BÁNKI KÖZLEMÉNYEK
1. ÉVFOLYAM 1. SZÁM

Technology specific geometric analysis of titanium alloy

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Abstract

This study introduces the specific geometric analysis of titanium alloys produced by casting and laser sintering. It extends to material structural problems that occur during casting and 3D printing. Furthermore, it reveals the aspects influencing geometrical features.

Casting process is based on lost-wax precision casting, where the model can be burned out from the embedding wax without the formation of sludge. The model can be designed and produced manually or virtually. This study extends to virtual-design computer models, because these can be examined exactly. Therefore the designed model can be compared to the real-life, produced model.

The complexity of lost-wax precision casting process can lead to errors. A significant problem is caused by thermal deformation, which originates from the silica-based ceramic material. Subsequently the material will not deform linearly and shape defects will occur. The other main cause is the metal's solidification shrinkage during casting process, which can be directly measured after heat treatment. After 3D printing process (Laser Metal Fusion) of metals i.e. additive manufacturing, flaws can arise due to incorrect post-production heat treatment. This can result in remaining stresses in the material.

The additive manufacturing process generates shape defects originating from the melting of each layer. These shape defects can be excessive surface roughness and rounded corners. This study also compares the material structural features of the two manufacturing technologies.

Keywords: Titanium, Casting, Laser Metal Fusion, Additive Manufacturing

1 INTRODUCTION

This study introduces the specific geometric analysis of titanium alloys produced by casting and laser sintering. It extends to material structural problems that occur during casting and 3D printing. Furthermore, it reveals the aspects influencing geometrical features. The study presents models designed in a virtual computer environment, because this makes exact experimentation possible. Furthermore, it extends to the geometric comparison of the two manufacturing technologies and their material structural differences. Apart from this, we mention the necessary post-processing steps connected to both of the two technologies.

This study presents the use of titanium in dental applications and the comparison of casting and additive manufacturing technologies. In the past decades, titanium was subjected to great attention in both medical and dental industry because of its outstanding biocompatibility and adequate chemical, physical, and mechanical properties. Currently, there are several materials of choice in dentistry i.e. metals, polymers, and ceramics. Metallic materials became the most widely-used materials for dental prostheses because of their high strength and good processability.

1.1 Titanium dental implant

Since the end of the 1980s, surface evaluation of titanium and titanium alloys was carried out using electron spectroscopy. As surface properties of titanium implants substantially influence the response of neighbouring tissues. Keller *et al.* characterized titanium surfaces after different surface treatments like sterilizing, cleansing processes, and acid etching [1, 2]. The tested sterilization procedures did not show significant changes in the chemical composition and morphology of the surfaces. In case of acid etching, the surface of commercially pure titanium was covered by a 3-nm-thick titanium-oxide layer. The same oxide layer thickness was 8 nm on the surface of Ti-6Al-4V alloy. Cleansing procedures were carried out using deionized water. During these, it was revealed that the surface of titanium alloy (Ti-6Al-4V) was followed by tendencies resembling commercially pure titanium [3, 4].

Cell and tissue reactions of titanium and titanium alloy implants were thoroughly investigated both in vitro (an experinemt performed outside the living organism) and in vivo (within a living organism). At the University of Iowa, several studies have appeared dealing with cell and tissue reactions on titanium surfaces with additional surface evaluations [5, 6]. The effect of titanium's surface roughness on cells were investigated, but no consistent result was found [7]. Higher adhesion was detected on sand-blasted surfaces compared to smooth surfaces [8]. Research team at University of Kentucky developed electrophoresis compression technique for implant production. [9] These implants showed rapid bone infiltration and optimal osseointegration properties. [10,11].

1.2 Precision catsing process of titanium

First titanium casts were procuced in 1954 in the United States [12]. Lost-wax casting, which was introduced in the middle of the 1950s, has become the dominant processing technology of titanium [13]. During this procedure, the wax casting mould was created with injection moulding.

Afterwards, the wax specimen was covered with ceramic coatings. The main properties of these coatings were low reactivity, and high thermal resistivity resultant from molten titanium. The more reactive is the frontal area, the thicker surface layer of α-phase was formed. The sequential layering of embedding coatings was carried out until the casting mould became strong and hard enough for further processing. Each ceramic layer had to be dried and conditioned in constantly checked temperature and humidity. After finishing the ceramic casting mould, the embedded wax specimen was smelted then burned out [14]. The casting process took place in vacuum, where molten titanium was poured into the ceramic embedding material and the casting mould. After the removal from the furnace, the solidified material was prepared for isostatic pressing. Isostatic pressing (uniformly pressed from all sides) is a possible solution for compressing materials, and happens under gas atmosphere [15]. The aim of the isostatic process was the elimination of internal pore defects [16]. Following that, casts were tested in order to find possible defects. These defects could be surface defects or inclusions [17, 18]. Surface defects were removed by grinding and polishing. Internal voids and inclusions were corrected with TIG (Tungsten Inert Gas) welding.

