3D-Modelling and Casting Simulation for The Fabrication of Megaprostheses Implant by Vacuum Centrifugal Casting

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Abstract. Recently, a high number of bone fracture incidents per year urges researchers in developing megaprostheses as artificial body parts. However, the complicated design and requirements for this custom-made prostheses are the key challenge. In accordance, this study focused on the preparation steps of 3D-modelling and casting simulation for the fabrication of megaprostheses implant by vacuum centrifugal casting. The reconstruction steps of 3D-modelling were started by observing the medical image data (i.e. CT-scan images). As the 3D-model was ready, the gating system was designed by placing two mandible bone models as the casting part with sprue and ingates where the design was respected to the gating system design for centrifugal casting. Moreover, the variation of casting part position, numbers, shapes and dimensions of the ingate, as well as the total surface area of ingates (Si) was applied while creating the gating system design for casting simulation. Chemically Pure Titanium (CP-Ti) with the pouring temperature and time of 1700˚C and 4s, respectively, were used as the parameters for casting simulation. The solidification test results showed that the shrinkage cavities tended to decrease in volumetric scale with increasing the total surface area of the ingates, while the casting part position, number, shape, and dimension of ingate showed the difference in effectivity of the solidification of molten metal on the shrinkage cavities formation.

Keywords: 3D-modelling, Biomaterials, Bone fracture, Casting simulation, Implant, Megaprostheses

1. Introduction
Recent interest in the development technologies on the artificial body part or better known as prostheses has been motivated by the search of materials and fabrication methods with good mechanical properties as well as its biocompatibility that supports the human body. The special prostheses that being used inside the human body, called endoprostheses, has been proven to help the patient for improving the prognosis and the survival rates to amputation [1]. Moreover, the replacement of the low-quality bone with custom-made endoprostheses implant or better known as megaprostheses implant is capable of being used on the case of musculoskeletal pains, malignant tumors, and large skeletal defects [2]. This
megaprostheses implant has been widely used in oncologic orthopedic surgery and is one of the leading ways for medical treatment of sarcoma patients [3].

Titanium and its alloys are considered as metallic materials for megaprostheses implant due to its good corrosion resistance and biocompatibility, low density and low modulus elasticity with good mechanical properties that suited to the human bone structure [4]. Commercially Pure Titanium (CP-Ti) and Ti-6Al-4V alloy are the most common materials used for biomedical applications, yet the Ti-6Al-4V has a possible toxic effect for permanent implant applications by releasing its aluminum and vanadium contents [5]. In the case of biocompatibility, titanium can create the thin passivation layer of titanium oxide (TiO2) on its surface that protects the materials from being corroded. Due to the high chemical activity of titanium and its alloys at high temperature, casting of the molten of titanium or its alloys is one of the precarious manufacturing processes for maintaining its composition purity from crucible and mold contaminations as well as atmospheric gases. Centrifugal casting has been developed mainly on the manufacturing of circular pattern parts on aircraft and automobile industries that provides high density and mechanical properties.

High dimensional accuracy is the main concern for implant development [5-6]. Thus we divide our process into two steps. Firstly, 3D-modelling focused on implant dimension accuracy, extracting model, and design for the casting process. Secondly, casting simulation was aimed to lower production cost by eliminating trial and error process, predicting the shrinkage cavity, optimizing the design, and maximizing cost efficiency.

This study was carried out to evaluate the 3D-model reconstruction and casting simulation of the lower jaw bone (or the mandible bone) as the megaprostheses implant model using 3D-modelling and casting simulation software. The 3-D model reconstruction steps, gating system design, and solidification simulation as well as the shrinkage cavities formation was studied for bone replacement using casted titanium with customized design. The casting simulation, the effects of the variation of casting part position, number, shape, and dimension of the ingate were also studied for solidification test on casting simulation of the megaprostheses implant model.

2. 3D-Modelling
A 3D model was prepared by modifying and converting the digital image data (DICOM files) from CT-scan images to 3D anatomical models using Osirix MD. Figure 1 showed the reconstruction steps started from the isometric view of CT-scan images where the bone fractures were on the lower jaw bone (or the mandible bone) and split into three parts such as the right mandible bone, chin bone (i.e., including the mental protuberance and mental tubercle of mandible bone), and the left mandible bone. Based on the structure of skeletal defects observation, the right mandible bone was chosen as a reference model for generating the megaprostheses implant that further modification could be able to replace the left mandible bone and chin bone. However, the actual right mandible bone showed the coarse surface contour on its surface topography. Smoothing and rendering were needed in order to make an easier modification for generating the megaprostheses implant model.

A 3D model of the megaprostheses was prepared by modifying and converting the digital image data (DICOM files) from CT-scan images to 3D anatomical models using Solid work CAD software, as shown in Figure 2. Figure 2a shows reconstructed jaws consist of the jaw bone and the jaw titanium. Figure 2b shows the implant model of titanium which was reconstructed. The implant model is lower jaw bone from condyle to the mid of lower jawbone. The implant will be connected to the original jawbone using a connection plate embedded in the implant.

