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Evaluation of titanium alloy fabricated using electron beam melting and traditional casting technique.

Khaja Moiduddin[1,2,3]*, Abdulrahman Al-Ahmari[1,2,3], Emad S. Abouel Nasr[3,4], Mohammed Al Kindi[5], Mohammed Hamid[1,2]

[1]Princess Fatima Alnijiris's Research Chair for Advanced Manufacturing Technology (FARCAMT), King Saud University, Riyadh- Saudi Arabia

[2]Advanced Manufacturing Institute (AMI), King Saud University, Riyadh- Saudi Arabia

[3]Industrial Engineering Department, College of Engineering, King Saud University, Riyadh- Saudi Arabia

[4]Mechanical Engineering Department, Faculty of Engineering, Helwan University, Cairo-Egypt

[5]College of Dentistry, King Saud University, Riyadh-Saudi Arabia

Abstract

Purpose: Recent advances in the field of medical industry have encouraged the surgeons and researchers to find alternative ways in the fabrication of implants. The average life of an implant depends on the implant material, its fabrication and patient fixation type.
Approach: Implants produced through casting are of standard shapes and sizes. Moreover, it involves several steps that increase the production cost and time. Alternatively, it is possible to produce custom design implant with Additive manufacturing technology in lesser amount of time with no material wastage.
Objective: The objective of this research is to outline the manufacturing technologies, involved in the fabrication of reconstruction plates and compare the mechanical properties between them.
Finding/Results: The results show a significant difference between the reconstruction plates produced through Electron beam melting (EBM) an additive manufacturing technology and commercial produced casting technique. The EBM produced plates has marginally higher tensile strength of 608 MPa when compared to the commercially available casting plate with the strength of 557 MPa.
Conclusion: The EBM is an effective technology exhibiting favourable results in fabricating customized reconstruction plates with better mechanical properties when compared to traditional fabrication methods. EBM produced implants decreases the implant failure and concomitantly reduces the number of revisions thus eliminating the psychological stress and pain of the patients.

Keywords: Electron beam melting, Ti6Al4V ELI, Reconstruction plates, Casting, Mechanical properties.

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Introduction

Each year, thousands of people undergo reconstruction surgery with metal implants. Among various metal implants, titanium is the most common. Titanium (Ti) and its alloys are one of the best suited materials for the medical implants because of its inertness, low weight, ease of production, lack of toxicity, superior mechanical properties, corrosion resistance, and modulus of elasticity closer to that of bone [1-3].

The majority of commercially available pure titanium (Cp Ti) implants has been processed variously using casting and wrought techniques [4,5]. Several commercial available reconstruction plates with various sizes are available in the market. Casting involves several steps that increase cost and production time. This traditional method of manufacturing implants has many drawbacks because it makes compromises in the design. Micro bubbles in the cast metal are one of the common weak points in the prosthesis [6,7]. During surgery, most of the prefabricated plates are shaped by hand-forming techniques to match the patient's anatomy [8]. A true passive implant fit in casting technique is difficult to achieve due to polymerization shrinkage and expansion of the material. Commercially available plates can develop frequent problems because they are manually bent prior to surgery and do not easily match the requirement of facial contours [9]. The prospects of fabricating custom-designed parts using titanium alloys, which are known to be a troublesome metal in machining and casting, drew an attention to the medical and dental community.

The Additive manufacturing (AM) process revolutionized the fabrication process in the medical industry with its unique technique of layer upon layer of metal deposition. AM is also referred as Free from fabrication, Rapid prototyping and 3D Printing etc. Electron beam melting (EBM) is an AM technology, which fabricates custom designs implants from Ti6Al4V ELI (grade 23) powder based on the computer-aided-design (CAD) model.

EBM, unlike traditional manufacturing, does not have any shape restrictions and generates less wastage when compared to most of the traditional methods. Previous studies have shown a 35% cost reduction for EBM produced reconstruction plates when compared to the conventional methods [10]. EBM produced implants eliminates the challenges faced in producing the commercial implants through machining and investment casting. The EBM process takes place under vacuum environment which eliminates the defects caused by oxidation. Previous studies have proved EBM as a valid option for custom designed implants in orthopaedic, craniofacial and maxillofacial surgeries [11-13].

In this study, reconstruction plates are fabricated using EBM from the Ti6Al4V ELI powder and their mechanical properties are compared with that of the commercially available casting plates. The purpose of this research is to investigate the potential application of EBM in the fabrication of customized reconstruction plates which can reduce the surgical time and provides best form, fit and function for a better quality of life to the patients.

