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ADVANCES IN Ti6Al4V ADDITIVE MANUFACTURING IN SOUTH AFRICA

W B du Preez[1] and G Booysen[2]
[1]Department of Mechanical and Mechatronics Engineering
[2]Centre for Rapid Prototyping and Manufacturing
Central University of Technology, Free State, Private Bag X20539, Bloemfontein 9300, South Africa

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Abstract

South Africa has the potential to add significant value to its titanium natural resource. Initiated by a National Research and Technology Foresight Project in 1999, a national consensus has grown regarding this beneficiation opportunity. It culminated in the establishment of the Titanium Centre of Competence in 2009. Additive manufacturing was included as technology platform of the Titanium Centre of Competence. In 2013 the Department of Science and Technology commissioned the development of a South African Additive Manufacturing Technology Roadmap.

This paper elaborates on the growth of additive manufacturing in South Africa, emphasising the successes achieved with producing customised medical implants from Ti6Al4V powder. Examples of internationally leading work on such implants in maxillofacial reconstructive surgery are given. The national Collaborative Programme in Additive Manufacturing and the sub-programme on qualification of Ti6Al4V medical implants and aerospace parts produced through additive manufacturing, are discussed. Initial achievements of this programme are shared.

Introduction

From its position as the world's second largest producer of titanium raw material, South Africa has the potential to add significant value to this natural resource. Following on initial recommendations in the 1999 Mining and Metallurgy report of the National Research and Technology Foresight Project, commissioned by the Department of Arts, Culture, Science and Technology [1], throughout the following decade a national consensus grew regarding this beneficiation opportunity. It culminated in the development of a national Titanium Metal Industry Strategy by the Department of Science and Technology (DST), and the establishment of the Titanium Centre of Competence (TiCoC), as implementation vehicle of this strategy, in 2009 [2]. By that time additive manufacturing (AM) had been identified as one of the technology platforms to be pursued by the TiCoC. In 2013, following on the need for a national additive manufacturing plan expressed by the Rapid Product Development Association of South Africa (RAPDASA) [3], the DST commissioned the development of a South African Additive Manufacturing Technology Roadmap.

This paper elaborates on the growth of additive manufacturing in South Africa, with particular emphasis on the successes achieved with producing customised medical implants from Ti6Al4V (ELI) powder. Examples of internationally leading work on applying such implants in maxillofacial reconstructive surgery are given. The emergence of the national Collaborative Programme in Additive Manufacturing and the prominence of the sub-programme on qualification of Ti6Al4V medical implants and aerospace parts produced through AM, are discussed.

Additive Manufacturing in South Africa

Since the first introduction of AM to South Africa in the early 1990s (a 3D Systems SLA 250 in 1991 and two Stratasys FDM 1500 systems in 1994), AM has become very well established in South Africa. The history and growth of the technology was described by De Beer [4] and Campbell, De Beer and Pei [5]. Figure 1 shows the acceleration in the acquisition of AM systems in South Africa since 2010, after the first years of slow growth.

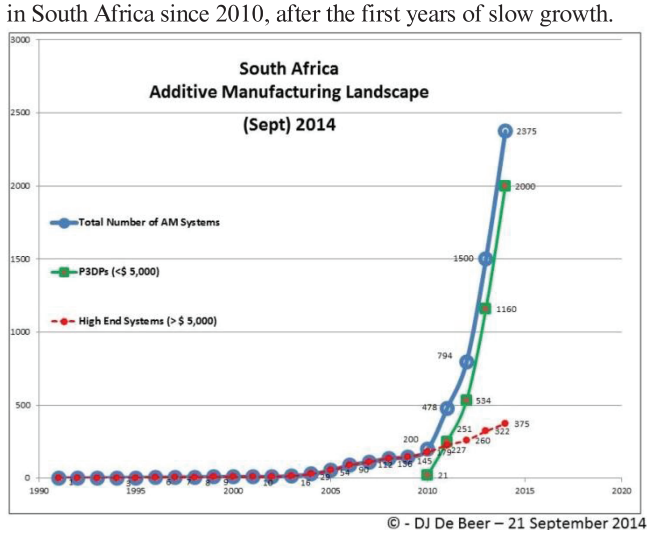

Figure 1: Growth in number of AM systems in South Africa [6]

From Figure 1 it is clear that the bulk of this growth can be attributed to the application of lower cost 3D printers (P3DPs) in industry and by individuals. Since the introduction of the first titanium AM system by the Central University of Technology, Free State (CUT) in 2007 and the establishment of the TiCoC, AM of titanium alloys has rapidly grown in prominence [3].

