 Design 2

Details:

- Heat exchanger width: 28.65 mm
- Heat exchanger height: 21.90 mm
- Channel length: 40.00 mm
- Channel size: 1.00 mm
- Number of channels: 20
- Number of rows: 15
- Estimated heat transfer: 3071 W

![Figure 4: 3-D CAD model of design 2.](image)

![Figure 5: Side view of design 2.](image)

![Figure 6: Top cross-section view of design 2.](image)
3.1.3 Design 3

Details:

Heat exchanger width: 72.15 mm  
Heat exchanger height: 72.15 mm  
Channel length: 50.00 mm  
Channel size: 2.00 mm  
Number of channels: 30  
Number of rows: 30  
Estimated heat transfer: 3008 W

![Figure 7: 3-D CAD model of design 3.](image)

![Figure 8: Side view of design 2.](image)  
![Figure 9: Top cross-section view of design 2.](image)

3.2 Design Considerations

Design reviews are of high importance as incompatible designs will not be manufactured as desired, some of these are described below. Process engineers of the CRPM reviewed and suggested improvements to the designs to make it compatible with SLS. The following section provides design considerations which should be considered when designing similar heat exchangers for production with additive manufacturing.

3.2.1 Manufacturing orientation

Selecting the correct manufacturing orientation is an important consideration for any AM product. Therefore it was the first consideration that was addressed by the CRPM. Manufacturing of heat exchangers with the channels in a horizontal orientation, (the arrows indicate manufacturing direction shown in Figure 10), will cause the channels to deform without adding supports. Figure 11 shows, indicated in red, how the channels will deform when the heat exchanger is manufactured in the horizontal orientation. With over 200 channels per heat exchanger, adding supports within the channels would unnecessarily complicate the cleaning process afterward while increasing build time and cost. Consequently, the orientation was changed from horizontal to vertical (as shown in Figure 12), which ensures the channels will be manufactured square as required (cf. Figure 13).
3.2.2 Holes and circular sections

It is also preferred to manufacture circular sections like pipes, with their axis in a vertical direction. If it is not possible, supports should be added to sections with diameters larger than 6 mm to ensure that the circular profile manufactures correctly. Figure 14 shows a circular section manufactured without a support and it can be seen (shown in red) how the top part of the section will sag during manufacturing, indicated in red. While supports are automatically added by the software used by CRPM, one may incorporate optimized supports within the CAD model to eliminate the need for removal. Software generated supports are removed after manufacturing, thus less supports equals less labour and time. Figure 15 shows how the same profile would be manufactured with an optimized support.
Holes within a body orientated in a horizontal direction also requires supports for diameters larger than 8 mm, however the CAD model can be adapted to create holes without supports. This can be achieved by changing the shape from round to a teardrop as shown in Figure 16). During the manufacturing process the teardrop shape acts as a self-supporting structure, allowing the hole to be manufactured without support.

![Figure 16: Shape adapted to create hole without supports.](image)

### 3.2.3 Sections at an angle

Sections such as transitioning sections, where a circular section becomes square, or sections forming an angle with the horizontal should be carefully considered. If not supported, these sections could deform during the AM process. With the heat exchanger design the supports within the transition sections would not be easily accessible for removal. A solution is to keep the angle, created with the horizontal plane, larger than 35°. If the angle to the horizontal plane is less than 35°, without supports, the material could curl up during manufacturing. Figure 17 shows how a section could deform during manufacturing (indicated in red), without support structures added to an angle less than 35°. Figure 18 shows the revised section of the design with an angle greater than 35° [17]. This does however increase the entrance loss experienced within the heat exchanger and should be carefully considered. Thus, supports could not be added to this section due to access restriction.

![Figure 17: Transitioning section with \( \alpha \) smaller than 35°.](image)

![Figure 18: Transitioning section with \( \alpha \) larger than 35°.](image)

### 3.2.4 Threaded holes, drilling and tapping

The ability additive manufacturing possesses to create intricate parts as one is very appealing, although not always preferred. For simplicity it is sometimes necessary to use fasteners to join the manufactured part to existing parts.

The heat exchanger design consists of three parts, two end flanges and a body. These parts will be joined with M4 screws. Threaded holes are thus required within the body of the heat exchanger. The initial idea was to manufacture the heat exchanger body with threaded holes. Process engineers of the CRPM advised that holes smaller than M10 has poor thread definition and should be added after the manufacturing process by drilling and tapping the holes manually.

After a consultation with the CRPM machinist, he indicated that it is possible to drill and tap M4 threaded holes into Ti-6Al-4V, but it is a difficult task. The hardness of the material may cause the taps to break when tapping holes smaller than M6. He suggested manufacturing the holes as clearance holes and using standard nuts and bolts to fix the flanges to the heat exchangers' body.
3.2.5 Cleaning and examination

After manufacturing, the part needs to be cleaned. This entails the removal of excess powder, support structures and rough edges that might have been created during the AM built process. After production, unsintered powder would be present within the heat exchangers’ core. This excess powder can then be removed with compressed air. The difficulty of this process would increase greatly if the core of the heat exchanger is completely enclosed. Therefore, the heat exchangers were designed with open ends which would allow visual inspection of the heat exchanger internal structure. During assembly, these ends are closed with flanges, as mentioned in the previous section and shown in Figure 19. This can also be used for service inspections and cleaning during the life cycle of the heat exchangers.

The supports created during the AM process were removed using conventional methods such as wire cutting, grinding, sawing, and drilling. The position of internal supports should be carefully considered as they need to be accessible for removal after manufacturing. The heat exchanger design has minimal internal supports and is designed to form part of the heat exchanger as they are not accessible for removal.

![Figure 19: 3-D model with flanges.](image)

The channel walls are extremely thin (0.35 mm) and it would be difficult to visually inspect their integrity throughout the channels. Thus, the heat exchangers will be sent to Stellenbosch University for internal examination of the channels’ wall integrity by means of a computerized axial tomography (CAT) scan. Channel wall porosity present within the walls which would cause fluid mixture between the primary and secondary fluid streams, which is highly undesirable.

3.2.6 Minimum thickness and surface roughness

The achievable limitations should be kept in mind when designing any part for additive manufacturing. One of the main limitations is the minimum wall thickness that can be achieved using the DMLS AM process. The minimum wall thickness recommended for Ti-6Al-4V is 0.35 mm, as thinner thicknesses are too fragile according to the CRPM process engineers. Using a minimum thickness for the heat exchanger channel walls reduces the heat transfer resistance which improves the heat transfer.

The surface roughness of additive manufactured parts varies along its axis’s and should thus be considered when designing a part. A study done at the CRPM revealed that the top surface, regarding the build direction, of a part is considerably smoother than the side surfaces, with the average surface roughness of $Ra = 5.9 \mu m$ and $Ra = 14.5 \mu m$ respectively [18]. According to Kandlikar SG [19], a pipe with a higher surface roughness yields greater heat transfer. The velocity boundary layer is broken, increasing the heat transfer within the channel [20]. Thus, manufacturing the heat exchangers with the channel walls to have a greater surface roughness would improve the heat transfer. This consideration refers back to the manufacturing orientation.

4. CONCLUSION

Using design considerations provided by CRPM and other sources, 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, produced from Ti-6Al-4V, for application in Organic Rankine Cycles. Although these considerations were guided by the heat exchanger design, they are still applicable to other additive manufacturing designs.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the South African Department of Science and Technology through the Collaborative Programme in Additive Manufacturing, for financial support (Contract No CSIR-NLC-CRPM-15-MOA-CUT-01). Furthermore, the authors would like to thank the process engineers at CRPM for their
input on the design considerations. Central University of Technology, Free State (CUT) for making the study a possibility and MerSETA for additional financial support throughout the study.

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EVALUATION OF HATCH DISTANCE AND POWDER FEED RATE EFFECTS IN Ti-6Al-4V ALLOY DEVELOPED BY LMD TECHNIQUE


ABSTRACT

Laser metal deposition provides various benefits over traditional manufacturing and has since become a research hotspot, as demand for advanced manufacturing persists. The effects of process parameter variation on structural integrity and dimensional accuracy of Ti-6Al-4V alloy fabricated through laser metal deposition was investigated. The laser power, scan speed and gas feed rate were kept constant while overlap distance was varied between 0.3375 and 1.0125mm, and the powder feed rate was varied between 1.6 and 3.8g/min. The microstructure and morphology of the powder and metallurgy prepared samples were examined by Scanning Electron Microscope incorporated with Energy Dispersive Spectrometry (SEM/EDS) and an optical microscope (OM). The density of samples was studied by Archimedes method using ethanol as a wetting liquid, and dimensions were evaluated using a digital Vernier calliper. The microhardness of specimen was measured using Vickers diamond base microhardness tester. The results revealed a decrease in density with an increase in overlap spacing, and the opposite effect was observed for increasing powder flowrate, whereby an increase in powder flowrate was found to decrease density. The evolution of large pores was favoured by higher powder feed rate at constant overlap spaces. In addition, the microhardness of all samples was found to exceed the conventionally fabricated Ti-6Al-4V alloy.

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1. INTRODUCTION

Laser metal deposition (LMD) is one of the laser-based directed energy deposition (DED) methods, which incorporates powders directly fed into the melt pool formed by laser irradiation to fabricate 3 dimensional components. The deposition occurs in a layer-by-layer fashion following the tracks directly from computer-aided design (CAD) data (Arthur, Malabi, Baloyi, Moller, & Pityana, 2016; Thompson, Bian, Shamsaei, & Yadollahi, 2015). In recent years, there has been a growing interest in the process as the technology provides the ability to fabricate complex material geometries, which are normally unattainable through traditional manufacturing techniques (Popoola, Farotade, Fatoha, & Popoola, 2016). Addition to this are countless other benefits, including permitting powder recycling, optimal raw material usage, reduced raw material stock size, fewer machine operations, reduced hard tooling requirements and reduced lead times (Portoles, Jordà, Jordà, Uriondo, & Esperon-miguez, 2016). Despite these significant advantages over conventional manufacturing, further advantages are hindered by the limited understanding of the correlation between process parameters, interaction mechanisms and resultant material properties (Emmelmann, Sander, Kranz, & Wycisk, 2011). The processing parameters such as laser power, scan speed, powder feed rate, feedstock quality, overlap distance and shielding gas flow rate greatly influence the properties of the deposited components. The above-mentioned properties comprise of deposition’s dimensional accuracy, microstructure and mechanical characteristics (Guo, Zou, Huang, & Gao, 2017; Sames, List, Pannala, Dehoff, & Babu, 2016; Shukla, Mahamood, Akinlabi, & Pityana, 2012). Therefore, the 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 (Bayode, Akinlabi, Pityana, & Shongwe, 2017; Shamsaei, Yadollahi, Bian, Thompson, 2015; Thompson et al., 2015).

Titanium and its alloys are advanced materials with an excellent combination of desirable properties such as a high specific strength, superior corrosion resistance and good biocompatibility (Hu, Wang, Ning, & Cong, 2016). Ti-6Al-4V, the most popular aerospace material, is known to be difficult to machine and expensive (Boyer, 1996). As a result, this material is a good candidate for near net shape processes such as LMD fabrication technologies as these technologies require minimal post processing thus the achievable cost saving fabrication operations can enable a wider application spectrum for the above mentioned material (Shukla et al., 2012). The materials compatible with laser-assisted additive manufacturing are still limited, fortunately titanium and its alloys are prominent to the process, thus enabling them to reap the benefits offered by Laser Additive Manufacturing (LAM) fabrication (Kumar & Pityana, 2011). However, attempting to improve the extent of these benefits requires a more advanced knowledge of the process’ underlying physics, which is yet to be established (Shukla et al., 2012).