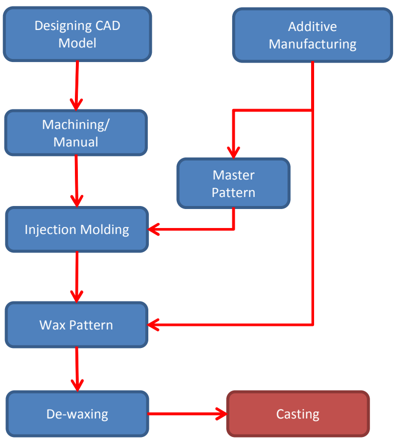

Figure 1. Flowchart of Rapid casting process.

Materials and Methods

The commercially available reconstruction plates (implants) are made of commercial pure titanium (Cp Ti, ASTM Grade 2). They are widely used as the load bearing implants in maxillofacial and orthopaedic regions. Cp Ti implants are almost similar or more superior to wrought products with enhanced crack propagation and creep resistance properties [14]. In the casting process, a wax model is extracted from silicon die which is then used in the investment casting for the production of implants. One of the major developments in the medical industry is the adoption of engineering principles in the form of CAD and Computer aided manufacturing (CAM). Currently, solid freeform fabrication or Rapid Prototyping (RP) process is used to produce directly or indirectly a master pattern for the forging, investment or wax casting [15,16]. Rapid casting technology is the combination of RP and traditional casting process. The flowchart of rapid casting technology is illustrated in Figure 1.

One of the major challenges in casting process is the fabrication of complex shapes. Moreover it has distinct mechanical limitations such as non-uniform microstructure and lower mechanical strength [17]. Figure 2 illustrates the flowchart of transforming the standard reconstruction plates (Figure 2a) into a patient specific plate (Figure 2e) used in mandibular surgery. The standard size reconstruction plates are cut (Figure 2b and bend Figure 2c) at one of the notches using cutting pliers and bending tools to match the patient's jaw. The cutting and bending of the reconstruction plates to match the facial bone contours are a manual operation prior to surgery and any mismatch between the plate and bone interface results in implant revision and failure.

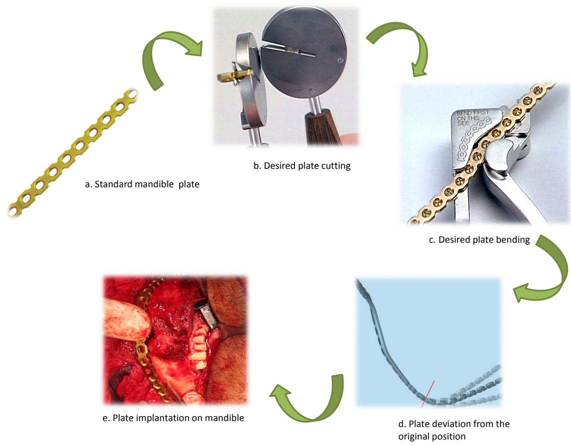

Figure 2. Commercial reconstruction plate and its implant on the mandible jaw.

The commercial available reconstruction plate is subjected to Energy-dispersive x-ray (EDX) analyses to obtain the elemental composition of the plate. EDX is done using JSM -6610LV scanning electron microscope to find it as pure titanium with more than 99.9% titanium (Figure 3). The reconstruction plate is supplied from a reputed company and due to intellectual property and trademark reason; we are unable to disclose the name of the company.

Additive manufacturing process

Additive Manufacturing (AM) is an emerging technology which has revolutionized the fabrication process. AM has improved the field of prosthetics and implantation. The EBM is a patent protected technology provided by ARCAM and approved by the US Food and Drug Administration (FDA) for the fabrication of medical implants [18]. It is a metal powder based process which produces fully dense parts with strength-to-weight, reducing the material cost and the component weight. The material Ti6Al4V ELI in the powder form of 50-100 microns is used in the EBM process, supplied by Arcam. Ti6Al4V ELI is the highest purity version because of a combination of high strength, light weight, good corrosion resistance, good fatigue strength, low modulus and high toughness [19,20]. The chemical composition is in the form of Aluminium-6%, Vanadian-4%, Carbon-0.03%, Iron–0.1%, Oxygen-0.1%, Nitrogen-0.01%, hydrogen<0.03% and the rest Titanium. The material Ti6Al4V ELI provides improved ductility and better fracture toughness when compare to Ti6Al4V. EBM manufactured parts using Ti6Al4V ELI material, possess microstructure properties better than cast Ti6Al4V ELI with a higher density and significantly finer grain structure [21].