Process of 3D printing

Selective laser melting is an additive manufacturing technology that appeared in the end of the 1980s and the beginning of the 1990s [19-21]. 3D printing provides several advantages compared to conventional manufacturing technologies, for example the reduction of processing steps, flexibility, and efficient material use. Due to the layer-by-layer buildup, 3D printing can create parts with high geometric complexity. However, the special circumstances during the process raise certain problems as well [22]. Previous studies have been investigating different process parameters during 3D printing. The effects of layer thickness, scanning distance, scanning strategy, laser power, and scanning speed on microstructure, mechanical properties [23-27] and other properties, such as density and surface quality were investigated [28-31]. Other studies were focusing on process optimization and monitoring [32-34].

2 Materials and methods

2.1 *Casting of specimens*

The specimens to be examined were created with a Dentaurum Universal 230 Autocast casting unit.

Production is based on a previously designed pattern. The wax pattern is embedded after adequate structural tension release. The embedding material and the casting pattern are burned out in a furnace. Afterwards, molten titanium is poured into the place of the inserted pattern with the use of a vacuum pressure casting unit. Melting and casting takes place in a modified atmosphere. Following the casting procedure, embedding material is removed from the cast. Then its positioning of to the specimen is carried out. Surface finishing is done manually. After this, we examine the specimen with the help of a micro CT to check porosity. There are certain difficulties in connection with the casting technique of titanium and titanium alloys. These problems can emerge because of the high melting point of titanium - approximately 1660°C -, and its high reactivity with the environment and the embedding material. Titanium and its alloys easily react with different gas particles e.g. hydrogen, nitrogen, and oxygen. Their melting at high temperatures is performed in argon atmosphere to prevent impurities and brittlement. The aims of the use of open-pore embedding material are to avoid interface reactions, and to create vacuum and gas flow inside the specimen. Passive embedding materials that contain refractory oxides are frequently used. Titanium cannot be casted by conventional techniques as it is oxidized at a temperature lower than its melting point. Thus, titanium casting is performed in an argon atmosphere. The material used for casting process is commercially pure Grade I titanium. Grade I titanium is the first among the four groups of commercially pure titanium materials. It has the lowest hardness, inferior mechanical properties, best deformability, outstanding corrosion resistance, and the highest impact resistance.

2.2 *3D printing of specimens*

3D printed specimens were produced by a Sisma Mysint100 additive manufacturing unit. This printer uses LMF (Laser Metal Fusion) technology. LMF technology is used to produce complex metallic parts from a metal powder. A laser melts the titanium powder layer by layer to create the given geometry. One of the advantages of this technology is that geometric design has almost no constraints here. Thus, special shapes and unique parts can be created rapidly, flexibly, and cost-effectively. The chosen material was Ti-6Al-4V ELI, Grade23, which is the high-purity variant of Ti-6Al-4V (Grade5). Among its advantages, we can mention for example its high strength, low specific weight, good corrosion resistance, and high toughness. It can be used in biomedical applications, i.e. implants, because of its good biocompatibility and low elastic modulus.

3 Results

3.1 *Defects originating from 3D printing*

In case of 3D printing, faults can originate from design or software problems. Human errors include the improper choice of metallic powder, and laser scanning strategy. In the following, we present some possible faults that result in defective 3D-printed parts.

Figure 1. presents a conventional ceramo-metallic partial denture, which was designed by a dental technician with a 3D design softwar. It was sent in an STL file format for laser sintering. It is possible that the model seems to be perfect for the dental technician during the design process. Even detailed inspection cannot always reveal problems that should be corrected. However, if the model is checked by the software, diverse model faults can be detected. The purple-coloured area appears if the program detects too small surface areas, inversely oriented vectors, or double faces. These are all called surface defects.