In considering the importance of process parameters regarding structural integrity and geometrical accuracy for achieving a high-quality component, Qiu et al. (Qiu et al., 2015) focused on a parametric study to investigate the influence of processing and design conditions on structural integrity, geometrical integrity, microstructure and mechanical properties of large Ti-6Al-4V structures fabricated through Laser Engineered Net Shaping (LENS). Results revealed that a lower powder feed rate coupled with a high laser power produce minimal porosity, decreasing powder resulted in the formation of lack-of-fusion pores, due to the incomplete melting of powders. In addition, authors pointed out that the specified vertical distance between the laser head and the build plate or previously built layers greatly affects the design-to-build error i.e. overbuild or underbuild ratio. In another study, Kummalil et al. (Kummalil, Sammarco, Skinner, Brown, & Rong, 2005) observed that an increase in mass flow rate or laser power resulted in an increase in the deposition height while increasing hatch-spacing or scan speed resulted in a reversed consequence. In addition, the authors pointed out that the effects of the mass flow rate and scan speed on dimensional accuracy were significantly greater than that of hatch distance and laser power. According to Shukla et al. (Shukla et al., 2012), the complexity of interactions occurring during laser deposition requires studying fewer (one or two) process parameters to ensure a proper grasp of knowledge.

The primary aim of the present work is to study and optimize LENS process parameters (particularly powder feed rate and overlap distance) to improve the relative density and design-to-part dimensional accuracy of the laser metal deposited Ti-6Al-4V alloy components. The former will help improve mechanical performance by reducing porosity while the later decreases the number of discarded components in production.

2. METHODOLOGY

The LENS technique was used to fabricate a total of four samples from gas atomised Ti-6Al-4V ELI spherical powder with particle size in the range of 40-90 µm. The test samples were built on 75 mm*75 mm*40 mm Ti-6Al-4V plate using a LENS system, which is mounted with a 1 KW IPG fibre laser. Laser deposition manufacturing was performed at the Council for Scientific and Industrial Research (CSIR) National Laser Centre (NLC) in Pretoria. The deposition process parameters are shown in Table 1. The powder feed rate was altered between 1.6 and 3.8 g/min and two hatch distances were used which were 0.3375mm and 1.0125mm. The substrates were sandblasted and cleaned with acetone prior to deposition in order to improve laser absorption and remove excess dirt. Once deposition was complete, a flat surface was achieved by grinding with P320 SiC grit paper using water as a lubricant and aka-allegran disk using the 3micron diamond suspension. Subsequently, polishing was...
undertaken in order to achieve a fine surface finish using aka-chemal cloth with 0.2µ fumed silica suspension. The Olympus BX51M optical microscope was used to capture the micrographs for evaluation of the effect of selected process parameters on microstructure. Density measurements were done by Archimedes method by means of Density test rig using distilled water as the wetting liquid. The microhardness of the test samples was conducted using a Vickers diamond base indenter along the cross section with the inter-indent spacing of 200µm. The dimensional accuracy of square samples was studied by comparing the design heights of 5.06mm with the build dimension achieved through Vernier Caliper measurements. The design dimensions of square samples were 10mm*10mm*5mm, and this was compared to the actual heights to measure the percentage over-build of LAM deposition, under-build was reported as negative over-build.

Table 1: LENS Processing Parameters used for deposition of samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Laser power (W)</th>
<th>Scan speed (mm/s)</th>
<th>Powder feed rate (g/min)</th>
<th>Hatch Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>300</td>
<td>16.93</td>
<td>1.6</td>
<td>0.3375</td>
</tr>
<tr>
<td>A-2</td>
<td>300</td>
<td>16.93</td>
<td>3.8</td>
<td>0.3375</td>
</tr>
<tr>
<td>B-1</td>
<td>300</td>
<td>16.93</td>
<td>1.6</td>
<td>1.0125</td>
</tr>
<tr>
<td>B-2</td>
<td>300</td>
<td>16.93</td>
<td>3.8</td>
<td>1.0125</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSIONS

The results revealed that both the overlap distance and powder feed rate have an influence on porosity of the samples as seen by the difference in pore density observed on micrographs in Figure 1.

![Figure 1: OM micrographs of Ti-6Al-4V by LENS at different process conditions a) B-1, b) B-2 c) A-1 and d) A-2.](image)

The powder feed rate had a relatively less influence on the porosity of samples, especially at low hatch spacing, in contrast to the hatch-spacing which shown significantly greater effect on porosity regardless of powder feed rate. Figure 1a) and c) reveals a defect/pore free morphology while Figure 1b) shows a relatively more pores distributed across the whole surface of the sample. The presence of these pores is attributed to a large hatch spacing resulting in gaps between laser tracks. In addition, high powder feed rate results in incomplete melting of powder, thus leading to the formation of lack-of-fusion pores. Figure 1d) shows a micrograph with pores to some degree though relatively less porous than b). The higher degree of porosity found in Figure 1b) as compared to d) though processed at similar powder feed rate serves as evidence of the influence of hatch spacing on the porosity of the builds.

The microstructural make up of additive manufactured components is influenced by the melt pool’s cooling rate of which is predetermined by process parameters. Figure 2 depicts the SEM micrograph and EDS spectra of the Ti-6Al-4V samples fabricated by.
The micrographs predominantly reveal a typical laser processed Ti-6Al-4V martensite microstructure consisting of the α’ needles contained in columnar prior β grains with a good metallurgical bond between scan tracks obtained under optimized process conditions, for instance small hatch spacings or high powder feed rates results in less gaps between scan tracks thus resulting in reduction in porosity and enhanced densification. The α’ martensitic structure attained therein is characteristic to the rapid cooling from above the martensite start temperature and the β transus achieved by localized instantaneous melting of the moving melt pool (Knowles, 2012). The pore density of B1, the sample with least densification is greatest amongst the other built samples as in seen in the circulate d regions in Figure 2. The EDS spectra in Figure 2c) reveal the expected chemical composition with major peaks for Titanium followed by aluminium and vanadium which are present in small contents.

The results revealed a significant height difference between samples fabricated at similar conditions but varied hatch spacing, with larger hatch spacing distances producing samples with relatively shorter heights. Table 2 and Figure 3 depicts the build height, density and Microhardness of the LENS fabricated samples. Sample A1 was closest to the designed height with a slight over-build of 0,18mm, sample B2 followed with an -0,54mm under-build, followed by sample A2 at 1,16mm over-build and sample B1 at -2.43 under-build. Illustrated in Figure 1 are the optical micrographs of the specimen deposited at varied hatch spaces and powder feed rates. All the observed hardness values of the samples were above that of conventionally fabricated Ti-6Al-4V alloy (344 HV) (Arthur et al., 2016). A comparison of samples at the same powder feed rate revealed that the smaller hatch-spacing produced elevated sample heights in comparison to their counterparts. This is shown in Figure 1.

Table 2: Summary of the Heights, Density and Microhardness results.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Height (mm)</th>
<th>Overbuild (mm)</th>
<th>Density (g/cm^3)</th>
<th>Average Hardness (HV₀.₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>5,18</td>
<td>0,18</td>
<td>4,4102</td>
<td>383,48 +/- 2,38</td>
</tr>
<tr>
<td>A-2</td>
<td>6,16</td>
<td>1,16</td>
<td>4,3272</td>
<td>374,63 +/- 2,87</td>
</tr>
<tr>
<td>B-1</td>
<td>2,57</td>
<td>-2,43</td>
<td>4,3976</td>
<td>386,19 +/- 2,19</td>
</tr>
<tr>
<td>B-1</td>
<td>4,46</td>
<td>-0,54</td>
<td>4,2487</td>
<td>368,37 +/- 3,11</td>
</tr>
</tbody>
</table>

Furthermore, the results reveal that the hardness substantially increases with a decrease in powder feed rate and improves with decreasing hatch spacing which can be attributed to full melting of powder thus leading to sufficient consolidation of powder. This observation is in line with the observation by Tang & Pistorius (2017).
4. CONCLUSION

The LENS additive manufacturing technique can produce depositions with properties similar or better to the commercially available manufacturing processes, as the hardness values obtained through the LENS process were higher than achievable in conventional manufacturing practices. In this study, it was revealed that increasing the hatch-spacing reduces the density. In addition, increasing the powder feed rate has a negative influence on densification due to the lack of fusion. The most accurate build in terms of design-to-build dimensions measured by heights is seen in the sample A1, built at the powder feed rate of 1.6 g/min and 0.3375 mm hatch spacing. This sample also had a hardness greater than that of the commercially available Ti-6Al-4V.

REFERENCES


DESIGN LESSONS FOR ADDITIVE MANUFACTURED SMALL RADIAL FLOW TI-6AL-4V TURBINES FOR APPLICATION IN ORGANIC RANKINE CYCLES

M.E. Cogho*, G.G, Jacobs** and J.J, Du Preez***

ABSTRACT

There is growing concern about the negative impact that fossil fuels have on climate change. Utilisation of waste heat will contribute to a smaller carbon footprint and reduced fossil fuels usage. The Organic Rankine Cycle (ORC) is a technology that is ideal to recover energy from waste heat. The present study aims to develop and characterise small radial inflow turbines for application in ORCs. For small systems it can be difficult to conventionally produce small intricate turbines. Additive manufacturing (AM) is an attractive technology to produce turbines for such systems. AM also makes it possible to manufacture one-off designs with little material wastage for custom sized systems. Titanium Ti-6Al-4V is used for the AM process due to its high specific strength. This paper reports the design, intended characterisation process as well as the design lessons learned for the additive manufacturing of a small Ti-6Al-4V radial inflow turbine for application in ORCs.

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1. INTRODUCTION

Fossil fuels have a significant impact on the global economy as well as on the environment. It is currently the main energy source used to power modern industry [1]. In 2011 it was reported that approximately 80% of energy was produced using fossil fuels, consisting mainly of oil, coal and natural gas [2]. It is desirable to improve the efficiency of current technologies relying on fossil fuelled power.

Combined heat and power (CHP) processes are attractive to recover waste heat from exhaust gasses. The waste heat expelled in a process can be utilised in a CHP process and converted into electrical energy, therefore increasing the process efficiency [3]. The Organic Rankine Cycle (ORC) is an attractive cycle for the recovery of low grade waste heat from exhaust gasses, when employed in CHP processes [4].

This study focuses on small scale ORC systems that can be easily be integrated into current systems for the recovery of waste heat. Additive manufacturing (AM) is considered attractive for the production of components for such systems. To produce intricate small radial inflow turbines for smaller applications poses significant challenges using conventional tooling and manufacturing techniques.

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 [5]. 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 [6].

2. LITERATURE REVIEW

2.1 Turbines

There are multiple turbine types that can be selected for use in an ORC. Two of the turbine types that are attractive for this process are radial flow turbines and axial turbines. For this study the radial inflow turbine was selected due to its small component numbers and its suitability for small turbine applications.

The radial inflow turbine can easily be adapted for various different working fluids [7]. Further advantages are the simpler blade profiles of these turbines and their robustness, allowing for higher operating speeds [8].

2.1.1 Small scale radial turbines

It is important to design the turbine to be as efficient as possible, although this study is more focused on understanding the design limitations and possibilities of AM turbines and their corresponding characteristics; which will form the baseline for future research and development. Small radial inflow turbines work most effectively at the following conditions [9]:

- Head coefficient greater than 1.0 and smaller than 6.0
- Flow coefficient greater than 0.095 and smaller than 0.8

Table 1 - List of symbols

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>$K$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$\eta$</td>
</tr>
<tr>
<td>Enthalpy</td>
<td>$s$</td>
</tr>
<tr>
<td>Entropy</td>
<td>$h$</td>
</tr>
<tr>
<td>Working fluid velocity</td>
<td>$c$</td>
</tr>
<tr>
<td>Relative velocity</td>
<td>$w$</td>
</tr>
<tr>
<td>Blade velocity</td>
<td>$U$</td>
</tr>
<tr>
<td>Number of blades</td>
<td>$Z$</td>
</tr>
<tr>
<td>Angle of working fluid</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>Blade angle</td>
<td>$\beta$</td>
</tr>
<tr>
<td>Rotor blade thickness</td>
<td>$t$</td>
</tr>
<tr>
<td>Rotor blade tip height</td>
<td>$s$</td>
</tr>
<tr>
<td>Blade incidence angle</td>
<td>$i$</td>
</tr>
<tr>
<td>Enthalpy loss coefficient</td>
<td>$\zeta$</td>
</tr>
<tr>
<td>Flow coefficient</td>
<td>$\Phi$</td>
</tr>
</tbody>
</table>
Specific speed greater than 0.2 and smaller than 1.0

The size of the turbine is also of importance. Increasing the size of the turbine will also increase the power that can be produced, but then a greater flow rate is needed. Therefore in order to maximise the efficiency of the turbine an inlet diameter smaller than 160mm is ideal [9].