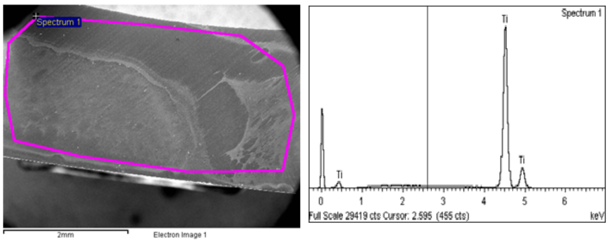

Figure 3*. EDX analysis on commercial reconstruction plate.*

The schematic overview of the EBM machine is illustrated in Figure 4b. The EBM machine consists of two main cabinets-electrical control cabinet and the build cabinet. The electrical cabinets consist of circuits, power suppliers, central processing unit, keyboard, LCD touch screen and programmable logic controllers. The build cabinet consist of two sections. The upper section is the electrical beam column and lower section is the build chamber. The electrical beam column consist of cathode assembly, anode cup, focus coils, deflection coils and astigmatism coils. The build chamber houses all the mechanical parts which include the powder hoppers, raking system, powder table and the build tank. The part is fabricated in the build chamber.

In this process, the highly energetic electrons are emitted and accelerate through the anode cup when the filament is heated to above 2500ºC. These high speeds of electrons are focused and controlled by three types of magnetic coils- astigmatism coil, focus coil and deflection coil. First the accelerating electrons pass through astigmatism coil which keeps the beam of electrons in focus and in round shape. In addition, the astigmatism coil eliminates the electro-optical artifacts during the build. The focus coil sharpens the electron beam to a desired diameter. The deflection coil controls the beam to a specific target onto the powder bed. The two attach powder containers known as hoppers feeds the build table with powder periodically. The focused beam of electrons travelling at a speed of the 4000 m/s when hits the powder, the kinetic energy is transformed into thermal energy and melts the powder particles.

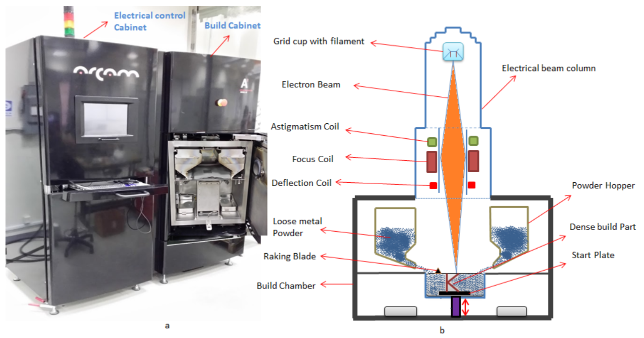

Figure 4a*. Arcam's A2 EBM machine* ***b****. Schematic overview of the EBM build cabinet.*

The melting of powder particles consists of two steps, melting the contours (outer and inner) and in-fill hatching as illustrated in Figure 5. First the contours are melted as per the boundary cross section of the 2D slice by multiple electron beams. In hatching, the beam current and the scan speed are increased to melt the area between the contours in a snaking melt strategy. Only the contours and the hatching part fuse the metal powder and leaves the rest of the powder untouched, which is recycled later. Preheating of the powder in between contouring and hatching takes place as required maintaining the build temperature to 750°C. The majority of the melting process is performed using hatching.