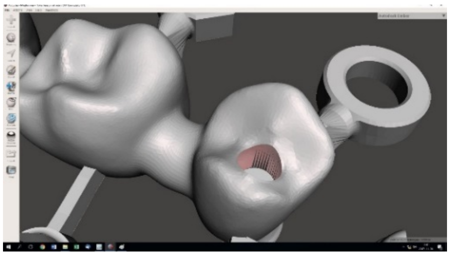

Fig. 1 a): Conventional ceramo-metallic partial denture, which was designed by a dental technician with a 3D design softwar

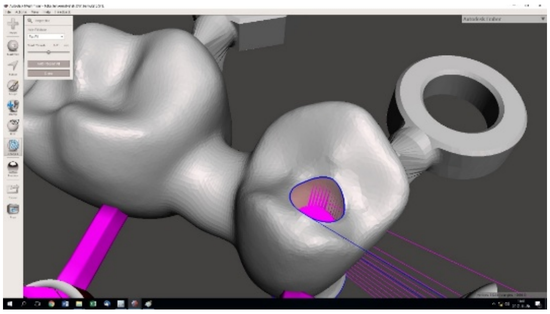

Fig. 1 b): The purple-coloured area means surface defects on the modell

The type of surface defect mentioned above can also be observed in the following figures, which show the 3D model of impression heads. It is important to mention here that the previously shown model was designed with a simpler dental design software, while the model of the impression heads shown in Figure 2 was created with a professional engineering design software. However, faults can also be found on this model. Based on this, we know that it is no matter where the model is coming from or what type of design method was chosen, all models have to be checked without any preconceptions. Purple colour highlights surface errors, while red colour suggests volumetric faults. In the 2 a) figure, the original model can be observed with highlighted errors. The 2 b) figure shows the model after going through the automatic repair mechanism of the software. It is conceivable that the automatic repair mechanism was not working properly in this case. It produced incoherent, unusable models. In this case, there are two possible options: the complete re-design of the model with great emphasis on the probable errors, or the step-by-step manual repair of the errors.

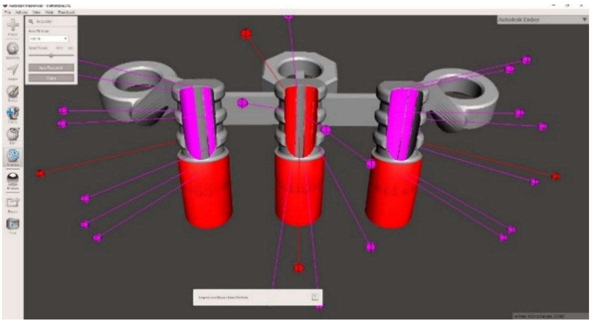

Fig 2 a): The original model with highlighted errors

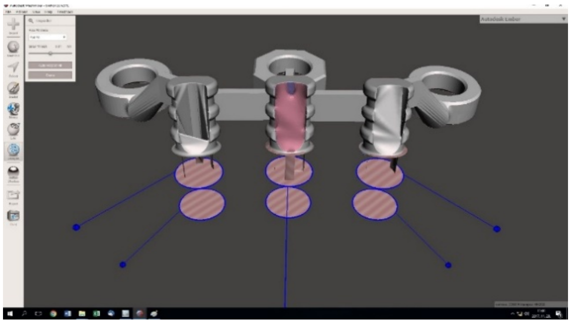

Fig. 2 b): The model after going through the automatic repair mechanism of the software

Such a case can also happen when the model itself is structurally perfect, there are no design faults present, but the CAM program of the laser sintering unit does not allow us to place the support material under the model to certain indended positions. It means that the design software generated the triangles - which make up the STL model file - in such a way that we are not able to position the support material to certain areas. This difficulty can cause insufficient support later. As a result of this, the product manufactured by the 3D printer is going to be defective. In figure 3, the blue rectangle shows the desired positions of the supporting material, but the software places them to outside areas. This case requires some level of correction to get the sufficient model support.

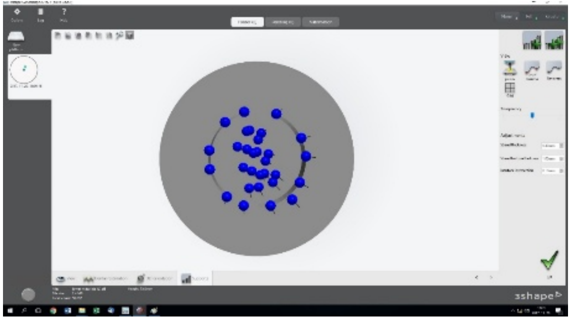

Fig. 3 a): The CAM program of the laser sintering unit does not allow us to place the support material under the model to certain indended positions.