South Africa's Additive Manufacturing Technology Roadmap

Through an inclusive process, commissioned by the South African Department of Science and Technology (DST), led by a core team of experts in AM and involving stakeholders from industry, academia, R&D institutions and the government, a South African AM Technology Roadmap was developed [6]. Workshops were held in three of the major cities of the country in which the preliminary findings of the core team were presented to the stakeholders for consideration, changes, further inputs and endorsement. The recommendations of the AM Technology Roadmap regarding the national focus areas for future interventions in the field of additive manufacturing are presented in Figure 2 (after Figure 23 in [6]). Future decision making on investment in research and development (R&D) and implementation of AM in the South African industry will be guided by the recommendations of this Roadmap.

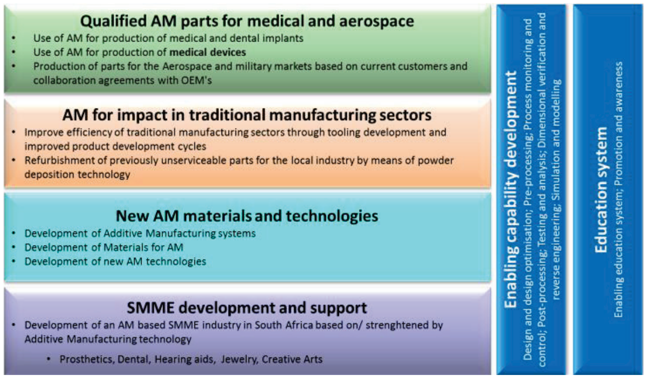

Figure 2: Focus areas recommended by the South African AM Technology Roadmap

Customised Ti6Al4V Medical Implants

Over the past decade the Centre for Rapid Prototyping and Manufacturing (CRPM) of the CUT has established itself as the South African leader in the field of applying AM to produce medical implants in Ti6Al4V.

In the Kimberley Hospital Complex, doctors successfully performed the country's first 3D-printed jaw bone implantation. The patient, a 31-year-old man from Kimberley, shown in Figure 3, was suffering from facial disfigurement due to cancer. The surgery to implant a titanium jaw was headed by Dr. Cules van den Heever, extraordinary professor at the CUT, who has extensive experience in prosthetic jaw implantations. He was assisted by Dr. Walleed Ikram, head of the Kimberley Hospital Dental Unit, Dr. Kobus Hoek, a maxillofacial surgeon, as well as Doctors Philip Johnsson and Riaan Liebenberg, both dentists at the Kimberley Hospital's Dental Department.


Figure 3: The patient suffering from facial disfigurement because of a cancer

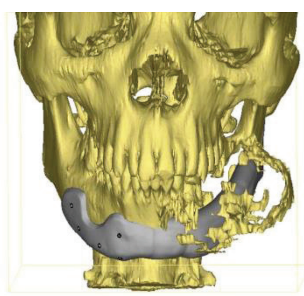
Figure 4: Design of the customised jaw implant

The implant was intended to fix the facial contour and restore its normal appearance and function. The customised jaw was designed (Figure 4) and manufactured on site at the CRPM with titanium powder (Figure 5) in an EOS M280 Direct Metal Laser Sintering (DMLS) machine. Figure 6 shows the patient one month after operation - infection free with a functional lower jaw.


Figure 5: Customised AM jaw from Ti6Al4V powder in an EOS M280 machine


Figure 6: Patient one month after operation

Another case involved a young woman from Gauteng and was planned and executed in collaboration with Dr Cules van den Heever, the company Southern Implants from Johannesburg and the CRPM. This patient presented a tumour in the upper jaw, as shown in Figure 7. Most of the upper jaw below the eyes was removed. This defective area had to be reconstructed for the patient to regain mastication functionality. An implant was designed and manufactured (Figure 8) from Ti6Al4V at the CRPM by means of DMLS.


Figure 7: Patient with a tumour in the upper jaw


Figure 8: DMLS-produced Ti6Al4V implant

A finite element analysis (FEA) analysis was conducted on the implant (fixed onto the skull) to determine the maximum displacement and stress induced [7]. The full model was analysed and the material properties of Ti6Al4V shown in Table 1 were applied to the implant.

