ADDITIVE MANUFACTURING OF INDIVIDUAL IMPLANTS FROM TITANIUM ALLOY

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Abstract

Additive manufacturing (AM) is a promising technique for producing complex parts layer by layer from different metal alloys. Selective Laser Melting (SLM) consists of melting a previously formed powder layer by laser and fusing layers together according to the CAD-data. SLM is a promising method for producing custom-made implants from titanium powders due to the possibility of creating geometrically complex parts with high mechanical properties directly from the CAD-file.

In the presented work, a hip implant was manufactured by SLM from plasma atomized Ti-6Al-4V powder. Computer-tomography data of the patient's deformed bone structure was used for 3D-printing the patient's hip bone model from polyamide. Then an implant prototype was made from polymer accounting the anatomical features of the patient. The implant model was 3D-scanned to obtain a CAD-file of the implants, which was further improved using CAD-software by partial texting of its surface. Titanium implant was produced by SLM and then annealed to achieve the better combination of tensile strength and elongation by partial decomposition of martensitic phase, which allowed the mechanical properties of the produced material meet the requirements of ASTM F2924 for additively manufactured Ti-6Al-4V alloy and ISO 5832-3 Implants for surgery from titanium 6-aluminum 4-vanadium alloy. The hip implant has been successfully installed to the patient. The postoperative supervision has shown a good result. Applying AM for producing the custom hip implant allowed decrease the operation time and lessen the risk of the infection ingress.

Keywords: Additive manufacturing, selective laser melting, titanium powder, laser processing

1. INTRODUCTION

Additive manufacturing (AM) technologies combine the use of digital design for creating a 3D-model of the part and producing the part by adding layers of material using different techniques. AM allows making not only prototypes, but fully functional components for aerospace, automobile industry, medicine and etc. [1, 2]. Given the layer-by-layer manufacturing manner, complex-shaped parts can be made without using additional tooling and joins. The SLM is one the most promising and used methods among metal AM techniques. The SLM consist of forming powder layers, melting them with a laser and fusing with the previous layer according to the CAD-data. Owing to the fully melting of powder particles, the produced parts have a high relative density close to 100%, and high cooling rates typical for this method [3, 4] induce fine-dispersed microstructure and high mechanical properties [5].

Titanium alloys, and Ti-6Al-4V in particular, are widely used in different industries. One of the applications of Ti-6Al-4V alloys is manufacturing of medical implants due to its high biocompatibility and a combination of mechanical properties [6, 7]. Since SLM technology allows manufacturing near net-shape parts with complex geometry, it is possible to make custom-made implants for each specific patient while also texturing the implant's surface with a lattice structure for better osseointergration.

The endoprosthesis replacement is one of the most successful techniques for surgical treatment of patients with injuries and hip joint diseases. The demand for endoprosthesis replacements is increasing globally [8].

Despite of high efficiency of the endoprosthesis replacement, a high percent of patients requires a revision surgery after 10-15 years after the first implantation [9].

In this paper the possibility of producing individual acetabular revision systems for carrying out a revision endoprosthesis replacement of a hip implant made of Ti-6Al-4V alloy by using AM and the computer data of the patient's bone configuration acquired by CT.

2. EXPERIMENTAL DETAILS

CT-data of the patient's hip-bone structure in DICOM file-format was used to make a physical model of the patient's hip-bone, which was manufactured by Selective Laser Sintering (SLS) from polyamid powder using 3D Systems Sinterstation HiQ+HS machine. After making a polyamid model of the patient's bone the design of the implant configuration was carried out using CAD-software. Owing to severe deformations of the hip-bone the physical model of the implant was made out of polymer clay taking into account the anatomical features of the patient. The implant later was 3D-scanned using Faro Platinum Arm scanner to obtain a CAD-file of the implant. After that the configuration of the implant was further improved using CAD-software, in particular, a partial texturing of the implant surface has been done.

Ti-6Al-4V powder was used as the initial material for manufacturing a metal implant, produced by plasma atomization. The particles have spherical form without any defects in form of satellites (see **Figure 1**) with the following particle size distribution: d_{10} = 27 µm; d_{50} = 47 µm; d_{90} = 76 µm. The metal implant was manufactured using SLM Solutions SLM 280HL machine with the parameters set providing the relative density ~99.9 % and described in the other authors' works [10].