2.2 Production method

To produce small and intricate components AM is an attractive method for situations where conventional tooling would be impractical or expensive [10]. AM can create components with a high degree of accuracy using a wide variety of different materials and alloys. Selective laser melting (SLM), an AM technology, is especially suitable for the production of metallic components. It allows for very precise control over geometry, mechanical and thermal properties, by altering the laser conditions [6].

Using SLM to produce small radial turbines for experimentation, this study can determine future possible applications or situations where SLM of Ti-6Al-4V turbo machinery components would be the preferred method of production. By determining the effect that the surface finish has on the efficiency of the small radial turbines it can be correlated and used for future development.

AM also has the benefit of reducing the parts count, by allowing certain parts to be produced partially or fully assembled. This can reduce and simplify assembly of the turbine and eventually the complete ORC system. It can also be used to produce more complex structures that can be used to save weight on the finished turbine and supporting components. In future the intension is also to produce turbine rotors with imbedded heat transfer channels that could enhance performance and efficiency.

2.3 Material selection

There is a wide range of materials available that are suitable for the production of a small radial inflow turbine. In order to make a selection it is important to assess the working conditions of said turbine. Due to the turbine being small, it will be rotating at high rotational speed and consequently will experience high centripetal forces. The working fluid is also at a high temperature and can possibly be corrosive.

Titanium has a low thermal conductivity while also having a high resistance to corrosion. Therefore titanium or a titanium alloy would be a suitable material for a small radial flow turbine due to its high elastic modulus and high specific strength [11].

Ti-6AL-4V is a popular material used in compressor discs, blades and stators. This is due to it having high ultimate tensile strength and Young’s modulus at high temperatures [11]. These properties combined with the high corrosion resistance of titanium makes Ti-6AL-4V an ideal candidate for producing a small radial inflow turbine using AM.

2.4 Working fluid

The working fluid used in a conventional Rankine cycle is steam, but due to the lower grade heat from exhaust gasses, it is not ideal for this system. When the temperature difference is too small steam becomes less effective due to being more susceptible to losses [12]. This is due to the steam not having a high enough expansion ratio at the lower temperatures [12].

Organic fluids are preferable at the lower temperatures due to the higher expansion ratio at these temperatures [13]. This ultimately leads towards the turbine being more efficient.
Figure 1 depicts the various working fluids that are most suited for a specific temperature range [12]. From Figure 1 it can be seen that R134a and R22 are ideal working fluids for lower temperature applications. These two working fluids are also easily acquired as they are commonly used in the refrigeration industry.

For initial experimentation air will be used to characterise the turbine. This will give a good indication of the performance of the turbine. Thereafter characterisation with one or more organic fluids will be conducted.

3. TURBINE DESIGN METHODOLOGY

3.1 Methodology

The turbines will be experimentally characterised. Test turbines will be produced using SLM 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 imposed by the SLM process.

Parameters that influenced the design of the turbine include size constraints, as the premise of the study is for small radial inflow 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 of construction for the turbine rotor due to its high strength to weight ratio, as well as its resistance to corrosion [14].

Three turbine rotors 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

3.2 Turbine Design

To characterise the performance of the turbine it is important to first design the turbine theoretically. The theoretical turbine design will in future be compared to the experimental turbine.
Figure 2 – Radial inflow turbine diagram (adapted from [15]).

Figure 2 depicts a diagrammatical view of a typical radial inflow turbine. It shows the path of the working fluid through the turbine. At point 1 the air will enter the turbine at the scroll, where it is distributed to all of the nozzles. From point 2 it passes through the nozzles onto the rotor blade inlet and the working fluid leaves the rotor at point 3 before it passes through point 4 which is the diffuser. The experimental turbine will not have a diffuser. Therefore point 3 represents the point where the working fluid is expelled to the atmosphere.

Figure 3 - Mollier diagram (adapted from [15]).

From the design, the process can be plotted on a Mollier diagram. For an ideal turbine the Mollier diagram is depicted in Figure 3. The subscript s depicts an ideal isentropic process and the 0 in front of a number indicates the stagnation conditions.

Figure 3 is a useful diagram to depict the energy in the working fluid throughout the turbine. If the energy content of the working fluid at turbine inlet and turbine exit, as well as the power delivered by the turbine, are known then efficiency of the turbine can be calculated. This is done by dividing the power generated from the turbine by the difference in the power of the working fluid at turbine inlet and outlet.

From Figure 3 the enthalpy values for points 1 to 3 can be acquired to calculate the energy difference in the working fluid between points 1 and 3 [15]:
\[ \eta_{ts} = \frac{h_{01} - h_{03}}{h_{01} - h_{3ss}} \]  

Where,

- \( h_{01} - h_{03} \)  \text{Actual heat lost through the process}
- \( h_{01} - h_{3ss} \)  \text{Ideal heat lost through the process}

Equation 1 shows the total to static efficiency of the turbine, which is used to gauge how effective the theoretical turbine is. This theoretical value can then be compared to the experimental efficiency to determine the performance of the turbine.

### 3.2.1 Impeller design

To design the impeller the following design specification was used:

- The turbine should produce 500W of power at the shaft
- It must be a small 90° inflow radial turbine for which a 40mm rotor diameter was selected
- The rotor must be produced using AM/SLM
- Ti-6Al-4V was the selected material

These specifications were used as a starting point to theoretically develop a turbine. Nominal conditions were selected as this makes for the most theoretically efficient turbine. Practically nominal conditions are not always the most ideal conditions as the working fluid is not always delivered at design point conditions. However for testing it will provide a good baseline for characterisation of the turbine.

![Figure 4](image)

**Figure 4 - Velocity triangles of turbine (adapted from [15]).**

In Figure 4 there are two velocity vector triangles, with the top triangle depicting the velocity vectors of the working fluid at the rotor blade inlet and the bottom triangle the working fluid at the rotor blades’ exit. These velocity vector triangles can be used to calculate the geometry of the turbine. Turbine specific work is determined with [15]:

\[ \Delta W = \frac{1}{2} \left[ \left( U_2^2 - U_3^2 \right) - \left( \omega_2^2 - \omega_3^2 \right) + \left( c_2^2 - c_3^2 \right) \right] \]  

Where,

- \( U \) = Velocity of the blade
- \( \omega \) = Relative velocity of the working fluid
- \( c \) = Velocity of the working fluid

Equation 2 can be used to determine the power that the turbine will produce. Theoretically the power equation is used to calculate these velocities in order to provide 500W of power.
Firstly the inlet conditions was calculated (design point 2 on the Mollier diagram). The inlet angle ($\alpha_2$) of the working fluid was also calculated. This is important as an ideal inlet angle is crucial to the performance of the turbine.

The exit conditions can be calculated using the rotor loss coefficient that varies between 0.70 and 0.85 for properly designed turbine rotors [15]. This provided the exit velocity of the working fluid. Thereafter blade exit angles ($\beta_3$) were selected. Three exit angles were selected for three different sets of rotors. These angles were: 0°, 25° and 50° respectively. This was done to ensure that the effect the exit angle has on the turbine performance can be accounted for when characterising the turbines.

A simple blade profile was used for the rotor blades with an incidence of 5°. This was done to reduce the amount of variables that can influence the performance of the turbine. Later studies can then use more intricate blade profiles that can then be compared with these to determine the performance increase or decrease at different operating conditions.

Selecting the number of rotor blades was done using Glassmans’ empirical relationship between the inlet angle and the number of blades [15]:

$$Z = \frac{\pi}{30} (110 - \alpha_2) \tan \alpha_2$$ (3)

Where $Z$ is the number of blades for the rotor. For smaller turbines Glassman’s correlation is preferred as using other correlations results in turbine rotors that have too many blades for the small size of the turbine. The turbine rotors were designed to have 10 blades each.

### 3.2.2 Guide vane design

The guide vanes were designed by using the inlet angle of the working fluid to the rotors and the area needed for the mass flow rate to provide the required inlet velocity. The area was determined to provide an inlet velocity that ensures that the maximum rotational speed is approximately 80 000 rpm. This is due to restrictions of the bearings used and safe operation requirements.

The guide vanes acts as guides to the working fluid to direct the working fluid to the rotor at a desired angle and velocity. This inlet angle and the amount of guide vanes were selected for optimal nominal conditions for the turbine.

The guide vanes were to be produced using AM/SLM. Three sets were designed in order to determine losses that will occur due to the clearance between the rotor tip and the guide vane insert, as well as the influence of the inlet angle. The material that was used was also Ti-6AL-4V so that the guide vane inserts can be produced at the same time as the rotors to reduce production time and costs.

### 3.2.3 Turbine specifications

<table>
<thead>
<tr>
<th>Description</th>
<th>Turbine rotor 1</th>
<th>Turbine rotor 2</th>
<th>Turbine rotor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_2$</td>
<td>20mm</td>
<td>20mm</td>
<td>20mm</td>
</tr>
<tr>
<td>$r_{3s}$</td>
<td>16mm</td>
<td>16mm</td>
<td>16mm</td>
</tr>
<tr>
<td>$r_{3h}$</td>
<td>6mm</td>
<td>6mm</td>
<td>6mm</td>
</tr>
<tr>
<td>Blade height</td>
<td>10mm</td>
<td>10mm</td>
<td>10mm</td>
</tr>
<tr>
<td>$\theta$</td>
<td>5°</td>
<td>5°</td>
<td>5°</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>50°</td>
<td>25°</td>
<td>0°</td>
</tr>
<tr>
<td>$t$</td>
<td>0.5mm</td>
<td>0.5mm</td>
<td>0.5mm</td>
</tr>
<tr>
<td>$s$</td>
<td>2.5mm</td>
<td>2.5mm</td>
<td>2.5mm</td>
</tr>
<tr>
<td>Base plate thickness</td>
<td>5.2mm</td>
<td>5.2mm</td>
<td>5.2mm</td>
</tr>
<tr>
<td>Material</td>
<td>Ti-6AL-4V</td>
<td>Ti-6AL-4V</td>
<td>Ti-6AL-4V</td>
</tr>
</tbody>
</table>

Table 2 summarises the specification of the three different turbine rotor designs. The only difference between these three turbine rotors is the exit angle of the blades. The turbine rotor with a 50° angle at exit is expected to be the most efficient, as it is the closest to the nominal design angle of 57.2°. The designs were slightly altered from ideal conditions due to physical limitations and constraints of manufacture by means of SLM, as well as having three different data point equally separated.
The relatively thick rotor backplate is required to ensure that there is enough depth to connect the shaft to the turbine using M3 machine screws. The M3 tapped holes will be produced with the thread and then cleaned up using a die after the SLM manufacturing process. This ensures that the locations of the hole are very accurate and saves time due to not having to drill and tap the holes afterwards.

![Figure 5 - Blade profiles of turbine rotors.](image)

Manufacturing of the blade profile of the turbine rotor, through SLM, is expected not to render problems due to the selected blade profile (refer to Figure 5). In future studies, more complex profiles, with embedded heat transfer channels, will be researched and developed in order to maximise turbine efficiency.