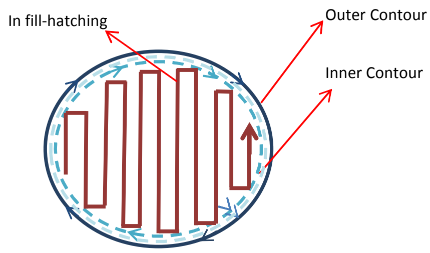

Figure 5*. Contouring and hatching during the melt process.*

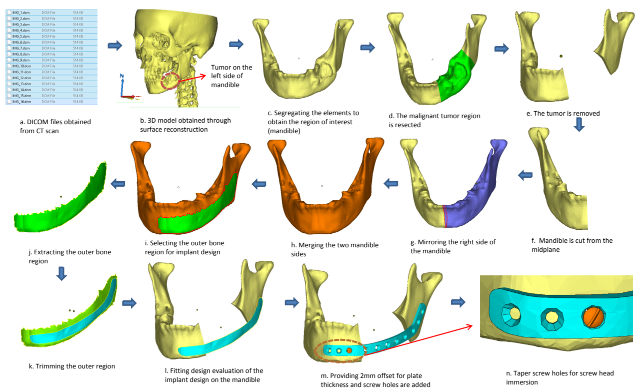

Figure 6*. Steps involved in the design of customized implant from the CT scan.*

Customized implant design process

The integration of Computer Aided Design (CAD), advanced imaging systems (CT or MRI) and additive manufacturing allows for the design, development and fabrication of customized complex structure. The customized implant provides better implant bone fitting with reduced operating time, implant revision and eliminating surgical errors. Figure 6 explains the steps involved in the design of customized implant from the CT scan. The DICOM files (Figure 6a) obtained from the CT/MRI scan are processed to obtain 3D model (Figure 6b) using medical modelling software. Segregation of the elements is done to obtain the region of interest the tumour mandible (Figure 6b). The malignant tumour region (Figure 6d-green) is resected to remove the cancerous part (Figure 6e). The mandible is then divided into two regions by selecting the midplane (Figure 6f) and the tumour side is replaced by the healthy right side (Figure 6g). Merge and wrap operation is performed to remove the gaps and to obtain a clean mandible without any tumour (Figure 6h). The outer layer of the clean mandible is selected (Figure 6i) and extracted from the mandible (Figure 6j). Trimming operation is performed (Figure 6k) and a 2 mm offset thickness is specified to obtain a customized mandible design implant (Figure 6i). The smoothing and other finishing operations are performed and taper screw holes are immersed to get the final implant design (Figure 6m). The screw holes are taper designed so that the screw head can completely sink inside the plate holes (Figure 6n). The final customized mandible implant fits perfectly on the jaw which is intended.

Fabrication of implants using EBM

In order to compare the mechanical properties of the commercial available reconstruction plate, a similar reconstruction plate CAD model is designed using CATIA. The EBM fabrication of the CAD design and the customized implant obtained from the CT scan is explained in Figure 7.

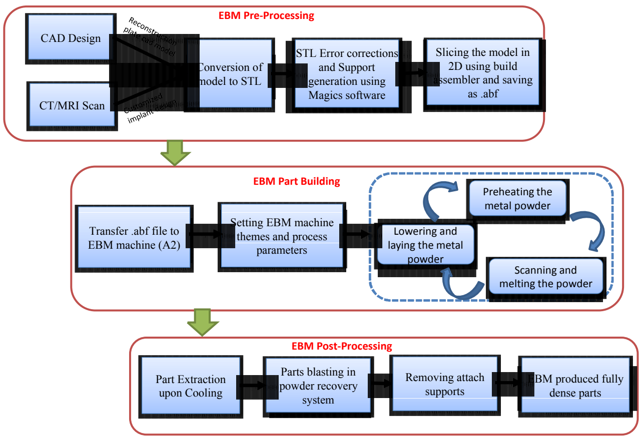

Figure 7. *EBM fabrication steps for reconstruction plates.*

The obtained STL files from CAD design and customized implant are imported into Magics® 18.03 software to treat and fix the STL errors such as overlapping and intersecting triangles, bad edges and other defects. Once the STL file is error free, proper supports are generated before slicing and simulation using EBM software build assembler®. The .abf file obtained from the build assembler® is loaded into the ARCAM A_2 EBM machine and the process parameters are defined. The EBM machine scans and melts the metal powder bed in the direction of X and Y co-ordinates. Prior to melting, the powder particles (Ti6Al4V ELI) are preheated to maintain the target temperature and to reduce the charging of the powder during the high energy-density melting stage. After melting, the powder bed is lowered and new powder is fed onto the bed using raking blades. This process of preheating, melting, lowering the platform and deposition of powder layer continues till the required physical model (reconstruction plate) is built.

The fabricated parts are then removed and blasted in the Powder recovery system (PRS) to remove the attached sintered powder on the side walls. The supports of the EBM fabricated plates are removed as shown in Figure 8 and sterilized before implantation. The EBM fabricated customized plate perfectly fits onto the bone contours without any bending or cutting process as shown in Figure 8a.