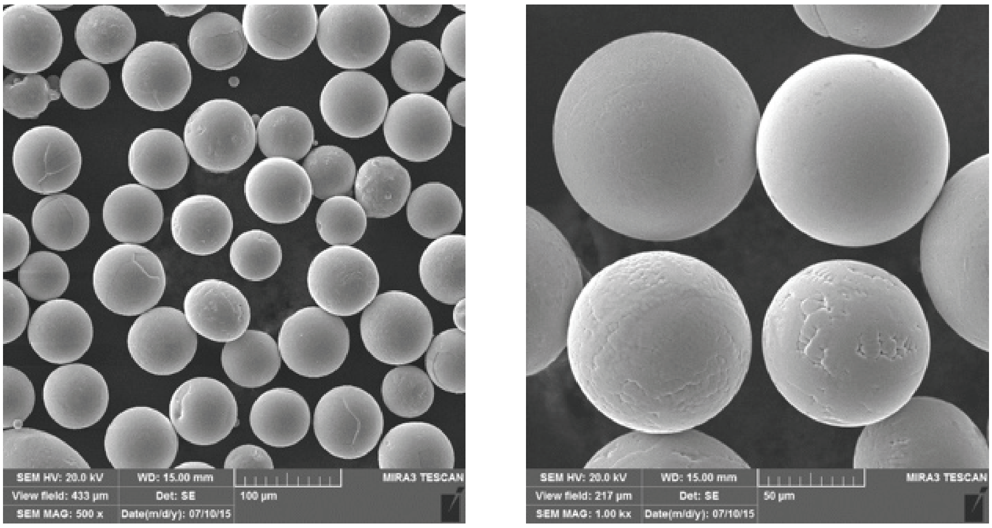


Figure 1 SEM images of Ti-6Al-4V powder particles, produced by plasma atomization

Microstructure studies were performed using Leica DMI 5000 light microscope. Mechanical tests were carried out on Zwick/Roell - Z100 machine. The annealing was carried out using a vacuum furnace ALD MonoTherm in a vacuum with pressure of 10^{-1}-10^{-2} Pa.

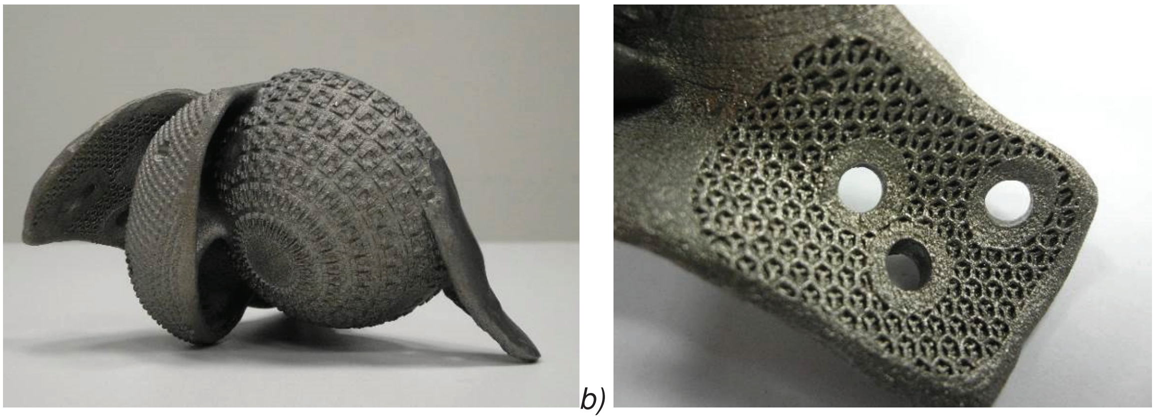
3. RESULTS AND DISCUSSION

Using CT-data of the patient's bone structure the 3D-model of the hip-bone was formed matching the size and form of the patient's bone. Then the polyamide model of the hip-bone was 3D-printed on a SLS machine (see **Figure 2**).

Figure 2 The polyamide model of the patient's hip-bone

In order to take into account severe deformations of the hip-bone the physical model of the acetabular hip implant was made out of polymer clay, which considers the deformations and future points of bearing. After that the polymer implant model was 3D-scanned, the implant configuration was further designed considering the implant's rotation center. Then using the CAD-model of the implant its surface was partially texturized to increase its roughness and create planes with high specific surface in order to increase contact surface and improve osseointergration [11]. The obtained CAD-model was used for producing a polyamide implant model and carrying out the simulation of the endoprosthesis replacement with made models.

The CAD-model of the implant was positioned relative to the building plate of the SLM machine using Materials Magics software, support structures were also created to preserve the implant geometry during the building process. Then the acetabular custom-made implant was produced by SLM out of Ti-6Al-4V powder (see **Figure 3**). After heat treatment, supports removal, additional preparation and cleaning the implant was installed to the patient during the surgery. The postoperative supervision has shown a good result; the patient can move with the installed implant.



a) *b)*

Figure 3 The Ti-6Al-4V hip implant produced by SLM: (*a*) general view with supports; (*b*) a close view of the texturized surface

