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

**Sutiyoko[1,2*], Suyitno[1], M Mahardika[1], F Akbar[3], Juliani[3], Setiawan[3] and Baroto[3]**

[1]Department of Mechanical and Industrial Engineering, Gadjah Mada University, Yogyakarta, Indonesia
[2]Foundry Department, Manufacturing Polytechnic of Ceper, Klaten, Indonesia
[3]National Nuclear Energy Agency (BATAN), South Tangerang, Indonesia

Email : yoko_styk@yahoo.com; suyitno@ugm.ac.id; muslim_mahardika@ugm.ac.id; ozie@batan.go.id

**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.

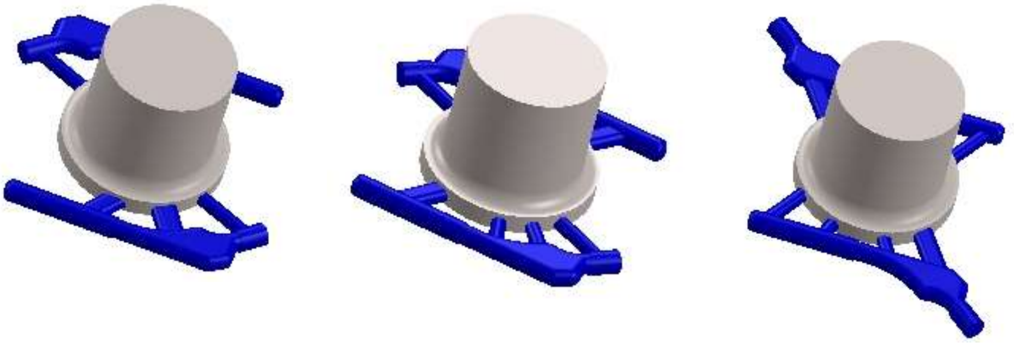
## 2. Experimental

### *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 $mm^2$, 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, $TiO_2$ 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.



(a) (b) (c)

**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

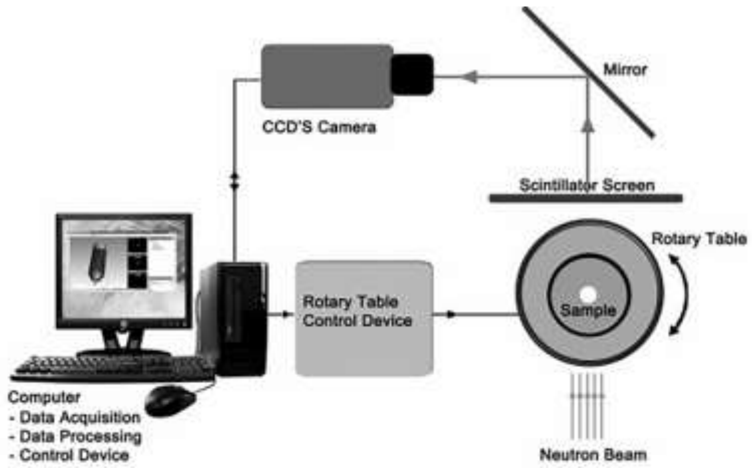



**Figure 3.** Apparatus schematic of neutron tomography [21]

In the neutron tomography, the femoral stem was rotated in 360 $^{o}$ 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 mm$^3$. 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.

