Neutron computed tomography investigation of the porosity on the titanium femoral knee investment casting

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Abstract. Rotational velocity in the centrifugal casting is one of the factors that affect to the porosity of the femoral knee cast. The objective of this research is to investigate the internal porosity of as-cast femoral knee prostheses. CP-titanium femoral knee was cast using vertical centrifugal investment casting. The three rotational velocities parameter utilized in the vertical centrifugal casting were 45, 55 and 65 rpm. Neutron computed tomography characterization was conducted to investigate the size, percentage, and location of pores. The maximum size of pores in casting with the rotational velocity of 45, 55, and 65 rpm are 14.78 mm$^3$, 14.98 mm$^3$, and 14.65 mm$^3$, respectively. The percentage of pores in the casting with the rotational velocity of 45, 55, and 65 rpm are 1.78%, 2.78% and 1.78% respectively. The size and percentage of the pores for casting at the rotational velocity of 65 rpm are smaller than the size and percentage of the casting at 45 and 55 rpm.

1. Introduction
Total knee replacement has been known as one of the surgical procedures to recover the function of defective knee joint due to osteoarthritis and rheumatoid arthritis diseases. The demand for total knee replacement was predicted to increase by more than 607 % from 2005-2030 [1]. The materials which are often used as hip and knee joint prostheses are stainless steel 316L, cobalt-chromium alloys, titanium and titanium alloys because they are offering sufficient mechanical properties, those are non-toxic, corrosion resistance and wear resistance. Biomaterials for load-bearing joint prostheses should be acceptable to the body and able to withstand cyclic loading in a corrosive environment [2]. Today, titanium and titanium alloys have been widely used in biomedical application due to the biocompatible, corrosion resistance, high strength to weight ratio and low modulus [3-5].

Manufacturing engineering is an important field in the production of joint prostheses especially to make a better quality and low-cost implant. The high quality and inexpensive implant from biomaterial are till interesting to study because it would have some impacts on the improvement of the quality of human life. The manufacturing of the joints prostheses can be done using casting technology. It is one of the competitive ways to reduce the production cost [6]. Investment casting or lost wax casting is known for the ability to produce a near-net shape workpiece with complex shape, dimensional accuracy, and good surface result. Unfortunately, the mechanical properties of castings are still inferior compared to the forgings because of the coarse of microstructure and porosity. Internal defects like shrinkage pore and porosity are the common problems which may cause deterioration of mechanical properties. The shrinkage pores are related to initiation sites of cracks[7].
To improve the quality of cast product, centrifugal investment casting has been developed recently [8–10]. The centrifugal force affects the improvement of fluidity, reduces pores, and increases dimension accuracy of casting [8].

Understanding the size, percentage, and distribution of porosity in the CP-titanium femoral knee casting is essential to characterize the casting soundness. X-ray and neutron computed tomography are the types of non-destructive tests which are increasingly used for industrial applications, specially for inspecting the inner defect or internal structure of the sample. The technique has been applied in numerous fields of research such as in cultural heritage for investigating the inner contour of clay sculpture [11] and the material for restoration of wooden-skull [12]. In civil engineering, this technique was used to study the water transports at fresh concrete that influencing in plastic shrinkage cracking [13]. In the metal casting, this method has been used to investigate the hidden defects in the Al casting [14] and titanium investment casting for aerospace industry [15,16]. There are still limited reports on the application of neutron computed tomography studies on the porosity in the centrifugal investment casting of CP-titanium. In this study, the effect of the rotational velocity of centrifugal investment casting on porosity size, percentage, and distribution was investigated using neutron computed tomography (NCT).

![Figure 1. Centrifugal investment casting (a) assemblies tree and (b) rotational direction molding bracket in the casting chamber](image)

2. Material and Methods

In this study, femoral knees were produced by using centrifugal investment casting method. The material used in this study was CP-titanium Grade 2. The dimensions of the as-cast CP-titanium femoral knee were 72 mm ×58 mm ×50 mm at its outermost points. Several steps were involved in this method. The first step was making the wax pattern of the femoral knee prosthesis. The wax femoral knee patterns were made by injecting the mushy wax into the aluminum die. Then, it was joined by wax sprue into the tree assemblies. After that, the tree assemblies were dipped into the ceramic slurry in eight layers and allowed it to dry and thus built a shell around the patterns (figure 1a). Furthermore, the ceramic shells were steamed to remove the wax from the ceramic shell mold. Prior to the casting, the shell molds were baked in the oven to sinter and strengthen the green body of ceramic shell mold.

The melting process was performed in a vacuum electric-arc furnace equipment (Flash Caster, Japan). The ceramics molding was installed in mold bracket and then it was entered into the casting chamber (figure 1b). Before the Argon gas (as shielding gas) was injected into the chamber, the casting chamber was set in vacuum condition. The CP-titanium was melted in a copper crucible that was installed in the middle and above the rotary mold bracket. In pouring the molten titanium into the ceramic mold, the crucible was tilted. The mold was turned vertically at anticlockwise direction (figure 1b). The molten titanium was filled into the cavity due to the centrifugal force. This
experiment used 45, 55, and 65 rpm rotational velocities. The melting, pouring, and solidifying processes were done in the argon environment. After the molten titanium was solidified, the shell was broken, and the sprues, gates and riser were cut off from the femoral knee casting. The as-cast femoral knee is shown in the figure 2.