Two types of heat treatment were applied to Ti-6Al-4V material after SLM. The annealing was carried out in vacuum with the following parameters: 1) 950 °C for 1.5 h; 2) 800 °C for 4 h; both with furnace cooling. The microstructure of the bulk material after SLM and after the second type of heat treatment is shown in **Figure 4**. Before annealing the microstructure consists of α'-phase (see **Figure 4a** and **b**). The material after SLM shows high tensile strength, but low elongation at break (see **Table 1**), wherefore annealing is needed to achieve better mechanical properties. After annealing (see **Figure 4c** and **d**) a partial decomposition of α'-phase into α- and β-phases occurred with enlargement of acicular α'-phase and formation of β-phase on grain boundaries and needles of martensitic phase. The heat treatment of the produced material leads to increased elongation at break with a slight decrease in tensile strength. Different annealing parameters used in this work did not affect the mechanical properties of the material noticeably. The overall mechanical properties of the produced material meet the requirements of ASTM F2924 for additively manufactured Ti-6Al-4V alloy and ISO 5832-3 Implants for surgery from titanium 6-aluminum 4-vanadium alloy.

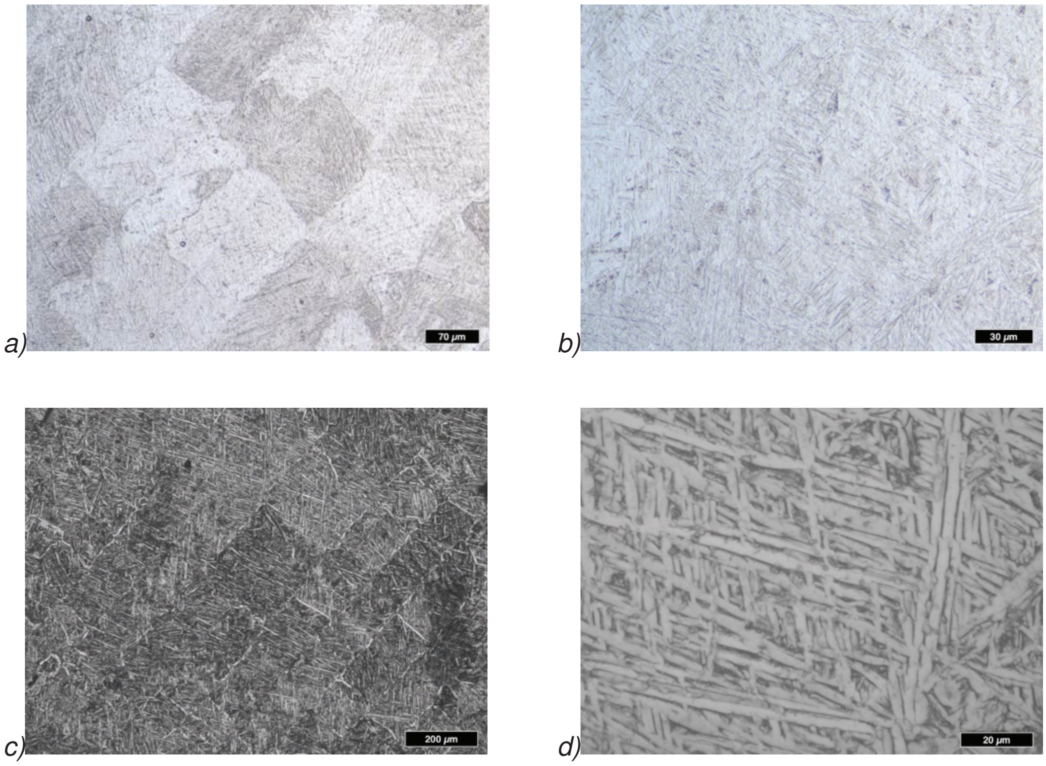


Figure 4 Microstructure of Ti-6Al-4V alloy produced by SLM before (*a*, *b*) and after annealing at 800°C (*c*, *d*)

Table 1 Mechanical properties of Ti-6Al-4V after SLM and heat treatment

Specimen	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
After SLM	1160-1280	1080-1200	2.5-4.0
800°C, 4 h	1070-1090	957-1005	9.8-10.3
950°C, 1.5 h	1080-1088	945-1012	10.4-10.7
ASTM F2924	≥825	≥895	6-10

4. CONCLUSION

The capabilities of additive manufacturing technologies were shown to successfully produce a custom-made component of a hip implant endoprosthesis from Ti-6Al-4V alloy. Since the configuration of the implant matches the anatomical features of the patient, the risk of early instability development is decreased, the surgery time is reduced together with blood loss and risk of infectious complication development. The possibility of creating a texturized surface of the implant by SLM technology allows improve osseointergration process. The microstructure of the produced material after annealing consists of partially decomposed α'-phase into α- and β-phases. The mechanical properties after annealing show a good combination of tensile strength and elongation at break and meet the requirements of ASTM F2924 for additively manufactured Ti6Al4V alloy and ISO 5832-3 Implants for surgery from titanium 6-aluminum 4-vanadium alloy.

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