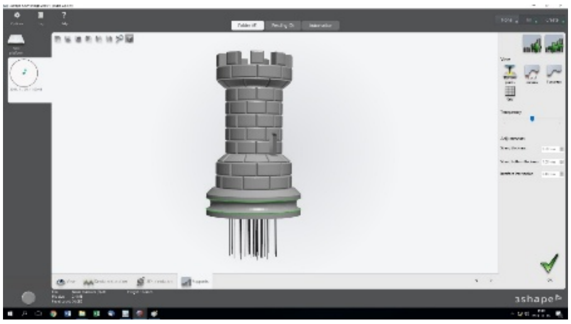

Fig. 3 b): The model and the supports front-wise

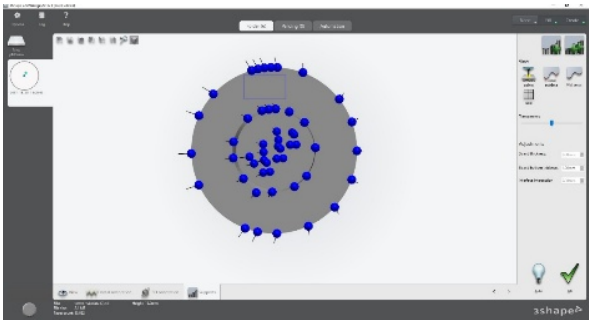

Fig. 3 c): This case requires some level of correction to get the sufficient model support

The following disc specimen presents the results of inadequate support structures. The support structure disintegrates, and as a result of this, the disc is elevated from the platform. Then, printing process continues in this defective way. During melting and solidification of particles, shrinking material tears up the previously solidified metal particles.

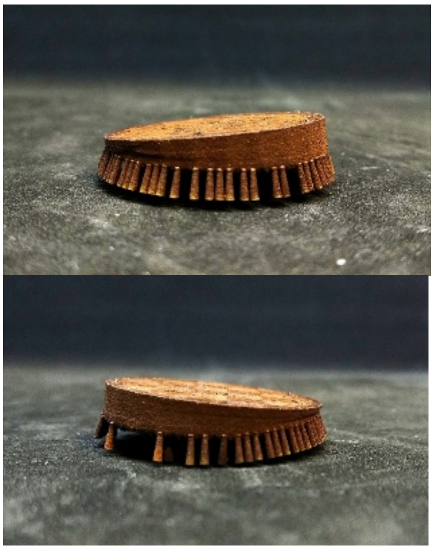

Fig. 4: The results of inadequate support structures

3.2 *Defects originating from casting process*

Casting problems usually originate from human errors. In the following, some possible faults are presented.

Figure 5, shows a cracked embedding material. This kind of failure can be the result of the following problems: thermal dilatation, heating and firing temperature problems, insufficient embedding material, or heat distortion.

Fig. 5: Cracked embedding material

The following figures show a workpiece with argon gas generated casting cavities. These kinds of gas bubbles can be induced by the inadequate choice of pressure or insufficient vacuum. As a result of this, the part's surface was perforated as visible on Figure 6.

Fig. 6: Workpiece with argon gas generated casting cavities

Figure 7 shows a defect originating from the cracking of the embedding material. It is a gypsum/silicate based special embedding material for titanium. The crack could appear in the furnace or during the casting process when pressure was applied by the machine.

Fig. 7: A defect originating from the cracking of the embedding material

A surface defect can occur due to argon gas bubbles, which is shown in Figure 8. Figure 8 shows a cortically suported individual implant with small bubbles present. Figure 8 demonstrates a magnified image of the bubble and the surface. Air bubble lodged in the embedding material results in a positive surface defect if the part was embedded in vacuum atmosphere. These surface defects can be eliminated by grinding and polishing the surface.

Fig. 8: A cortically suported individual implant with small bubbles present

Inclusions can be detected by CT imaging, which were carried out in Széchenyi István University. Next figure shows a cortically supported individual implant. Inclusions are detected by CT imaging, then the problem is eliminated with the utilization of laser welding. The disadvantage of laser welding is its long process time, during which the frame is weakened and it can possibly break as well.

Fig. 9 a): A cortically supported individual implant

Fig. 9 b): Inclusions can be detected by CT imaging

4 SUMMARY

In conclusion, we assume that laser sintering is going to replace titanium casting as a processing technology in dental applications in the near future. The homogenity of products created by additive manufacturing processes is more uniform. The external geometry is going to be identical to the designed part. Defects (surface, contour, corners) originating from metallic 3D printing and melting strategy are familiar. Optimal process parameters can be determined. Different surface topology and roughness characterizes external surfaces. Support, side, and closing surfaces are distinguished. The post-processing of 3D printed products is simple, and can be carried out by manual processing. In case of casting, spruing and embedding have a key-role. During casting, inclusions can be formed inside the structure. A special embedding material is needed, which is more expensive compared to other embedding materials. Post-processing is complicated, complex, and therefore requires professional manual experience and skills. However, this also does not guarantee the preciseness of the finished product. 3D printing is more productive and structures can be manufactured in shorter time interwalls. The price of the laser sintering unit and its support equipment is considerably higher compared to the casting machine with its support units. Although in the long run, this investment will pay off. And as we can see, additive technologies are becoming widespread in the medical field.

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