![Table 3 - Guide vane inserts specification.](image)

<table>
<thead>
<tr>
<th>Description</th>
<th>Guide vane insert 1</th>
<th>Guide vane insert 2</th>
<th>Guide vane insert 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>r_{inside}</td>
<td>20.5mm</td>
<td>20.75mm</td>
<td>20.5mm</td>
</tr>
<tr>
<td>r_{outside}</td>
<td>30.5mm</td>
<td>30.5mm</td>
<td>30.5mm</td>
</tr>
<tr>
<td>Passage height</td>
<td>2mm</td>
<td>2mm</td>
<td>2mm</td>
</tr>
<tr>
<td>Total height</td>
<td>12mm</td>
<td>12mm</td>
<td>12mm</td>
</tr>
<tr>
<td>Number of passages</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>\alpha</td>
<td>65^\circ</td>
<td>65^\circ</td>
<td>55^\circ</td>
</tr>
<tr>
<td>Clearance</td>
<td>0.5mm</td>
<td>0.75mm</td>
<td>0.5mm</td>
</tr>
</tbody>
</table>

From 3 it can be seen that insert 1 and 2 have different inside diameters and that insert three has a different inlet angle to the rotors. The difference in the clearance is to determine the losses caused by the clearance in the turbine. Where the difference in angle is to determine the effect that the inlet angle has on the performance.

![Figure 6 - Guide vane inserts.](image)

The guide vane inserts had to be produced in two parts as can be seen in Figure 6. This was due to the small passage height and the requirement for supporting structures in the guide vane passage. These supporting structures cannot be removed after production, therefore it had to be produced in two parts in order to allow easy removal of the supporting structures afterwards.
The bottom part of the insert will lay on the base of the casing where the top part is placed into the fitting grooves. The casing then fastens in such a manner as to press the top securely into the bottom to ensure proper control over flow direction.

### 3.2.4 Expected influence of clearances and other losses

In order to compare the theoretical model with the experimental one it is important to calculate the theoretical losses. The purpose of the study is to determine the effect that the production method has on the performance of the turbine. The effect of the surface roughness are one of the important parameters on turbine performance to be investigated.

In order to determine the effect that the surface roughness has on the turbine all other losses must be accounted for. These losses include inter alia the losses through the guide vanes, rotor losses and tip clearance losses.

The losses due to the tip clearance will be calculated using different clearances. By changing the clearance the effect that this has on the performance can be isolated and calculated. Whereas the losses through the nozzles tend to be very small with a coefficient of between 0.9 - 0.97 [15]. This value can be estimated to a reasonable degree of accuracy using the nozzle’s (guide vane insert) flow coefficient.

\[ \zeta_N = \frac{1}{\phi_N^2} - 1 \]  \hspace{1cm} (4)

Equation 4 is used to calculate the flow coefficient of the nozzle.

The rotor losses are due to the energy lost from the working fluid as it passes over the rotor blades. This will include the losses due to the effects of the surface roughness due to the production method, namely SLM.

The unfinished surface produced with SLM is expected to cause a slight increase in resistance and therefore increase the drag over the surface. This should result in the flow coefficient over the rotors to be slightly higher, reducing the efficiency of the turbines. If this causes a significant reduction in efficiency of the turbine, follow up studies can be done to improve the surface finish of the rotor blades. Candidate methods to improve surface finish are electro plating, shot peening and polishing.

### 4. EXPERIMENTAL METHODOLOGY AND DESIGN

#### 4.1 Experiment design

**4.1.1 Measured parameters**

In order to determine the efficiency of the turbine it is important to measure certain parameters that will be used to compare the experimental turbine with the theoretical turbine. These parameters are:

- Inlet pressure and temperature
- Outlet pressure and temperature
- Mass flow rate of the working fluid
- Rotational speed of the turbine shaft
- Torque produced by the turbine shaft

The inlet and outlet conditions will allow to set up a theoretical model using the Mollier diagram for each set of experimental results. This will ensure that the theoretical conditions are similar to the experimental conditions.

The rotational speed and torque of the turbine will be used to calculate the actual power that is created by the turbine. This value can then be compared to the theoretical value to determine the performance of the turbine.
4.1.2 Experimental equipment and setup

Figure 7 - Process flow diagram of the experimental setup.

Figure 7 depicts a process flow diagram of the experimental setup on which instrumentation position and type is also shown. The working fluid will be introduced into the system via a gate valve, after which a pressure regulator will regulate the pressure of the fluid. Two needle valves will be used to adjust the flow rate with precision. After the working fluid has passed through the turbine it will be expelled into the atmosphere.

To record the inlet and outlet temperatures RTD temperature probes will be used to ensure accurate results are captured. The inlet and outlet pressures are recorded using pressure sensors. This recorded data is then sent to a data acquisition system using transmitters in order to record the results.

The flow rate will be measured with a rotameter. Shaft torque is measured with a Prony brake that applies a load to a load cell. In conjunction with the tachometer the power of the turbine can be calculated.

4.1.3 Experiment Conditions and recording of results

Experimentation will be conducted at steady state conditions. This means that the mass flow rate will be constant throughout the system and that the turbine runs at a constant speed. This will negate any transience at start-up and effects due to the inertia from the mass of the turbine and shaft.

The percentage of error of each piece of equipment will also be brought into account. Using the ISO type B uncertainty analysis [16]. A type B analysis has to be used due to the scarcity of data available. A coverage factor of two will be used to obtain a confidence level of 95%.

5. DISCUSSION

5.1 Design Lessons

Support structures:
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.

Surface roughness:
The SLM process produces surface finishes in the order of 30 μm, which can be considered as coarse in the intended application. The impact of such a coarse surface finish on turbine performance will be negative. It is uncertain by how much the efficiency will suffer and is an objective of this study.

Orientation during manufacturing:
Component orientation, during the SLM process, has a significant impact on manufacturing cost. Build height must be minimised since build cost is a function of material usage and machine time. In selecting the orientation it is also important to consider the limitations of the SLM process. Horizontal structures for example require support structures to prevent sagging.

The SLM process has limitations on incidence angle of produced wall sections without support. The current limitation is 35° with respect to the vertical plane. These structures must later be removed manually. It is therefore important to carefully consider the manufacturing orientation and limitations on build angles when designing the component. It cannot be done without intimate knowledge of limitations of the SLM process. It is best done in conjunction with experienced SLM manufacturing engineers.

Reduction of parts count:
The ideal is to minimise the parts count. There are however limitations imposed by build orientation and manufacturing cost limits. In this case the option of a solid turbine rotor-shaft assembly was considered. However that would imply that the shaft had to be produced in the vertical position with the turbine rotor centred and perpendicular to it. Another possible orientation option would be to produce the shaft in the horizontal position with the turbine rotor centred and perpendicular to it.

Both these options would require excessive support structures and the build time, and thus costs, would significantly increase. There is thus a limitation in the parts count reduction achievable.

Design flexibility:
Although the SLM process allows for significant design flexibility there are SLM process and cost limitations that must be taken into account when designing an AM radial inflow turbine. Wall thickness and radii limitations makes it difficult to produce thin walled and sharp edged sections which must, if desired, be produced by post-production machining.

Screw threads:
Another limitation from the SLM 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.

Material:
Due to the high rotational velocity of the turbines it is subjected to high centrifugal forces that induce stress in the material. The magnitude of the force is a result of the weight of the rotating mass and the velocity at which it rotates. Using Ti-6Al-4V the blade thickness of the rotor can be reduced due to the high specific strength. This in turn allows for higher safe operating speeds, which increase the performance of the turbine.

The SLM process used to manufacture the rotors requires sufficient thickness to ensure the structural integrity of the material. The blade thickness of the rotors could have been made smaller, but due to restrictions because of the SLM process a safe blade thickness of 0.5mm was selected.

The high yield strength at higher temperatures and corrosion resistance of Ti-6Al-4V makes this an attractive material for an ORC turbine. This is due to the turbine operating at elevated temperatures for extended periods of time. Retaining a high strength at higher temperatures will ensure a longer life for the turbine. Some refrigerants used in ORCs is corrosive and Ti-6Al-4V’s resistance to corrosion also improves the life of these turbines.

6. SUMMARY AND CONCLUSION

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

The article on the design lesson learned is based on a work in progress for characterising turbines produced using SLM. In the near future, results from the experimentation will give an indication of the performance of turbines produced using SLM. This will assist in understanding the viability of the SLM process to produce radial inflow turbines for application in ORCs.

It will also be the basis for further studies on improving the current turbine design. Especially investigating more complex blade profiles, lower parts counts and faster production times. All of which can either increase the efficiency of the turbine or reduce production costs. These will in turn lead to optimising a complete ORC system and the optimisation thereof.
ACKNOWLEDGEMENTS

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REFERENCES

CAN ADDITIVE MANUFACTURING HELP WIN THE RACE?

Ch. Hands¹, A. Du Plessis², N. Minnaar³, Ba. Blakey-Milner¹ and Eh Burger³

ABSTRACT

This paper provides an overview of the new CPAM Project on Additive Manufacturing (AM) in design and simulation, focusing on topology & lattice structure optimization for a light-weighting advantage. This industry/academia collaboration project aims to utilize existing hardware and software tools, and investigate the practical limits of the technologies, providing eventual guidelines for 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 also incorporating lattice optimized design, both from Ti6Al4V and load-bearing components, to be utilized in the Nelson Mandela University (NMU) Eco-Car Project in competition, late in 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 finishing off the design process. Detailed structural integrity assessment of these parts are included - the question remains: can Additive Manufacturing help win the race?

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³ Altair SA, Stellenbosch, South Africa
1. INTRODUCTION

The newly established CPAM project in lattice structure designs has provided an opportunity to investigate the practical limits and challenges of this technology, using state of the art hardware and software tools. The project is aimed at investigating and advancing the use of lightweight and lattice designs in AM, from fundamental aspects to practical application.

While the topic is widely known and reviewed in more detail in (Yang et al.[1]), its practical use is actually limited by the wide design space: the user is not normally sure what design constraints to use, where in the part to use lattices or what kind of lattice designs are possible to be practically incorporated. Currently the designs created are limited by typical settings in the software packages used, and not yet fully exploiting the complexity available. Furthermore, the manufacturability and suitability of different lattice designs are still in their infancy. Current work in progress in this project is aimed at analyzing different lattice unit cell designs, investigating manufacturability, directional mechanical properties, permeability and other parameters which vary for different lattice designs (du Plessis et al.[2]).

Current state of the art lattice structure production by AM has been reviewed recently for bone replacement implants (Zhang et al.[3]; Wang et al.[4]). Other light-weighting applications using lattices are widely studied but few examples exist in literature thus far; a good example is reported in (Orme et al.[5]). Besides lattice designs, manufacturing limits exist which affect mechanical properties of lattices and parts containing lattices. This project will further investigate this: particularly internal porosity in struts of lattices, directionally-dependent thickness variations in production (eg. thicker horizontal struts vs vertical struts), and surface roughness all play a role in strength, stiffness and fatigue life of lattice parts and need further investigation to provide suitable guidelines for lattice designs.

Finally, to fully exploit the complex design space, it’s possible to incorporate biomimetic design rules, ie. using design concepts from nature. This is further investigated by using specific biological structures and analyzing their successful structural details in terms of lattice and lightweight design - one recent investigation is reported for impact protective design based on design of an animal’s body armour (du Plessis et al.[6]), and its application to metal additively manufactured body armour units, reported in (du Plessis et al.[7]).

MicroCT use is crucial in quality inspection of produced parts, as has been reviewed in (du Plessis et al.[8]). This kind of inspection and analysis becomes especially important for thin-walled components and latticed parts which may contain internal porosity or unconsolidated powder, or may have small cracks from unexpected residual stresses, due to the complex shapes produced. By combining all above topics, this project aims towards practical application, with load bearing parts designed using incorporated topology- and lattice optimization. The hope is that this project will deliver practical guidelines assisting users in the wider adoption of the methods of topology optimized and latticed AM parts.

Topology Optimized design for AM is a topic of intense research and application currently, resulting in efficient design by expanding available design space and allowing greater design complexity as a result of design freedom offered by additive manufacturing (Liu et al.[9]).

