Neutron radiography and tomography investigations on the porosity of the as-cast titanium femoral stem

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Abstract. Gating system design in the centrifugal casting is one of the factors that influence the porosity of the femoral stem. The objective of this research is to analysis the porosity in the as-cast titanium femoral stem by neutron radiography and tomography. Three gating system designs which in three-ingates, four-ingates, and four-ingates by inversed position of the femoral stem were casted by a vertical centrifugal casting in investment mold. The porosity distribution in the titanium femoral stem was investigated by the neutron radiography film and followed by neutron tomography. The results indicate that there are large internal porosity in the subsurface region on both of the four-ingates designs but only small internal porosity on the three-ingates design. The large porosity also takes place in largest part of the femoral stem at all of the gating system designs. The product may be rejected due to the sub-surface porosity. The three-ingates design has the smallest risk on the reject product.

1. Introduction

Femoral stem is a part of hip prostheses, inserted in femur. It can be made from metallic biomaterials such as stainless steel 316L, Ti and Ti alloy, and CoCr alloys [1]. Titanium and Ti alloys have some excellent properties such low weight, high resistant to corrosion, good biocompatibility, as well as mechanical properties that are similar to gold alloys, but at a lower cost [2]. Several methods can be used to manufacture the femoral stem such as rapid prototyping [3] and casting [4]. Each method has advantages and limitations in process or in the final product.

The investment casting process is widely used to manufacture near net-shape component [5]. Therefore, the machining process can be minimized by this method and a complex shape can be manufactured in relatively low cost [6]. One of the serious problems in the casting is the porosity. Although the titanium femoral stem was casted in vacuum setting, the porosity may still occurs in this product. The porosity may be caused by shrinkage volume [7] and entrapped gas [8]. This defect reduces the mechanical properties and makes imperfect shape of the femoral stem.

There are several methods to determine the internal porosity in the materials. The Archimedes method usually used in the quantity of the porosity based on the density of material in air and liquid [9–11] This method is non-destructive test, quick and relatively inexpensive. It can only be used to
determine a global density value relative to the reference fluid while the position of the porosity cannot
be detected. A gas pycnometry method determines the porosity also in the density-based testing. The
part density in an absolute sense is computed by measuring part of mass and part of volume separately.
The gas displacement determines the part volume[10]. A thermography method detects the porosity of
an electrode layer. This method based on heating and sensing the specimen by the irradiation power in
the infra-red spectrum range [12]. An innovative non-destruction test measuring technique has been
recently utilized for internal porosity detections. Computer tomography thanks to its capability for
providing a completely analysis of shape, size, volume and distribution of pores within entire analyzed
volume [13].

Neutron tomography detects the porosity of material by non-destruction test (NDT) method.
Comparison between the X-ray and neutron tomography, the neutron is much better to penetrate the
thick metal walls than the X-ray [14]. Neutron tomography is beneficial for deep investigation of
explosive materials and narcotic hidden inside metals or materials with high atomic numbers [15].
Neutron film radiography results in two-dimensional visualization, while neutron tomography (NT) is
a powerful method for three-dimensional visualization of materials. The different of neutron source as
nuclear reactors, spallation sources, standard particles accelerators makes the facilities of the
experimental and safety condition very different from each other [16]. A particular facility for
tomography consists of scintillator screen, rotating table, charge coupled devices (CCD) digital video
camera, and plane mirror [17]. The neutron tomography method had proved useful in many different
areas such as geology, biology, cultural heritages, sciences and industrials application. A neutron
image for radiography test, two-dimensional projections of the internal surface of the objects is
acquired by films and track detectors. Processing of neutron image occurs by irradiation the object in a
polychromatic neutron beam while a converter screen changes the transmitted neutron intensity into
ionizing radiation. The final result is a cross-section image of the sample [18].

The neutron tomography is useful to obtain the detail inside the material such as the volume
distribution of the biotic-muscovite grains inside the rock [19], and the porosity of titanium aerospace
part [20]. The porosity usually becomes a common defect in the casting that cannot be detected by
naked eye. The neutron radiography and tomography can be promoted as one of the methods to
investigate the internal porosity of the casting result in more detail. The objective of this research is to
obtain a detail of the internal porosity of the as-cast titanium femoral stem by the neutron radiography
and tomography.

2. Experimental

2.1. Material and casting design
The commercially pure titanium femoral stems of this investigation were casted by the vertical
centrifugal casting in the three designs of gating system as shown in figure 1. The first design has three
ingates at cross section area: 78.5; 157.0; 128.5 mm², that the biggest cross section area was designed
in the middle of the femoral stem. The second design was equal to the first design but the largest cross
section area was divided into two similar ingates. In other word, it has four ingates. The third design
was similar with second design but the femoral stem position was inversed. The as-cast femoral stems
were removed from the gating system as shown in figure 2.