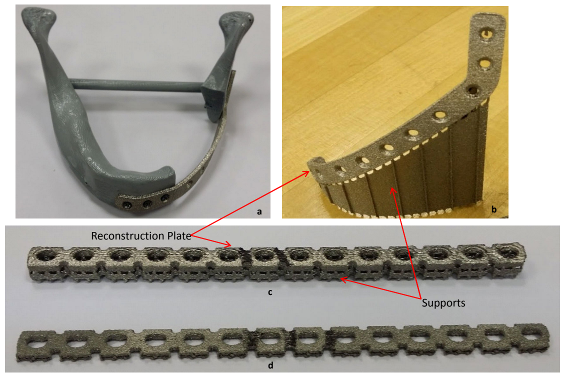

Figure 8a. *EBM fabricated customized reconstruction plate fitted to the mandible model.* ***b.*** *Customized plate with supports.* ***c.*** *EBM fabricated plates from CAD design with supports.* ***d.*** *After support removal.*

The EBM reconstructed parts are subjected to Energy-dispersive X-ray spectroscopy (EDX) analysis for chemical characterization and elemental identification. As illustrated in Figure 9.b, the peaks corresponding to the various elements in the EBM built part with Ti peaks being more pronounced than the Aluminium (Al) and Vanadium (V) as expected.

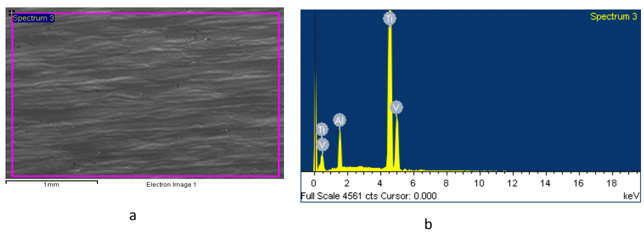

Figure 9a. *Selected area for EDX;* ***b.*** *EDX Spectrum of EBM built Ti6Al4V ELI plate.*

The overall composition of the EBM plate is given in Table 1. Based on the composition results, it can be said that the chemical composition of the EBM fabricated plate did not differ much from the original composition of the feedstock powder.

***Table 1.** Quantitative EDX analysis results of EBM produced plate.*

Element	Weight%	Atomic%
Al K	6.23	10.59
Ti k	89.87	85.91
V K	3.88	3.50

Scanning electron microscopy (SEM) analysis is performed on the EBM fabricated plate (specimen) to investigate the surface morphology. The EBM parts are prepared using grinding and polishing, and examined using JSM-6610LV machine at low magnification. The SEM image shows non-uniformly distributed spherical pores. The biggest void observed was about ~ 35 µm in diameter as illustrated in Figure 10a. These voids are due to the trapped Argon gas bubbles inside the powder particles owed to the gas atomization of the powder [22]. These small amounts of pores in the range of less than 100 µm will have no effect on the mechanical properties of the EBM built specimen [23]. These voids can be easily removed using surface treatment such as hot isotactic pressing and hydroxyapatite (HAp) coating [24].

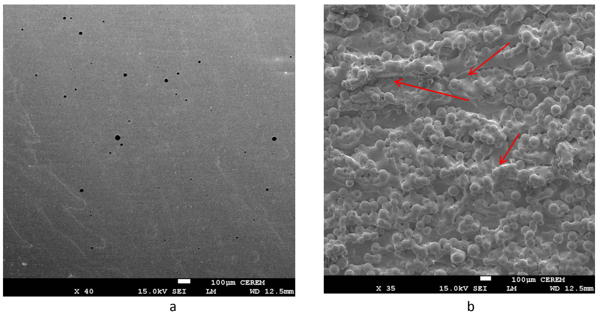

***Figure 10a.** SEM images showing Complete melt of the powder particles on the top surface **b.** Rougher side walls of the EBM built part with arrows indicating the ridges/valleys on the surface.*

It can be observed from the micrographs from Figure 10, that the specimen top surface has better surface finish when compared to the sides. The top surface of the build specimen is the last layer to be melted and solidified. The specimen side walls are always surrounded or embedded by unmelted or partially melted powder particles. These powder particles provide the rough surface on the side walls whereas the top surface which melts and solidifies does not face any problem with adjacent powder. The ridges and valleys as shown with red arrows (Figure 10b). on the side walls correspond to the stacking of the melted powder layers. However, there are various methods to improve the surface finish such as laser ablation, electro polishing etc.

Mechanical testing on reconstruction plates

Tensile tests: Three random EBM produced and Cp Ti plates (specimen) are used for tensile and hardness test. The EBM built plates and the Cp Ti specimen are of the same dimension with thickness of 2.0 mm. Zwick Roell testing machine is used for the tensile test. Three tests are carried out in each case and mean values are recorded. The results of the yield and tensile strength of the EBM produced reconstruction plate and commercial available Cp Ti plates are determined from the stress-strain curve as showed in Figure 11. The mean values of the yield and tensile strength are recorded in Table 2. Figure 12 illustrates the EBM and the commercial plates after tensile test.