Its main purpose is to produce an efficient design by either light-weighting the part or maximizing 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 optimized structure.

As a next step, it is possible to add lattice structures to the optimized design space where low stresses are found, or where stiffness can be tailored to suit the application. The output structure often requires some data post-processing in the form of smoothing and defining solid support material regions, to deliver a practical design input for additive manufacturing. All of this is typically done in Topology Optimization enabled software such as in Altair Inspire, in tandem with specialized AM preparation software, all of which was used in this work.

The former software, which incorporates many state-of-the-art technology features that will be further detailed in Section 3, facilitates simulation-driven design exploration and its use in the design process. Applications similar to ones documented in this project have been validated many times over as evidenced by a number of commercial success stories from vendors (eg. Robot Bike Company[10], Ryerson University[11] & Gator Motorsports[12]).

2. THE ECO-CAR PROJECT

The NMU Eco-Car Project was initiated off the back of the institution’s Solar Car Project back in 2014 when that project became too expensive to continue. With the focus on design for light-weighting, in tandem with the carbon compositing experience already established via the Solar Car project, the Eco-Car Project was deemed an ideal fit to continue with the research done into lightweighting and specifically Topology Optimization techniques.
The establishment of the annual Shell Eco-Marathon: South Africa in 2014 provided an ideal outlet for this project. The Shell Eco-Marathon (SEM) is a global event held in many countries with the Americas, European and Asian events considered the main blue-flag events internationally, with several newer events like South Africa being termed Challenger events.

The intent of the SEM is for student teams to conceive, design, manufacture and compete in the event to try and achieve the furthest possible distance on an equivalent 1 litre of standard fuel. It is a multi-disciplinary project directly tying in with the current global engineering strategies being prioritized by OEMs of light-weighting, efficiency, fuel-saving, advanced design and manufacturing techniques applied to the automotive and aerospace supply chain.

Two main categories exist in the SEM: Prototype and Urban Concept, the South African event catering only for Prototype category. There are also several sub-classes iro power source, with the local event only allowing Electrical and Internal Combustion Engine (ICE) options.

The NMU Eco-Car (Figure 1) chose to use ICE as their power option mainly due to the established prevalence of automotive manufacturers in the Eastern Cape region using traditional ICE options, but are considering an Electric option in the future - this was pre-conceived in the initial modular design to allow for easy swapping of power sources.

Figure 1: The NMU Eco-Car in the 2017 Shell Eco-Marathon: South Africa.

The NMU Eco-Car Team has been fortunate to be Champions in their category in the last two events, 2016 & 2017, setting consecutive event records on each occasion and are hoping to achieve an even better distance with the latest design iteration sporting several metal AM components in a continuous effort to lighten the car and to optimize the design even further.

In this paper, two case studies will be detailed, consisting of:
   i. a topology optimized mounting C-bracket, and
   ii. a topology optimized and latticed large steering arch.

2.1 Project Initiation

The project initiated through Altair SA’s Ernst Burger establishing contact between the University of Stellenbosch’s Prof Anton du Plessis and the NMU Eco-Car Team, as a result of the common bond of use of Altair software products, and the shared interest in developing Metal AM techniques, Topology Optimization & Lattice Design for Light-weighting purposes.

Prof du Plessis had sourced funding supported by the South African Collaborative Program in Additive Manufacturing (CPAM) to conduct research into lattice structure design and application. Additionally, his current research efforts involve the standardization of MicroCT non-destructive analysis techniques to improve accessibility and cost effectiveness of the process, in order to promote wider uptake of the process to users in the AM community.

As such, an applied project was needed to test designed & optimized metal AM components in a real-world application, which the Eco-Car Project provided, and so proved a perfect fit for all to achieve their objectives. The combined Project was thus established in mid-Feb 2018 and soon evolved into a multi-pronged program which continues to expand promisingly.

2.2 Component Identification

The Eco-Car’s design was conceived on the basis of shrink-wrapping the aero package around a full carbon-fibre monocoque consisting of certain core components: the driver, wheels & engine - after that, the design freedom was reasonably unrestricted.
The expense of the composite monocoque & bodyshell components means focus on successive iterations has been on increasing efficiency and light-weighting of inner components rather than re-design - with the aim to further light-weight by 5 [kg] from a version-1 mass of 52 [kg]. As each partial gram is shed, this target proves an increasingly difficult challenge.

This door opened by the metal AM option allowed not only light-weighting on certain chosen components, but enabled more sophisticated designs utilizing both topology optimization and lattice-design techniques, further stiffening of components for structural performance, as well as consolidation in the number of parts required to perform exactly the same task.

This led to a selection option in which components were prioritized within the structures of the funding allocation - a wish-list was created and then honed down. An initial urgent need for a round-robin test saw the front corner C-Bracket being chosen as first priority, and then the Steering Arch was selected as a primary load-bearing structure (Figure 2). The process behind the development and final printing of these components will be detailed next.

Further components are also being considered depending on funding and manufacture availability, with the hope that the completed components could be installed on the Eco-Car in time for the 2018 Shell Eco-Marathon: South Africa in October.

### DESIGN TECHNOLOGIES FOR ADDITIVE MANUFACTURE

The performance of a load-bearing structure may be measured in various ways eg. max. sustainable load, mass, compliance/stiffness. Meanwhile, a factor which greatly affects these performance measures in a structure is the layout of material within its boundaries. The design of this material layout is a complex task since it presents designers with many degrees of freedom, most of which effect structural performance in non-intuitive ways.

One method for handling this design complexity is to inform the design process using Topology Optimization (TO). Additional design strategies such as replacement in the design domain of continuous material with lattice units can lead to even greater structural performances. This section will describe the technologies which yield optimal structural performances in AM products, and Altair Inspire has been used in this project to administer these technologies.

#### 3.1 Topology Optimization

Topology Optimization is an algorithmic approach in which structural performance iteratively drives the modification of material layout in a load-bearing structure. The algorithm has been implemented on top of finite element analysis (FEA) codes, since it is FEA which is utilized for the evaluation of structural performance. While Topology Optimization only found application in niche designs in the distant past, the technology is now well integrated into many modernized industries (eg. aerospace (Zhu et al[13]) and automotive (Yildiz[14])).

The AM industry in particular has the most to gain from Topology Optimization since a synergy exists between the two technological fields. Specifically, AM releases manufacturing freedom while TO releases design freedom in a product development process. The marriage of these two technologies therefore truly liberates the product’s optimal performance as a structure.

Adoptions have previously been made to TO implementations to account for the manufacturing constraints of traditional manufacturing processes (Vatanabe et al[15]) as the optimizations inherently produce concepts with complex shapes and are thus not generally manufacturable (Gibson et al[16]). Until recently, however, no adoptions had been available to address a significant limitation in the space of AM. More specifically, in the case of metal laser powder bed fusion, significant support structure may be required for production since high residual stresses cause warpage. The support structure is therefore necessary to facilitate a warpage-reducing connection between the part and its print-bed base. However, support structure also drives waste production and induces the need for sometimes significant post-manufacture-processing. To mitigate these drawbacks, one strategy for minimizing the necessary support structures is to limit overhang angles in the design from the offset.
Overhang angles describe the angle between the vector which connects consecutive points on the boundaries of part and the vector parallel to the build plate (Figure 3). Post-optimization, ad-hoc modifications have typically been made to part designs to mitigate overhang angle violations from the results of Topology Optimization.

Optistruct (Optistruct User Guide[17]), which forms the kernel of Altair Inspire 2018, offers a state-of-the-art TO adoption which has been leveraged in this project to reduce overhang where practical. The technology is available via two implementations. In the first implementation, the topology of the optimized design may be strictly prohibited if it violates overhang angle constraints (Gaynor et al[18]).

Secondly, unique to Optistruct, designers may penalize overhang angles in their designs instead of removing them completely. This is achieved using a method whereby the objective of the optimization is penalized in a predefined proportion to the degree of overhang violations in the generated designs. This offers superior convergence and a mechanism to tune designs towards functionality, manufacturability, or perfect balance between the two.

3.2 Lattice Optimization

A state-of-the-art feature in some FEA codes, exclusive to designs that are intended for AM, is the ability to replace solid and continuous design regions with optimized lattice-unit structures. These lattice structures are efficient from multiple perspectives e.g. they have high strength-to-weight ratios structurally, high surface area-to-volume ratios thermally, and they exhibit high biomedical compatibility due to their effective porosity (Helou et al [19]). In addition, the utilization of lattice-units in a design process can be coupled onto the results of a TO. Resulting designs are radically different from ones designed using traditional design strategies, an example is the steering arch designed in this project.

Individual lattice units (Figure 4) exhibit unique structural behavior since they have unique configurations whereas every unit of continuous material behaves identically. Lattice-units thus essentially allow designers to utilize localized effective material properties instead of applying a single global material property to the entire design domain.

The expense of this design freedom, however, is that the designer introduces many new design variables into the process since each unit of lattice in the domain needs to be assigned a configuration and associated dimensions. To mitigate this multitude of design variables, designers can offload the complexity onto optimization-enabled FEA codes to generate lattice configurations and optimization technology to choose the best values for the associated dimensions.

The fundamental design variable in the Topology Optimization stage of this project, and in general, is the element-by-element material density within the design domain. Since intermediately dense material cannot be used during fabrication of a part, optimal element densities in the final optimization results of a pure TO are mapped to a discrete solution. This means that all elements in the design domain are forced to be either fully dense or void.

The lattice optimization step offers a pragmatic solution for fabricating intermediately dense elements if coupled to the TO. This is because lattice units have an effective intermediate density when compared to a fully solid unit of equal volume. This is implemented by introducing a second optimization step where the optimal topology (or subset of the topology) from the pure TO step is replaced by lattice elements; the associated strut diameters are optimized with a constraint on the incident stress. The lattices produced are conformal to the geometry of the part and correspond to the tetrahedral mesh used for simulation. It is not currently possible to incorporate more complex lattice designs into TO designs.
4. METHODOLOGY AND RESULTS

4.1 Case Study 1: C-Bracket Design Process

4.1.1 Initial Design Need
The front corner C-Bracket (Figure 5) was first choice as a pilot component because:

- it was small,
- it could benefit from further stiffening,
- a lightweighting advantage could possibly be gained, and
- a solution was relatively quickly achievable.

The function of the part is to connect the front corners to the steering arch, which in turn was bonded in to the monocoque/tub of the vehicle. The performance of all current structures had already proved themselves in past events.

The original structure was a multi-layered, full carbon structure, laid-up utilizing a simple long mould structure with many layers of stacked fabric. The cured product then cut to size and each bracket subsequently post-processed via standard machining processes.

It was decided to carry out the design optimization using purely topology optimization to keep things relatively simple for the pilot project due to the urgent need, to test whether the physical outcome and envisaged outcome were comparable, and to limit the possible challenges coming out of the whole print process.

4.1.2 Design & Optimization Process
Geometric properties were captured from both existing CAD documents and verified by rigorously measuring existing physical parts. A plastic 3d printed AM test piece was then also produced to verify correct fitment into the vehicle.

The Design Space (Figure 6) of the original component was then expanded to its logical extents to maximize the volume for the topology optimization process, in order to ensure as many variants of solution as possible.

Non-design spaces are defined separately to ensure that critical mounting elements, such as bushing housings and bolt holes, are not affected by the optimization process design - red regions in Figure 6 indicate design space and grey regions are non-design spaces.

Loads and constraints were then applied from existing known load cases and adapted for the bracket. Six envisaged worst-case load combinations were considered to guarantee the bracket’s safety under extreme circumstances, these being combined into an overall envelope, enhancing the safety margin to a hyper-conservative degree. Symmetry constraints about two planes were imposed to ensure the final part can be orientated in any direction and on any side of the vehicle, as well as to simplify the computational overhead in analysis.

TO analyses were carried out for over 60 iterations, using various optimization constraints to generate an optimal part. As more extreme target volumes were explored, manufacturing constraints began to dictate limits of the optimization, so a minimum dimension was imposed to avoid too small a cross-section being generated to be viably printed in the AM process.