2.2. Experimental procedure
The neutron radiography and tomography facilities were installed at a 15 MW nuclear research reactor
in Indonesia. The neutron radiography in this research used radiography film firstly to investigate the
porosity quickly in 2D visualization. The main apparatus in the neutron tomography consists of
scintillator screen Li6ZnS 200 µm, CCD camera 1024 × 1024 pixel resolution, TiO2 high quality
mirror, rotating table a 35-kg maximum load, rotary table control device and computer set. The
apparatus schematic of the neutron tomography is shown in figure 3.
Figure 1. Three gating system designs of the femoral stem in the vertical centrifugal casting (a) first design (b) second design (c) third design

Figure 2. As-cast femoral stems without the gating system (a) first design (b) second design (c) third design

Figure 3. Apparatus schematic of neutron tomography [21]
In the neutron tomography, the femoral stem was rotated in 360° and bombarded by neutron beam to obtain 400 images. The images were taken using a CCD camera during 200 s/image. These images were reconstructed by Octopus 8.8 to obtain the cross section images and 3D visualization was carried out using VG Studio Max 2.2. The porosity was analyzed based on the results of neutron radiography film and neutron tomography in the 3D visualization.

3. Result and discussion
The neutron radiography film of the three gating system designs are shown in figure 4. The first design has small porosity in near-surface region of the femoral stem but in the second and third designs have several large porosities also in near-surface region. These porosities take place at the femoral stem on the ingate location. The internal porosity in the second design is detected obscurely at the middle of the femoral stem as referred by the arrow. However, it cannot be detected in the first and third designs. The neutron tomography results of the femoral are shown in figure 5, while the middle slice longitudinally is shown in Fig.6. The colour bar beside of the femoral stem represents volumes of the internal porosity as 0-50 mm³. According to figure 5 and figure 6, the large internal porosity in all of designs occur in the biggest part. The large internal porosity is also detected in the middle of the femoral stem at both of the first and second designs. The small internal porosity was spread out in the middle of the largest part of the femoral stem at all of gating system designs.

The porosity is caused by internal shrinkage [7] and the entrapped gas [8] in the liquid metal. Although the casting chamber was set in vacuum condition, the cover gas such as the inert argon gas which is commonly used in Ti casting process, may follow the liquid metal from melting chamber into the mold cavity. The gas also can be generated by metallurgical reactions [7]. According to the neutron radiography results, the porosity where the ingate is located, indicates that the ingate solidified faster than the casting. The internal shrinkage occurs in the casting and results the porosity. The first design has the smallest porosity near the ingate. In the first ingate design, the solidification time between the ingate and the casting is smaller than other designs.

![Figure 4. Neutron radiography film from the femoral stems; A is first design, B is second design, and C is third design](image-url)
Based on the results of neutron tomography, the porosity volume about 50 mm$^3$ takes place in the largest part of the femoral stem at all of the ingate designs. It also occurs in the middle of the femoral stem at both the first and second designs. It shows that the largest part of the femoral stem solidifies slower than its surrounding, results the shrinkage porosity. It can be controlled using an engineering approach based on modulus. Modulus is ratio of the volume to surface area or crudely the heat to be removed by the removal rate [22].

![Figure 5. Neutron tomography transparently of the femoral stems (a) first design (b) second design (c) third design](image)

![Figure 6. Middle slice longitudinally on the neutron tomography of the femoral stems (a) first design (b) second design (c) third design](image)

Uniformity of liquid metal solidification is the key issue in controlling the position of defect [23]. The first design has two large porosities in middle of the femoral stem and a small porosity in sub-
surface region. The second design has three large porosities at the middle of the femoral stem and several large porosities in subsurface region. Both the several large porosities in sub-surface region and large porosities in the largest region occur at the third design. The large porosity in sub-surface region may cause a reject product at the casting. Based on the results of the three designs of gating system, the second design is the worse design while the first design may be promote as the better design.

4. Conclusion
The neutron radiography and tomography are the methods in non-destruction test (NDT) of materials. The neutron tomography represents the internal condition of the materials. The porosity of the femoral stem which was casted in three gating system designs is investigated to obtain the best gating system design. The large porosity distributed in the largest part of the femoral stem at all of the gating system designs while it occurs in sub-surface region at both the second and the third designs. The first design may be promote as the best design.

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