Table 1: Properties of Ti6Al4V used in the FEA

Titanium Property	Value
Density	4430 kg/m^3
Modulus of Elasticity	120 000 MPa
Poisson's Ratio	0.33

The properties of zygomatic bone shown in Table 2 were applied to the whole skull.

Table 2: Properties of zygomatic bone used in the FEA

Zygomatic Bone Property	Value
Density	1700 kg/m^3
Modulus of Elasticity	11000 MPa
Poisson's Ratio	0.4

Due to limited time, only one 2400 N point load was applied to a concentrated area at the centre of the upper jaw, which simulated a worst-case scenario. The Von Mises stresses in the skull and the implant for the applied load are shown in Figure 9.

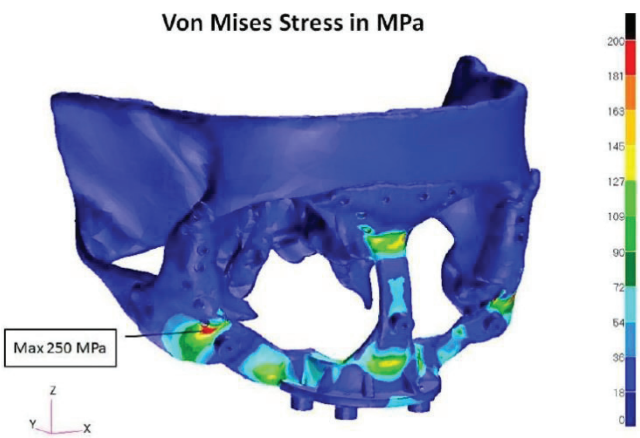

Figure 9: Von Mises stress in the skull and implant [7]

When a 2400 N point load is applied, a stress concentration occurs at the point of application. The stress concentration at this point amounts to 3000 MPa (see Figure 10). This is not a realistic stress because the load would in reality be distributed over a larger area and the stress concentration would therefore reduce dramatically. The remainder of the stresses in the implant (maximum 250 MPa) and the skull are well below the yield stress of the materials.

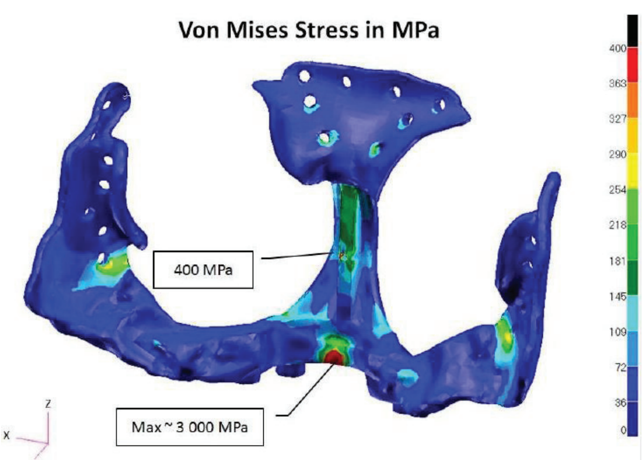

Figure 10: Von Mises stress in the implant with the point load.

A nylon drill guide (Figure 11) was also manufactured to aid the surgeons where holes for the surgical screws had to be drilled at the correct angles to hold the implant in place, while avoiding critical anatomical structures being damaged during the drilling. The titanium implant was sent to Southern Implants for cleaning and sterilization. The operation was successful and the patient received a clip-on silicone prosthesis (Figure 12).

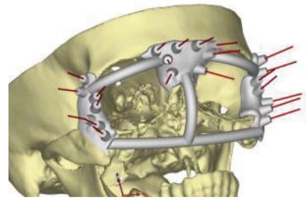

Figure 11: Nylon drill guide designed and manufactured by CRPM

Figure 12: Patient after operation with clip-on silicone prosthesis

In a more recent case, conducted in early 2015, a patient diagnosed with cancer in half of the top jaw, had to undergo an operation to remove the hemi-maxilla and orbital floor. Due to the extent and complexity of the defect, it was decided to fabricate an anatomical model of the hard tissues for planning a possible fabrication of a Ti6Al4V laser sintered framework for the patient. Computer Tomography (CT) was used as a starting platform and the Digital Imaging and Communications in Medicine (DICOM) files from the scanner were converted to Standard Triangulation Language (.stl) format (Figure 13) using Mimics™ dedicated software from Materialise. The software allows altering the grey scale values from the DICOM images to differentiate between soft tissue and bone.