Table 1 below lists the 10 best iterations achieved by the optimization, based on mass, while still achieving a safe stress limit - here target volume is the input, and Factor of Safety, Total Mass, max. Major Principal Stress, max. von Mises Stress and max. Displacement the analysis outputs of the TO process. The tensile strength of Ti64 is 1000 [MPa].
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4%</td>
<td>45</td>
<td>load case envelope</td>
<td>2.4</td>
<td>24</td>
<td>369</td>
<td>347</td>
<td>0.676</td>
</tr>
<tr>
<td>7%</td>
<td>27</td>
<td>load case envelope</td>
<td>3.9</td>
<td>28</td>
<td>304</td>
<td>213</td>
<td>0.438</td>
</tr>
<tr>
<td>8%</td>
<td>26</td>
<td>load case envelope</td>
<td>4.9</td>
<td>30.3</td>
<td>233</td>
<td>168</td>
<td>0.368</td>
</tr>
<tr>
<td>10%</td>
<td>25</td>
<td>load case envelope</td>
<td>6.2</td>
<td>34.6</td>
<td>182</td>
<td>133</td>
<td>0.297</td>
</tr>
<tr>
<td>11%</td>
<td>24</td>
<td>load case envelope</td>
<td>6.6</td>
<td>36.7</td>
<td>170</td>
<td>126</td>
<td>0.275</td>
</tr>
<tr>
<td>13%</td>
<td>23</td>
<td>load case envelope</td>
<td>7.9</td>
<td>44.8</td>
<td>142</td>
<td>104</td>
<td>0.215</td>
</tr>
<tr>
<td>15%</td>
<td>18</td>
<td>load case envelope</td>
<td>9.9</td>
<td>55.7</td>
<td>110</td>
<td>83.3</td>
<td>0.178</td>
</tr>
<tr>
<td>20%</td>
<td>17</td>
<td>load case envelope</td>
<td>11.7</td>
<td>68.3</td>
<td>94.8</td>
<td>70.8</td>
<td>0.156</td>
</tr>
<tr>
<td>25%</td>
<td>16</td>
<td>load case envelope</td>
<td>13.6</td>
<td>81.2</td>
<td>84.8</td>
<td>61</td>
<td>0.142</td>
</tr>
<tr>
<td>30%</td>
<td>15</td>
<td>load case envelope</td>
<td>13.6</td>
<td>81.2</td>
<td>84.8</td>
<td>61</td>
<td>0.142</td>
</tr>
</tbody>
</table>

Table 1: Topology optimization iterations in order of ascending mass.

As more aggressive target volumes were tested, there was a corresponding increase in Major Principal, von Mises stresses as well as Displacement. This was expected as the bracket has numerous constraints in the optimization process, such as symmetry about two planes as shown in Figure 6 and a low overall volume relative to the loading involved; these constraints stop the topology optimization process from producing branch-like structures which tend to, as target volume decreases, create non-linear jumps in stresses at branch events.

Also shown in Table 1 above, is that as the mass of an optimized part decreases, the maximum displacement increases. This shows the sacrifice of stiffness to achieve lighter components shared by most topology optimizations with the goal of smaller volumes.

The most aggressive target volume achieved was 4% of the original design volume with a mass of 24 [g] and an overall minimum safety factor of 2.4, this mainly due to geometric and constraint effects.

As the target volume goal decreased (Figure 7), the two halves of the bracket begin to separate, creating a less stiff part while decreasing the weight - this would also result in significant misalignment challenges on installation, affecting performance.

The next step was to generate a smooth free-form body using PolyNURBS techniques (Figure 8), thereby eliminating all the jagged/tessellated features resultant from the topology optimization process.

A design decision was made to join the two symmetrical halves with a bridge of material ensuring ease of alignment during installation and to further stiffen the structure. Finally, geometric entities were created on any significant edges to further reduce any sharpness to improve printability overall - the whole iterative analysis procedure taking approximately 180 hours in total for the full process.

4.1.3 Design Evolution & Simulation Results

Figure 9 below depicts the evolvement of the optimized design in Ti-6-4 showing projected weight-saving of 41% on this component alone, from the original carbon-fibre bracket on the vehicle to final computational model form.
After smoothing via PolyNURBS, further FEA tests were carried out on the final structure to verify no initial design constraints were unintentionally violated, resulting in expected improved results than from the raw, unrefined structure resultants in the TO iterations - as all stress concentrations from any tessellated surfaces would have been relieved, and additional material would have also been added to the design as a result – Figure 10 depicts samples of these results showing Displacement, von Mises and Major Principal stress outputs.

4.1.4 Final Product

The final design model was sent through for additive manufacturing in Ti64 at various facilities in a round robin study - which will be reported elsewhere - and non-destructive tests were conducted post-printing to establish conformity of the final component with the design.

Parts in this paper were manufactured using laser powder bed fusion using standard process parameters in an EOS M280 system at Central University of Technology. Typical parts from this process have been analyzed in detail previously (Yadroitsev et al[20]; du Plessis et al[21]). Typical parts from this process contain minimal porosity, and 10 mm test cubes were also printed with the first C-Bracket as comparative test specimens - these were then analyzed at high resolution to confirm low levels of porosity; the use of microCT in AM (du Plessis et al[8]) is globally an accepted industry standard. MicroCT was performed at the Stellenbosch CT Scanning facility (du Plessis et al[22]). The cube volume was measured using accurate sub-voxel surface determination in microCT data, and combined with mass from an accurate scale, provided a mean density of 4.504 [g/cm³], well within the Ti6Al4V density range.

The microCT images (Figure 11) show some small porosity as expected with a total volumetric percentage of 0.012 %, They depict the microCT data of this 10 mm cube as a surface- and transparent-view showing the even distribution of the micro-porosity. Larger parts, difficult to test at this resolution by microCT, are expected to have the same micro-porosity distribution, considered acceptable at this low level, as long as it is evenly distributed.
The final topology optimized Ti-6-4 product (Figure 12) is shown after stress-relief heat treatment, as well as removal of support material & base support; no further physical post-processing was carried out. Also depicted are standard pieces utilized in the testing process for detailed analysis of mean density, porosity, and possible stop-start flaws.

The brackets were then tested via microCT, and the microCT scan on the C-bracket (compared to the 10 mm cube) showed no macro-porosity. Large unexpected pores or flaws can sometimes be present due to major build errors or contamination, for example. They were found to have no detectable porosity > 135µm or unexpected internal flaws either. Compared to the CAD, the two arms of the bracket slightly warped inwards by a maximum of 0.5 mm on both sides, with horizontal offset also approx. 0.5 mm (Figure 13).

The mass of each Ti-6-4 metal printed C-bracket is 27.0 grams saving 45% compared to the original design, which was an already very light carbon-fibre part. The mass progression (Table 2 below) of the C-Bracket structure through the whole process was as follows:

<table>
<thead>
<tr>
<th>structure</th>
<th>mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>original carbon structure with inserts</td>
<td>49.5</td>
</tr>
<tr>
<td>structure reverted to solid titanium</td>
<td>177.29</td>
</tr>
<tr>
<td>titanium structure topology optimized</td>
<td>24</td>
</tr>
<tr>
<td>polyNURBed smoothed solution</td>
<td>29.33</td>
</tr>
<tr>
<td>final printed part</td>
<td>27</td>
</tr>
</tbody>
</table>

The mass progression of the C-Bracket structure through the whole process was as follows:

4.2 Case Study 2: Steering Arch Design Process

4.2.1 Initial Design Need

The existing steering arch is a carbon structure, designed to neatly surround the driver’s legs (Figure 14). The existing structure was cut from high-density polystyrene block via robot-CNC and the structure then over-laid with multiple layers of carbon-fibre.

This structure has proved itself more than up to the task, stiffness and compliance-wise, over several competitions already, so this choice was mainly based on three issues:

- increasing stiffness of the structure to improve loss of efficiency through the steering,
- to consolidate parts to one single component, thereby saving weight,
- to explore how additional latticed optimization could further enhance the design

To further attempt to add to the general light-weighting requirement and efficiency of design, it was decided very early in the design process to apply a lattice-work design optimization to the structure. The deployment of a latticed Ti-6-4 structure will appreciably add to the stiffness of the component, which is important as it carries both front corners as well as the steering system & all driver controls, and any compliance that may exist there.
4.2.2 Design & Optimization Process

Again, existing geometry in CAD was checked to ensure conformity to the physical component. All loading and constraints were then adapted to the new consolidated design space. The Design Space (Figure 15) expanded as far as practicable to allow the topology optimization free-reign to generate alternative un-envisioned options.

Table 3 below shows 5 selected iterations of the topology optimization phase out of 65 carried out, with the objective of maximizing stiffness while removing enough weight for the lattice optimization to still be competitive. The inputs were Target Volume and Maximize Stiffness while the outputs were Minimum Factor of Safety, Total Mass, Maximum Major Principle Stress, Maximum von Mises Stress and Maximum Displacement.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>29</td>
<td>load case envelope</td>
<td>11</td>
<td>1.63</td>
<td>68.7</td>
<td>75.4</td>
<td>0.118</td>
</tr>
<tr>
<td>15%</td>
<td>48</td>
<td>load case envelope</td>
<td>14.4</td>
<td>1.36</td>
<td>70.5</td>
<td>57.3</td>
<td>0.203</td>
</tr>
<tr>
<td>10%</td>
<td>46</td>
<td>load case envelope</td>
<td>15.1</td>
<td>1.10</td>
<td>67.6</td>
<td>54.8</td>
<td>0.241</td>
</tr>
<tr>
<td>8%</td>
<td>50</td>
<td>load case envelope</td>
<td>8</td>
<td>0.986</td>
<td>88.8</td>
<td>103</td>
<td>0.270</td>
</tr>
<tr>
<td>5%</td>
<td>44</td>
<td>load case envelope</td>
<td>5.3</td>
<td>1.09</td>
<td>166</td>
<td>155</td>
<td>0.317</td>
</tr>
</tbody>
</table>

Table 3: selected TO iterations to obtain optimal design volume in order of ascending displacement.

As the volume of the arch is decreased the maximum stresses present do not always decrease, this is due to varying branching structures developed by the optimization sacrificing strength for stiffness. Iteration 29 achieved the lowest maximum displacement while remaining in range of the final mass target for the lattice stage. It also was the only iteration to produce more than one arch across the gap which increases the stiffness at the lattice stage output.

PolyNURBS techniques were used to smooth out any jagged/tesselated edges produced by the TO analyses, thereby preparing the model for a further lattice optimization phase. The primary constraint to this was a pre-advised manufacturing constraint of a 2 [mm] min. diameter for any lattice beams in the component. This substantially limited the min. mass achievable as smaller lattice structures, particularly micro lattice structures, would have performed better on a weight saving basis, whilst still retaining design objectives.

Lattice optimizations were then performed varying input parameters and constraints to reduce the weight of the final arch design. Table 4 below shows the 10 best iterations out of a total of 89 carried out, in order of ascending mass, with the input parameters of target length, minimum diameter and maximum diameter of lattice beam sections, while the outputs are FEA results such as minimum factor of safety, maximum major principle stress, maximum von Mises stress and maximum displacement as well as the mass of the component.
Table 4 shows, as lattice beams become ever more slender, greater mass savings can obviously be achieved, but that stresses do not tend to converge to their limits in relation to mass as usually seen in optimizations - this was due to stress concentrations being relocated to different points on the lattice structure, and each mesh size having different optimal diameter inputs, restricted by the 2 [mm] min. diameter print machine hardware constraint.

Also, the max. displacement increases by as much as 14-fold over the purely TO component, showing how lattice structures tend to deflect while still maintaining relative strength and reducing mass. This, however, was still well within the imposed design constraint.

The lowest mass of 752 [g] was achieved by iteration 61 with a min. safety factor of 2.8; this safety factor caused by stress concentrations that were resolved and improved on in the following smoothing phase. This particular iteration also created some slender lattice beams and voids in some areas, which would be unprintable by available printers. However, a subsequent smoothing phase would remedy all of these anomalies.