The neutron radiography and tomography experiments were done in G.A. Siwabessy nuclear reactor Indonesia with 15 MW power. The femoral knee was rotated and bombarded by neutron beam. Neutron beam projection images were recorded at 200 s per image with 1° stepwise angle rotation of the sample. Octopus 8.5 software was used to reconstruct the 3D volume data, whereas the analysis was conducted using the software of Volume Graphics VG Studio Max 2.2 with additional modules to analyze the defect. The algorithm defect analysis was carried out using the default (v2.1) with the analysis mode voids, and material parameters were determined using determine surface. The parameters set of the software were the probability threshold of 0.5, the volume of the defect at the minimum of 2 mm³, and the activated functions of neighborhood checking.

![Figure 2. Femoral knee CP-titanium as-cast (a) with gating and (b) cut off from the sprue gating](image)

3. Result and Discussion

Figure 3 shows the image neutron radiography of the as-cast femoral knee with different rotational velocities. In the case of neutron radiography images, solid areas are brighter than pores areas. There was no void on the surface and subsurface for all casting parameter. The internal pores in the as-cast femoral knee were not visible while detected by the neutron radiography.

![Figure 3. Neutron radiography of femoral knee investment casting with different rotational velocity. (a) 45 rpm, (b) 55 rpm and (c) 65 rpm](image)
Figure 4 shows the defect volume of the internal porosity in femoral knee CP-titanium casting. The internal porosity was dominated by the small size of porosity (0-5 mm$^3$), while the large size porosity, (more than 5 mm$^3$), only occurred at several sites. The 3D images of the femoral knee were made full-transparent to view the size and location of the porosity. From the distribution and size of the defect shown in figure 4 (a-c), it can be seen that the location of the largest internal porosity in all the casting occurred under the pin section. The module of automatic defect analysis will be finding the pores and classifying the pores according to the volume size. The maximum size of pores in casting with the rotational velocity of 45, 55, and 65 rpm were 14.78 mm$^3$, 14.98 mm$^3$, and 14.65 mm$^3$, respectively. The percentage of voids in casting with the rotational velocity of 45, 55, and 65 rpm were 1.78, 2.78 and 1.78%, respectively. In particular, the casting with 55 rpm had the largest defects which were found in several sites of the casting, whereas the casting at 65 rpm had smaller volume and number of defects than those of the casting at 45 and 55 rpm.

![Figure 4](image1.png)

**Figure 4.** Defect volume of internal pores of as-cast femoral knee centrifugal investment casting, (a) 45 rpm, (b) 55 rpm, (c) 65 rpm

Figure 5 shows the slice side view for the as-cast femoral knee with rotational velocity 45 rpm. It shows that the largest void was located beneath the pin section. Figure 6 shows the voids distributions which grouped in three range. The majority pores volume were (below 5 mm$^3$) for all the casting parameter.

![Figure 5](image2.png)

**Figure 5.** Side slice view of as-cast femoral knee with rotational velocity 45 rpm
In general, voids can be formed due to shrinkage during solidification and by the entrapped gas. The voids by the gas formed due to the process of releasing the gas from the face mold wall when the molten metal flows to fill it. The entrapped gasses could have been occurred due to the ceramic molds absorb air which contains moisture. The shape of pores has been grouped in three categorize by Wan as gas pores, gas-shrinkage pores, and shrinkage pores. The gas pores were near round shape. The shape of gas-shrinkage pore was presented as gas pore with many convexes and long tails. The shrinkage pore was very complex shape [17]. Figure 4 also shows gas-shrinkage and shrinkage porosity are dominant in the casting. In this study, the shape of porosity tends to the two type of pores are gas-shrinkage and shrinkage pores due to the shape sphere with a complex long tail and complex shapes pores.

The defects which are formed beneath the pin occur due to the shrinkage because the pin solidifies first before the thicker sections do. Shrinkage voids are the results from the reduction of the volume and contraction as the molten titanium solidifies [18]. Increased rotation velocity will improve the quality of castings because it increases the centrifugal force. Furthermore, the centrifugal force provides additional force so that the molten metal can fill the cavity in the mold [19]. The molten metal will flow towards the outside of the center of rotation radially. It produces casting without any defects on the surface. The casting parameters processes such as rotational direction, rotational radius, and rotational velocity play a significant role in the soundness of casting [19].

This study shows that the effect of the rotation velocity on the removal of pores is less due to a low rotation velocity. Withal, in this casting process, the mold is not preheated so that the cooling rate will be faster on the outside than the inside of the work piece. Therefore, the defects that formed are dominated by shrinkage pores. To reduce the internal pores, some researchers is using a design of complex gating system [20] and using hot isostatic pressing [8,21]. According to neutron computed tomography, the centrifugal investment casting of CP-titanium of the femoral knee with the rotational velocity of 65 rpm is the best result because it has fewest and smallest porosity.

4. Conclusions
In this study, the size and location of porosity of the as-cast CP titanium femoral knee which was made by the vertical centrifugal casting method with different rotational velocity were studied using neutron computed tomography. There are no defects were found in the surface and subsurface for all the casting. The maximum size of pores in casting with the rotational velocity of 45, 55, and 65 rpm are 14.78 mm$^3$, 14.98 mm$^3$ and 14.65 mm$^3$, respectively. The percentage of voids in casting with the rotational velocity of 45, 55, and 65 rpm are 1.78, 2.78 and 1.78%, respectively. The fewest and smallest porosity are achieved by casting with rotational velocity 65 rpm.
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