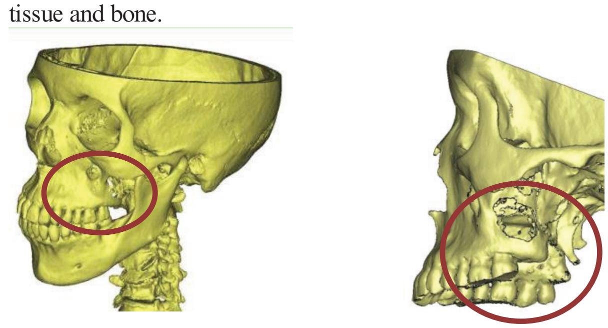

Figure 13: CT conversion to .stl format

The region of interest was then masked and calculated as a 3D model, which was exported as an .stl file, sliced using RP Tools, and sent to the AM machine to manufacture the planning models. The CRPM did the CT segmentation of the skull and produced the 3D model in an EOS P385 Laser Sintering machine in PA 2200 polyamide material at 150 µm layer thickness (Figures 14 and 15).

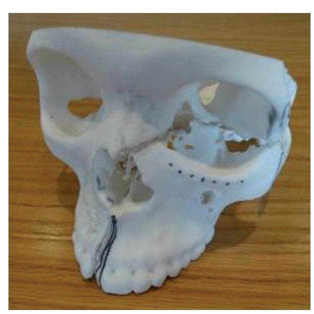

Figure 14: Skull manufactured in PA 2200 polyamide material

Figure 15: Nylon model cut where the bone resection was planned

The CRPM had only two weeks to design and manufacture the Ti6Al4V implant, due to the severity of the cancer. It was decided to send the 3D model to the surgeon to cut the nylon model where the bone resection was planned. Furthermore, the prosthodontist made a wax model of the planned titanium frame (Figure 16). The wax model and skull were reversed engineered using a Minolta 3D camera and Geomagic® software (Figure 17).

Figure 16: Wax model of the planned titanium frame

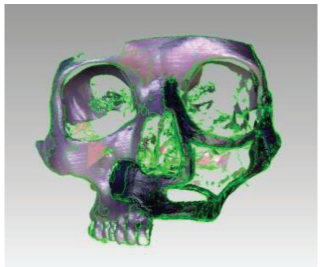

Figure 17: Reverse Engineering data in Geomagic® software

The reversed engineered geometry was used to identify the boundaries and fixation areas of the planned implant. The 3D data was imported into 3-MATIC® (from Materialise) in order to design the implant (Figure 18).

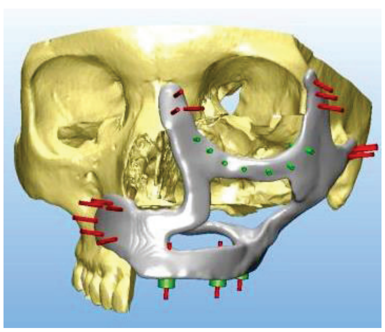

Figure 18: Implant design done on 3-MATIC®

The implant design was exported as an .stl file, which was converted to a slice file and transferred to an EOS M280 DMLS machine. The implant was manufactured from a biocompatible Ti6Al4V (ELI) powder of sub-40 µm particle size (Figure 19). The DMLS implant was removed from the titanium substrate. The support structures were removed and the implant was manually polished. The implant's fitment was checked on the pre-operative model (Figure 20).

Figure 19: DMLS implant in Ti6Al4V

Figure 20: Checking the implant's fitment on the pre-operative model

A cutting guide (Figure 21) was designed and manufactured in nylon on the EOS P385 machine. The surgeons used this guide to remove the affected bone at the correct angles.

Figure 21: AM nylon cutting guide

Figure 22: DMLS Ti6Al4V prosthesis in position as successfully implanted

The DMLS titanium prosthesis was successfully implanted during a nine-hour operation (Figure 22). The patient was transferred to the Intensive Care Unit and a week later to a general ward. The post-operative review was good and many valuable lessons were learned from this case study.