The next major challenge was to ensure that there was clear delineation between the lattice structures and the support material generated by the printing process, and to eliminate any possibility of the lattice being compromised in post-processing removal of support material.

Support shell surfaces in a range of 1-2 [mm] thickness were then created to facilitate this, taking into consideration the optimum orientation on the printer bed. Furthermore, the overall outer design extents of the steering arch was such that it excluded the possibility of being printed on any of the available printer options in the country, bar one at AeroSwift, and this itself has constraints that dictated the orientation of the component, and hence the amount of support material created, and its connection points to the printed structure.

Horizontal (‘face-down’ - Figure 16) or vertical (‘upright’ - Figure 17) orientations proved to be the best options, showing the support shell surfaces that would need to be created to facilitate this, as well as the orientation on the available print-beds.

Figure 16: Identification of optimum support shell regions for ‘face-down’ print-bed orientation (l) front view depicting required shell regions, and (r) the structure orientated on the print bed.

Figure 17: Identification of optimum support shell regions for ‘upright’ print-bed orientation (l) bottom view depicting required shell regions, and (r) the structure orientated on the print bed.

This was a major challenge due to restricted capability on current available software and was not easily achievable, requiring jumping between multiple software platforms to achieve successful integration. These surfaces needed to be placed between the lattice beams and the support material structures, yet still ensuring direct connection. This is easily achievable in some high-end platforms, but, even in academic option, they are financially prohibitive.
As depicted in Figure 18 below, the optimal generated support material, in blue, joining to the components defined support material shell structures is displayed for both orientations - this was the most efficient layout into support material joining onto the main arch structure, as well as available print bed constraints, according to available software options.

![Figure 18: support material generation based on print-bed orientation](image1)

In a unique application of microCT-based voxel software, the component was further smoothed using image processing methods (Figure 19) with the yellow envelope line showing a smoothed model compared to the original design (white). This removes sharp corners and ridges, which may act as stress raisers and could also make final printing challenging.

![Figure 19: (l) Voxel-based image smoothing of the final model (yellow lines), and (r) the final model wall thickness analysis, to check the final design prior to printing.](image2)

The final smoothed part is then subjected to Wall Thickness Analysis to ensure no parts are too thin. Despite minimal strut thickness constraints, some struts may be created thinner. When they are non-circular in cross-sectional shape, the smoothing process may make them significantly thinner than expected. This process of smoothing (Figure 20) may be modified if this is the case. Final model volume can be checked as this process fills in significant amounts of material up to about 30% volume increase, increasing the weight of the arch to 857 [g].

![Figure 20: close-up comparison between (l) original model STL file, and (r) the final voxel-based smoothed part.](image3)

The final smoothed latticed structures including support material shell surfaces are depicted in Figure 21 below. The full iterative analysis procedure taking approx. 500 hours.
4.3 Design Evolution & Simulation Results

Figure 22 shows the design evolution of the optimized, latticed design in Ti-6-4 with a projected mass-saving of 14%, from the original carbon-fibre steering arch on the vehicle.

After smoothing via PolyNURBS, further FEA tests were carried out on the final computational model to verify that initial design constraints were not unintentionally violated, resulting in expected improved results than from the raw, unrefined structure resultants from the TO iterations depicted in Table 4 - Figure 23 depicts a sample of some of these results showing Displacement and von Mises stress: the critical stress zones being understandably where the lattice meets the shelled monocoque insertion regions - however, this is still well within the design constraints, and would also be improved by the voxel-based smoothing process.

4.3.1 Final Product

At the point of submission of this paper, the printed final product was still due for printing at AeroSwift, a government-backed project launched in collaboration between Aerosud and the CSIR. As it turned out, the printer orientation would be dictated by printer constraints, and the upright orientation would be the only option available due to print-bed restrictions, necessitating further adjustments to the design to accommodate the configuration - further compliance, porosity and variance testing will be carried before installation into the Eco-Car.
The projected mass of the Ti-6-4 metal printed Steering Arch is 857.0 [g] saving 16% compared to the original design, which was an already very light carbon-fibre part. The mass progression (Table 5 below) through the whole process was as follows:

<table>
<thead>
<tr>
<th>structure</th>
<th>mass [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>original carbon structure with inserts</td>
<td>994.16</td>
</tr>
<tr>
<td>structure reverted to solid titanium</td>
<td>2805</td>
</tr>
<tr>
<td>titanium structure topology optimized</td>
<td>1630</td>
</tr>
<tr>
<td>polyNURBed solution</td>
<td>1840</td>
</tr>
<tr>
<td>latticed structure</td>
<td>752</td>
</tr>
<tr>
<td>smoothed lattice structure</td>
<td>857</td>
</tr>
</tbody>
</table>

Table 5, mass progression of C-Bracket design.

5. CONCLUSIONS

In this work, two case studies of topology optimized and latticed optimized components were presented. These case studies demonstrated the topology optimization process, with its challenges and practical aspects. The bracket was produced successfully and the use of microCT showed lack of major porosity and acceptable variance between computational and physical product. This process demonstrated how AM techniques can be used to further light-weight components from an already-lightweight composite option in an experimental vehicle.

The second case study (that of a steering arch) incorporated lattice optimization into a topology optimized design. The design process was outlined, especially the addition of a solid shell structure to simplify the removal of support material from the part, and also highlighted challenges encountered in a process of this nature with both current hardware and software.

A unique final smoothing phase using voxel-based image analysis software was also demonstrated including wall thickness analysis validation utilizing the same software. The steering arch is now ready for production on a large-bed additive manufacturing system, to be tested in the NMU Eco-Car, and which will be reported in future work.

REFERENCES


CONFORMAL COOLING CHANNEL DESIGN FOR DIRECT METAL LASER SINTERING OF MARAGING STEEL INJECTION MOULD INSERTS

I. Adam¹, W. B. du Preez², J. Combrinck³ and M Zwemstra⁴

ABSTRACT

The design capabilities of tool designers have been enhanced through the use of additive manufacturing in the tool making environment, by lending its greatest advantage: freedom of design. The efficiency of injection mould 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 additive manufacturing in the injection moulding industry. This paper reports on a determination of the limitations of conformal cooling channels built through Direct Metal Laser Sintering.

¹ The author was enrolled for an M Eng (Mechanical) degree in the Department of Mechanical and Mechatronics Engineering, Central University of Technology, Free State
1. INTRODUCTION

Additive manufacturing (AM) has developed a reputation as an essential manufacturing process for the production of prototype components. Often, these components are just conceptual models and are not durable for long term use. However, the development of various AM techniques as well as materials for AM use, has seen AM becoming a formidable addition to the manufacturing industry at large. Through its convenient layered build fashion AM provides virtual freedom of design and is increasingly being used as a valuable complementary technique to conventional manufacturing techniques and serves to enhance the current manufacturing environment.

An increase in global competition has seen a general trend to reduce costs and improve product quality in the injection moulding (IM) industry. The IM process requires a molten polymer to be injected into a mould, which consists of two halves that are clamped into position. The mould is allowed to cool down to a certain temperature where after the mould is opened and the solidified plastic object is ejected. In this manner geometrically similar objects are mass produced [1]. The IM process thus consists of the following phases: filling, cooling and ejection, with the cost efficiency of the process being dependent on the moulding cycle time [2].

Since cooling time contributes approximately to more than 50% of the IM cycle time, there exists a direct correlation between the manufacturing costs of plastic components and the IM cycle time [1, 3]. Hence, IM has come under scrutiny to drastically reduce the IM cycle time, thereby increasing production and ultimately increasing profits [4]. When considering a simplified heat flow equation, Equation 1, as described in Figure 1, the variable which would result in more efficient cooling is the reduction of the distance \( x_m \) between the mould cavity surface and the cooling channel [5].

\[
\hat{Q} = \frac{\gamma A}{x} (t_1 - t_2) \quad (1)
\]

In Equation 1 and Figure 1 \( Q_{in} \) is heat inserted into the system, \( Q_{out} \) heat removed from the system, \( t_1 \) is the temperature of the injected plastic, \( t_2 \) is the temperature of the cooling medium, \( \hat{Q} \) is the heat flow through the system, \( \gamma \) is the thermal conductivity coefficient of the mould material and \( A \) is the cross-sectional area through which the heat flow occurs.

![Figure 1: Deflection of a rectangular channel, showing simplified heat transfer [5].](image)

In developing Equation 2 below [6], the worst case scenario was considered, whereby a rectangular channel was loaded with the injection pressure \( P_m \) 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 \( P_m \) can be expressed by Equation 2 [6]:

\[
\sigma = \frac{P_m D_h^2}{2 x_m^2} \quad (2)
\]

Where
- \( \sigma \) = Stress experienced under the applied injection pressure
- \( P_m \) = Injection pressure
- \( D_h \) = Hydraulic diameter of the cooling channel
- \( x_m \) = Distance between the mould cavity surface and cooling channel

Through manipulation of this expression it is possible to calculate the distance \( x_m \) at which the 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, where the mould insert material will not fail. This is of importance as a current lack of published conformal cooling design criteria results in tool designers to over compensate for the mould material strength, thus sacrificing on cooling efficiency [1].
While this holds true, another option of improving IM tool cooling efficiency includes making use of a mould material having better heat conduction properties. However, the physical limitations set by conventional manufacturing techniques make the reduction of this distance $x_m$ virtually impossible in tools having complex geometries. 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 of the IM tool. 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 also place cooling channels closer to the mould cavity surface, which would further enhance the cooling efficiency of the moulding cycle [3].

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. The material used in this study, maraging steel (MS1 powder) has excellent mechanical properties in the as-built state. The MS1 properties as specified by the supplier, EOS [7], compare well with the DIN/EN (1.2312) specification (40CrMnMoS8-6) [3, 8, 9]. Maraging steel, an iron-nickel steel alloy, is well known for a combination of good material properties such as high strength, high toughness, good weldability and dimensional stability during aging heat treatment. This superior strength, hardness and toughness is achieved by aging the martensitic phase, making maraging steel ideal for high strength applications as required by the aircraft industry as well as the tooling industry. What sets maraging steels apart from conventional high strength steels, is the hardening mechanism used during the hardening process. Where maraging steels are concerned, the relatively soft body-centered cubic martensite, which is formed upon cooling, is hardened by the precipitation of intermetallic compounds at prolonged exposure to a temperature of 495°C [10,11]. It is from this martensitic aging process that the term “maraging steel” is derived.

The cooling of IM tooling is crucial to the performance of the tool set, influencing the rate of the IM process as well as the quality of the parts produced. Tool designers have always been limited to the capabilities of conventional manufacturing methods, while this is effective, the full potential of IM tool cooling systems is yet to be unlocked. The refinement of design rules for conformal cooling channels serves to further enhance the use of additive manufacturing in the IM industry. This paper reports on the development of a minimum distance $x_m$ between the cooling channel and mould wall for conformal cooling channels built through Direct Metal Laser Sintering (DMLS).

2. METHODOLOGY

In order to verify the material strength specifications of the powder supplier Electro-Optical Systems (EOS) GmbH, mechanical tests were performed on six test samples. These samples were produced on an EOSINT M280 machine at the Centre for Rapid Prototyping and Manufacturing (CRPM) in Bloemfontein, South Africa. Of the six samples, three were in an as-built state and three were stress relieved and age-hardened.

The stress-relieving process occurred at a temperature of 890 °C with a soaking time of 3 hours, while the age-hardenning occurred post stress-relieving at a temperature of 495 °C with a soaking time of 6 hours [10, 11, 12]. The resultant alloy properties were then compared with that provided by the supplier EOS [7].

In order to gain a better understanding of the mechanical test results, optical microscopy was conducted on cross sections of the specimens. The specimens were mounted, polished and etched with a 10% Nital solution, where after the optical microscopy was performed using an Axioskop optical microscope using various magnifications. Further microscopy was performed using a JEOL scanning electron microscope (SEM). Energy-dispersive X-ray spectroscopy (EDS) was conducted on an age-hardened specimen to allow for further understanding of the material compound.