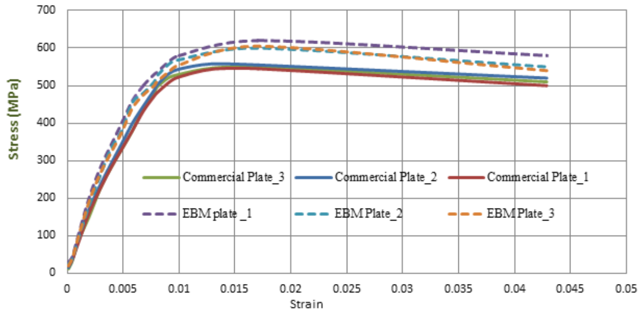

***Figure 11.** Stress-strain curve of EBM and casting produced commercial plates.*

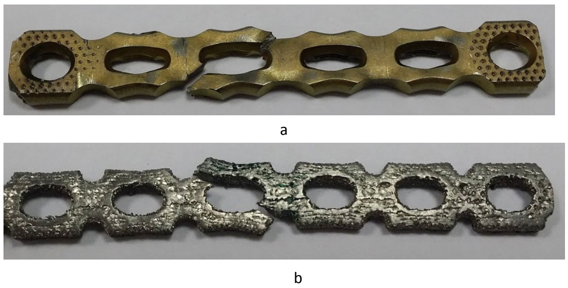

***Figure 12a.** Cp Ti specimen. **b.** EBM produced plates after the tensile test.*

Micro hardness: Rockwell hardness tests are performed on the EBM built and Cp Ti specimens to determine the resistance of material to deformation. The hardness test is determined by a WOLPERT UH930 machine using a Rockwell C-scale indentor. The specimens were first polished using water cooled sandpapers with 400, 600 and 1200 grits. The indentations were generated with a 10 kg load using a cone diamond inductor and standard indentation time was recorded as 5 Sec. Three random areas are chosen on the Cp Ti and EBM produced plates and mean values are recorded in Table 2.

Results and discussion

In this study, the material and the mechanical properties of EBM produced reconstruction plate and commercially available casting plates (Cp Ti) are investigated. The mechanical tests reveal that the EBM produced reconstruction plates have marginally higher tensile strength of 608 MPa than that of the commercially available cast plate of 556 MPa. The measured mechanical properties are in good agreement with earlier reported comparisons of EBM produced titanium and casting techniques [25,26]. However the mechanical strength is lower when compared to ASTM standards due to different geometrical dimension. The comparison is done neither on the same design reconstruction plates produced through casting and EBM nor on the ASTM standard dog bone specimen. The hardness values of the EBM produced specimen and Cp Ti plate are in accordance to the ASTM standard with almost similar results between them. These results enhance the understanding of the fabrication of reconstruction plates produced through traditional casting techniques and state-of-art EBM process.

Table 2. *Mechanical properties of EBM and commercial produced casting specimen after tests.*

Mechanical Properties	EBM built plate	Commercial plate	ASTM Standard F136
Yield Strength (MPa)	520	494	795
Ultimate Tensile Strength (MPa)	608	556	860
Rockwell Hardness (HRC)	32	31.5	

Conclusion

Titanium and its alloy due to its excellent biocompatible properties, is most widely used material for reconstruction plates. Commercially available reconstruction plates are produced through different traditional manufacturing methods involving several processing steps which therefore influence the final properties of the implantable devices. Instead of traditional processes with multiple labour intensive process steps, AM is a highly automated process. EBM unlike traditional technique have no shape restriction and can produce customized parts with lesser amount of material and with fewer steps.

The objective of this research is to establish that the EBM produced reconstruction plate's exhibits better mechanical properties when compared to commercially available reconstruction plates. The yield strength and tensile strength of the EBM produced plates was found to be 520 and 608 MPa which is better comparatively to the casting produced commercial plates. Moreover, the surface morphology on the EBM fabricated plates proves that they are free from residual stresses and internal defects. The hardness value is almost similar and within the range of ASTM standard. EBM plate due to its flexibility in customization and fabrication of light weight structures has great a potential for improvement in clinical applications. In the future we aim to focus on the evaluation of the two fabrication techniques as an *in vivo* study.

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*Correspondance to:

Khaja Moiduddin

Princess Fatima Alnijiris's Research Chair for Advanced Manufacturing Technology (FARCAMT)

King Saud University

Saudi Arabia