Challenges encountered with DMLS implant manufacturing

The DMLS process uses a cold bed platform which induces high residual stress in the manufactured part. The parts need to be stress relieved at 650°C in a argon atmosphere while still fixed on the titanium substrate. Initial research showed that between 76 to 81% of the residual stress can be removed with this stress relieving cycle [8]. In this study the researchers used recrystallizing, duplex and beta-annealing processes to further remove the residual stress to levels up to 97%. As-grown the parts are still too brittle for medical use and need to be heat-treated at 1000°C to increase the elongation to above 10%, as required for medical implants. Further in-depth research needs to be conducted to fully quantify residual stresses, as well as optimise stress relieving and heat-treatment cycles.

In the current practice the part integrity is tested by scanning all the implants using X-ray micro computer tomography (microCT). For this a commercial system from the Central Analytical Facilities at Stellenbosch University (SU), a General Electric Phoenix V|Tome|X L240, is used. X-ray settings are 180 kV and 160 µA, using a directional X-ray source. This is done to detect any microscopic voids and cracks that could cause implant failure under fatigue. Furthermore, test pieces for destructive testing (Figure 23) are manufactured on the same platform as the implants and are tested in as-grown and heat-treated state.

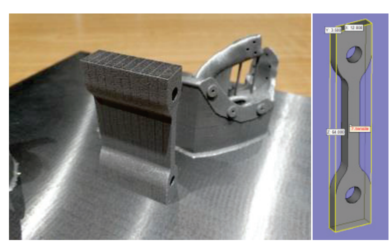

Figure 23: Test pieces for destructive mechanical testing

Although ultimate tensile and yield strength properties meeting standard specifications for Ti6Al4V wrought material, are generally achieved for these implants, fatigue properties have not been shown to meet these specifications.

Collaborative Program in Additive Manufacturing

In a pro-active response to the findings of the SA AM Technology Roadmap, R&D leaders from South African universities leading in AM (CUT, SU, Vaal University of Technology (VUT) and North West University (NWU)) in collaboration with the National Laser Centre (NLC) at the CSIR and a leading aerospace manufacturer, Aerosud, developed an R&D program aimed at aligning with a number of the focus areas recommended by the Roadmap. A key part of this collaborative R&D program deals with the qualification of AM of Ti6Al4V for medical implants and aerospace components. This is based on the realisation that acceptance of AM for applications in these important industry sectors can only be expected if in-depth understanding of the ability of the technology to meet the required material standards, supported by extensive data, is established. The second part of the program aims at growing the expertise and establishing novel approaches in the field of design for AM, while the third sub-program focuses on developing polymer AM processes to meet the industry standards applicable to parts manufactured from polymers.

This Collaborative Program in Additive Manufacturing was successfully submitted to the DST for funding and towards the end of 2014 the DST contracted the CSIR to manage the national implementation of this program over the following two and a half years.

The program was launched at the beginning of 2015 with the initiation of thirty masters and doctorate level projects at the collaborating universities. To ensure a similar material basis for all the projects, AM powder was purchased from a supplier approved by all the collaborators. On receipt, this powder will be fully characterized, where after experimental AM parts for the projects will be built in two selective laser melting (SLM) systems, i.e. the EOS M280 (200W) at the CRPM of the CUT, and the Concept Laser M2 system at SU. Similar parts will be built in the powder blown Optomec 850R laser engineering net shaping (LENS) system of the NLC. These experimental parts will be extensively tested and analysed in as-built condition, as well as in as-built followed by post-processing treatment condition, in the different projects run simultaneously across the country. The results from these projects will be interpreted and the findings shared among the collaborators. In this way a national pool of fundamental understanding and competence in this field of AM will be established in South Africa.

Conclusion

The establishment and growth of AM in South Africa over the past two decades, as well as the national program to establish a South African Titanium Metal Industry, have resulted in novel and cutting-edge work on designing and building customised Ti6Al4V implants for surgical reconstruction. The recent development and publication of the South African Additive Manufacturing Technology Roadmap has provided strategic focus and direction to the country's research and development, as well as transfer of AM technology to industry. Recognising the imperative to fully qualify the AM processes used for industrial applications, a South African consortium of universities and industry has embarked on a government funded program to achieve this. This program has been launched and promises to significantly deepen and strengthen the South African expertise and competence in applying AM in the medical implant and aerospace industries.

Acknowledgement

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