With material strength verification in mind, values for the distance $x_m$ were calculated at which the mould material was expected to fail. Through the use of SIGMASOFT® virtual mould simulation software, it was possible to determine the stresses and deformation in the cavity walls due to the injection pressure. In order to determine a value for the distance $x_m$ at which the mould material would fail, a maximum plastic injection pressure of 260 MPa was used for both the theoretical calculations as well as the SIGMASOFT® virtual mould simulations. This plastic injection pressure of 260 MPa is the maximum found in the IM industry [13]. Computer Aided Design (CAD) files were generated and test inserts were produced from MS1 powder using the DMLS process, to the geometry shown in Figure 2.
In order to further verify the theoretical results, experimental test runs were done on a DKM H268T IM machine using the various mould inserts. The experimental test runs reported on in this paper could only be conducted using a maximum available plastic injection pressure of 140 MPa, which is still an acceptable injection pressure used commonly in the IM industry [13]. Table 1 shows the various conformal cooling channel diameters used in this study. These channel diameters are based on the DMLS limitations for circular holes which are perpendicular to the Z-axis of the build plate [14].

Table 1: Channel diameter considerations.

<table>
<thead>
<tr>
<th>$D_H$ (mm)</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
</table>

3. RESULTS AND DISCUSSION

3.1 Material properties

Table 2 provides a comparison between the mechanical properties determined for the test specimens built through DMLS from MS1 powder and the data as specified by the supplier, EOS [7].

Table 2: Comparison of the experimentally determined mechanical properties with the EOS data for as-built and age-hardened specimens.

<table>
<thead>
<tr>
<th></th>
<th>As-built</th>
<th>EOS</th>
<th>Test Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength (MPa)</td>
<td>1100 ± 100</td>
<td>1022 ± 35.35</td>
<td></td>
</tr>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>1100 ± 100</td>
<td>1161 ± 20.41</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>180 ± 20</td>
<td>168 ± 2.026</td>
<td></td>
</tr>
<tr>
<td>% elongation at break</td>
<td>8% ± 3%</td>
<td>7.33% ± 3.65%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Age-hardened</th>
<th>EOS</th>
<th>Test Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength (MPa)</td>
<td>1900 ± 100</td>
<td>1967 ± 10.02</td>
<td></td>
</tr>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>1950 ± 100</td>
<td>2031 ± 50.90</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>180 ± 20</td>
<td>189 ± 2.956</td>
<td></td>
</tr>
<tr>
<td>% elongation at break</td>
<td>2% ± 1%</td>
<td>3.93% ± 2.797%</td>
<td></td>
</tr>
</tbody>
</table>

The yield strength (YS) of the DMLS specimens in the as-built state is approximately 78 MPa lower than the EOS specification, while in the age-hardened state the YS is approximately 67 MPa higher than the EOS specification. The ultimate tensile strength (UTS) is 61 MPa higher than the EOS specification in the as-built state and 81 MPa higher in the age-hardened state. In the as-built state, the Young’s modulus (E) is approximately 12 GPa lower than the specification, while in the age-hardened state it is approximately 9 GPa higher. However, given the measurement uncertainty shown in Table 2, the experimental values lie within the EOS specified range.

The microstructures shown in Figures 3(a) and (b) highlights the microstructure of the test specimens in an as-built and an age-hardened state, respectively. In the as-built state (Figure 3(a)), a microstructure is presented which shows the typical DMLS layered tracks. From the observed microstructure it is evident that the metal powder fused thoroughly and an almost parabolic edge characterized the solidification pattern of each track of the molten powder. From this it can be deduced that each layer solidified on the underlying layer, with the laser tracks overlapping each other, thereby reducing any porosity [15].
Figure 3(b), shows the microstructure in the age-hardened state in which the track boundaries shown in Figure 3(a) are no longer visible and a more homogenous microstructure appears to have formed. This can be as result of the stress-relieving annealing heat treatment which occurred prior to the age-hardening. In this treatment the specimens were soaked at a temperature of 890°C for 3 hours.

Point A in Figure 3(b) is a typical precipitate formed during the age-hardening process, of which the material composition was analysed using the EDS technique. Table 3 shows the material composition of this precipitate in the age-hardened state as acquired through EDS analysis.
Table 3: Material composition of a precipitate in the age-hardened DMLS MS1 maraging steel.

<table>
<thead>
<tr>
<th>Elements</th>
<th>%wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>63.54</td>
</tr>
<tr>
<td>Ni</td>
<td>16.76</td>
</tr>
<tr>
<td>Co</td>
<td>9.38</td>
</tr>
<tr>
<td>C</td>
<td>5.71</td>
</tr>
<tr>
<td>Mo</td>
<td>3.8</td>
</tr>
<tr>
<td>Ti</td>
<td>0.83</td>
</tr>
</tbody>
</table>

From Table 3, it is evident that the detected percentages of Ni, Co, Mo and Ti confirm that this precipitate has a composition of 16Ni9Co4MoTi, which is typical of an age-hardened maraging steel [9]. The 63.54 wt % Fe is from the surrounding steel matrix.

As expected from the age-hardening process, there is an increase in both the YS and UTS when comparing the as-built data with the age-hardened data. This is as a result of the hardening mechanism acting in the age-hardening process, whereby the material is hardened by the precipitation of intermetallic compounds during prolonged exposure to a temperature of 495°C [3,4]. An increase in Young’s modulus to 189 GPa after applying the heat treatment was observed. This increase in Young’s modulus is as a result of the formation of Ni3(Mo, Ti) precipitates, which restricts the homogenous distribution of nickel in the martensitic matrix [16]. The decrease in ductility indicated by the increase in Young’s modulus is further confirmed by the reduction of the percentage elongation from 7.33 % in the as-built state to 3.93 % in the age-hardened state.

Figure 4 shows typical SEM secondary electron images (SEIs) of the fracture surfaces of as-built and age-hardened DMLS MS1 tensile specimens. The as-built specimen shown in Figure 4(a) fractured after substantial plastic deformation, in which the formation of dimples, typical of ductile fracture, is observed. Figure 4(b) shows a SEM image of the fracture surface of the test sample which was age-hardened. On the latter fracture surface micro-cavities are observed which are indicative of the presence of precipitates expected in the age-hardened metal.
(b) Inter- and trans- granular fracture in the age-hardened specimen.

Figure 4: SEI images of fracture surfaces of the DMLS MS1 as-built and age-hardened tensile specimens.

3.2 Distance between mould surface and cooling channel

By manipulating equation 1, it was possible to calculate a value for $x_m$ at which the mould insert material was predicted to fail. Since the strength specifications were within the specifications of the supplier EOS, it was decided to make use of the data provided by EOS, because it was readily available to designers. This approach would be more conservative than using the experimentally obtained mechanical test properties.

By applying a maximum plastic injection pressure of 260 MPa and using the UTS for age-hardened MS1 (1950 MPa), the value of $x_m$ was calculated as follows:

For $D_H = 4$ mm:

From (1):

$$\sigma = \frac{P_m D_H^2}{2 x_m h}$$

$$x_m = \frac{P_m D_H^2}{2 \sigma_{UTS}}$$

$$\approx 1 \text{ mm}$$

Table 4 provides values of $x_m$ for the various channel diameters at which the mould material was expected to fail. In order to achieve a comparable safe distance for $x_m$, various distances were simulated and tested experimentally. These distances were determined by increasing the calculated distance where $x_m$ was expected to fail (1 mm) by increments of 0.5 mm.

Table 4: Calculated values of $x_m$ for the selected channel diameters

<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>

Figure 5 shows the simulated stress distribution experienced by the mould inserts having a conformal cooling channel cross-section of 4 mm in diameter.
From Figure 5 it was observed that the maximum pressure exerted on the cavity wall was 19.13 MPa as highlighted in green on the insert with a distance $x_m$ of 1mm.

The insert experiencing the least pressure on the mould cavity surface, was the insert having a distance $x_m$ of 2.5mm, where the maximum pressure exerted on the mould wall is observed to be 9.58 MPa as indicated in turquoise in Figure 5.

Figure 6 shows the stress experienced by the mould inserts having a conformal cooling channel with a cross-section of 6 mm in diameter. It is observed that the maximum pressure exerted on the mould wall was 38.61 MPa as highlighted in orange on the insert having a distance $x_m$ of 1.5 mm. The insert experiencing the least pressure on the mould cavity surface, was the insert having a distance $x_m$ of 3 mm, where the maximum pressure exerted on the mould wall was observed to be 19.34 MPa as indicated in light green in Figure 6.

Figure 7 shows the stress experienced by the mould inserts having a conformal cooling channel with a cross-section of 10 mm in diameter.
Figure 7: Stress experienced by 10 mm conformal cooling channels.

It is observed that the maximum pressure exerted on the mould wall was 95.3 MPa as highlighted in green on the insert having a distance $x_m$ of 2.5 mm. The insert experiencing the least pressure on the mould cavity surface, was the insert having a distance $x_m$ of 4 mm, where the maximum pressure exerted on the mould wall was observed to be 23.8 MPa as indicated in turquoise in Figure 7.

The data acquired through SIGMASOFT® virtual mould simulation software indicates that under an injection pressure of 260 MPa the inserts underwent deflection on the mould cavity surface which is greater than the applied minimum distance $x_m$, as shown in Table 5. It is thus evident that at this deflection the mould material will fail.

Table 5: Deflection of mould cavity surfaces under an injection pressure of 260 MPa.

<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>
<tr>
<td>Deflection (mm)</td>
<td>1.4</td>
<td>1.6</td>
<td>2.1</td>
<td>8.3</td>
</tr>
</tbody>
</table>

From the results obtained through SIGMASOFT® virtual mould simulation software, it is evident that the inserts having conformal cooling channels placed further away from the mould surface experiences significantly less stress. It was also noted that the inserts experienced some stress at the outlet of the mould gate as a result of the shear experienced by the injected plastic due to the sudden change in flow direction. This stress can be neglected as it does not influence the deformation of the cavity surface where the cooling channels are placed.

Figure 8 shows the deflection on the inserts having a 4 mm conformal cooling channel as obtained through the use of SIGMASOFT® virtual mould simulation software. It is seen that for an insert having a minimum distance $x_m$ of 1 mm, the predicted deflection was 0.00067mm under an injection pressure of 140 MPa. Through IM trials with this insert it was shown that the insert having a 4 mm conformal cooling channel with a minimum distance for $x_m$ of 1 mm showed little to no displacement under an injection pressure of 140 MPa, which coincides with the results acquired from SIGMASOFT® virtual mould simulation software.
Figure 8: Deflection experienced by 4 mm conformal cooling channels under an injection pressure of 140 MPa.

From this it was possible to deduce that a safe minimum distance for $x_m$ for a channel having a $D_H$ of 4 mm under an injection pressure of 140 MPa is 1 mm. The results yielded by the experimental tests verified that SIGMASOFT® virtual mould simulation software is indeed a valuable tool which can be used to aid the design process.

4. CONCLUSION

The metallography conducted indicated the use of stress relieving followed by age-hardening to be beneficial to this application of MS1 components produced using the DMLS process. The microstructure of the age-hardened samples was indeed a homogenous precipitation hardened structure.

From the IM trials with an insert having a 4 mm conformal cooling channel it became evident that the theoretical calculations as well as experimental results verified the reliability of the SIGMASOFT® virtual mould simulation software. This confirmed that this simulation software could be a valuable tool to augment the IM mould design process.

Although the SIGMASOFT® virtual mould simulation software predicted the pressure exerted on the mould wall, as well as the displacement, it could not predict whether any plastic deformation would take place. This need to be determined experimentally. Further experimental tests have to be conducted for channels having a $D_H$ of 6, 8 and 10 mm.

ACKNOWLEDGEMENTS

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