3. Casting Simulation
Casting simulation was conducted using Solidcast 7 to evaluate cooling behavior. Figure 3 shows the configuration of the gating system for the casting process. It consists of sprue as pouring target of the molten titanium and ingate to supply molten titanium from the sprue to the casting parts. Different orientation of the casting part is shown in Figure 3.b-c. To obtain casting product with low porosity, a variation of the ingate size and shape were carried out as shown in Figure 3 d-g.
Figure 1. The reconstruction step images from the patient with the fracture through the mandible bone: a) isometric view, and b) fracture view, and c) from left to right: before (as an actual) and after smoothing and rendering the surface using 3D-modelling software.

Figure 2. 3D-modelling images of the mandible bones: a) after reconstruction from medical image data with additional part of the plate for joining purpose; and b) the mandible bone model which was selected for megaprostheses implant.

Systematic of simulation variation of gating systems, includes gating dimension and geometry are shown in table 1. Design A1, A2, A3 and B1 were using three ingates under different gating size, while B2 and B3 were using four ingates; i.e. B4, B5, C1, C2, and C3 using rectangle and circle. Besides, a various number of ingates were also studied with a maintained cross section of the ingate at 207.54 mm².
Figure 3. The variation of gating system for casting simulation of the mandible bone model: a) – c) Design A series: casting part positions with total surface area of ingates (Si) < theoretical surface area of ingates (Asm); d) – f) Design B series: number and shape of ingates with Si ≈ Asm; and g) Design C series: with Si > Asm.

Table 1. The variation of casting design based on the shapes and dimensions of ingate with their surface areas.

| Design series | Dimension of ingate (mm) | Surface area of ingate (mm²) |
|---------------|--------------------------|-------------------------------|
|               | Ø1        | Ø2        | Ø3 | Ø4 | Total (Si) | Theoretical (Asm) |
| Design A1     | 4.65      | 4.65      | 4.65 | -  | 50.97     | 207.54             |
| Design A2     | 4.65      | 4.65      | 4.65 | -  | 50.97     | 207.54             |
| Design A3     | 4.65      | 4.65      | 4.65 | -  | 50.97     | 207.54             |
| Design B1     | 12.00     | 10.00     | 4.50 | -  | 207.63    | 207.54             |
| Design B2     | 10.00     | 8.00      | 8.00 | 6.00 | 207.43    | 207.54             |
| Design B3     | 12.00     | 7.00      | 6.00 | 6.00 | 208.20    | 207.54             |
| Design B4     | Ø = 10, 1 = 10, w = 5 | 10.40     | 5.00 | -  | 208.20    | 207.54             |
| Design B5     | Ø = 12, 1 = 12, w = 5 | 8.00      | 5.00 | -  | 208.07    | 207.54             |
| Design C1     | Ø = 12, 1 = 12, w = 7 | Ø = 12, 1 = 12, w = 3 | 5.00 | -  | 303.93    | 207.54             |
| Design C2     | Ø = 12, 1 = 12, w = 8 | Ø = 12, 1 = 12, w = 5 | 5.00 | -  | 334.93    | 207.54             |
| Design C3     | 1 = 12, w = 16,  fillet Ø = 5 | 5.00 | -  | 368.93 | 207.54   |
|               |           |           |     |     |           |                   |
Simulation steps using solid cast 7 are shown in Figure 4. Sprue, ingate and casting part were arranged and meshed as shown in in Figure 4a. Then it was covered with mold material (Figure 4b). The filling simulation was carried out in order to observe hot molten metal entering the cavity of the casting part. Solidification of the casting part was conducted to evaluate shrinkage that promotes porosity. Chemically Pure Titanium (CP-Ti) with the pouring temperature and time of 1700°C and 4s, respectively, was used as the parameter for casting simulation.

**Figure 4.** The isometric views of the solidification test using SolidCast 7 casting simulation software: a) meshing and b) molding of the casting parts and its gating system; c) – d) the filling time of 60 and 90 %, respectively; and e) – f) the solidification time with the solid part of 1 and 5 %, respectively.

4. **Simulation Results**

Evaluation of the casting simulation of the titanium casting was focused on the porosity which leads to mechanical failure on the implant. The porosity of the titanium casting is one of the main issues in titanium casting due to the low density of the titanium which tends to make a reduction of titanium during solidification. The void during solidification can be reduced with appropriate gating system to provide enough supply of molten titanium [6]. Shrinkage of titanium was reported at 1-2 % which means the higher tendency for shrinkage porosity [7].

In the design for the implant, additional riser was limited to maintain dimensional accuracy. Therefore, minimization of the gating system without riser was applied in this simulation. The result has shown a variation of gating systems provide various shrinkage phenomena. Shrinkage was found in the thick section of the part as shown in Figure 5 in which the gas void is high at smaller ingate. Gas void volume decreased with an increasing cross-section of the ingate. The optimum gas void is achieved at C type gating system especially C3 gating system.
Figure 5. The top views of shrinkage cavities resulted from the solidification test using SolidCast 7 casting simulation software: a) – c) Design A series with Si < Asm; d) – h) Design B series with Si = Asm; and i) – j) Design C series with Si > Asm.

5. Conclusion
This study has successfully performed initial steps for megaprostheses fabrication, both 3-D modeling and casting simulation, using chemically pure titanium as the material. The investigation has shown that increasing total surface area and details of the ingates could lead to the minimization of shrinkage cavities as well as enhancement of effectivity. In this work, C3 design shows the best result that will further proceed for the real fabrication process.

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