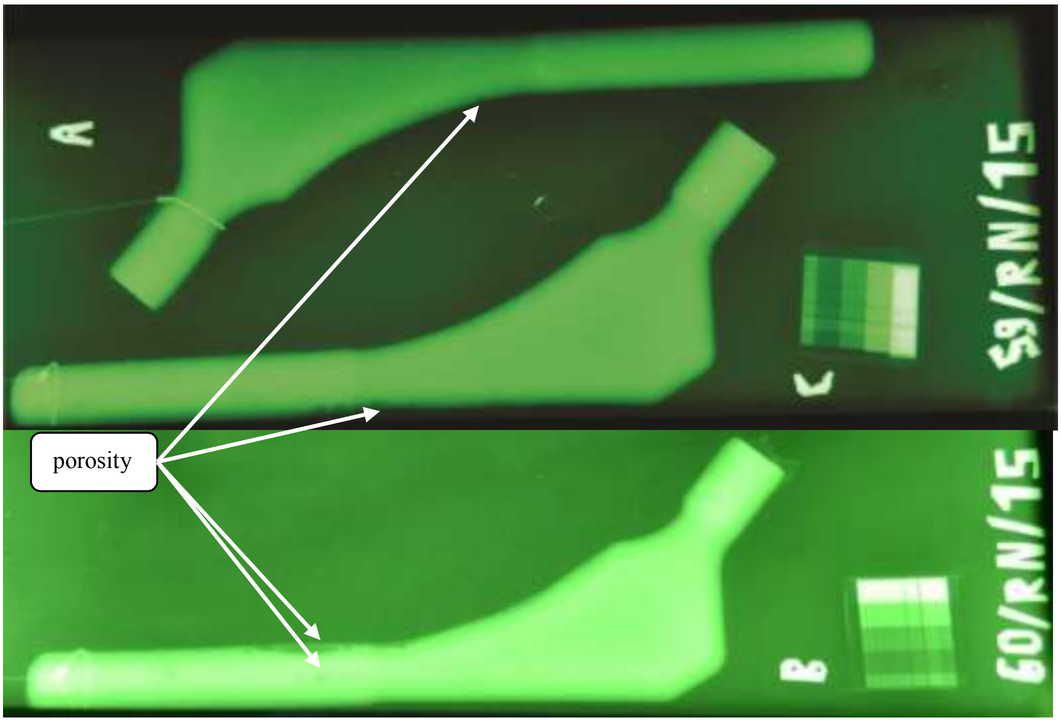



**Figure 4.** Neutron radiography film from the femoral stems; A is first design, B is second design, and C is third design

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].

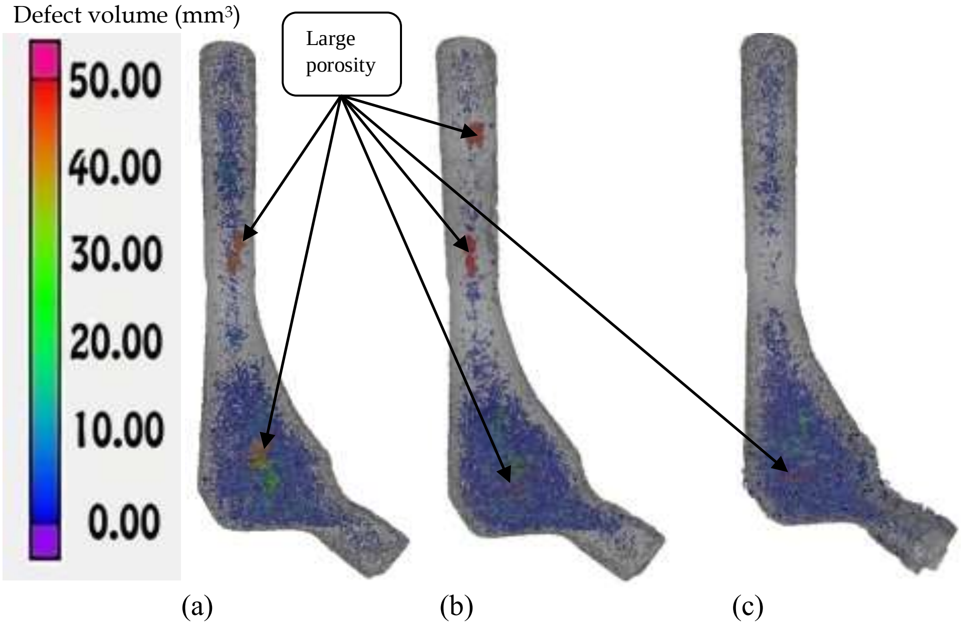



**Figure 5.** Neutron tomography transparently of the femoral stems (a) first design (b) second design (c) third design

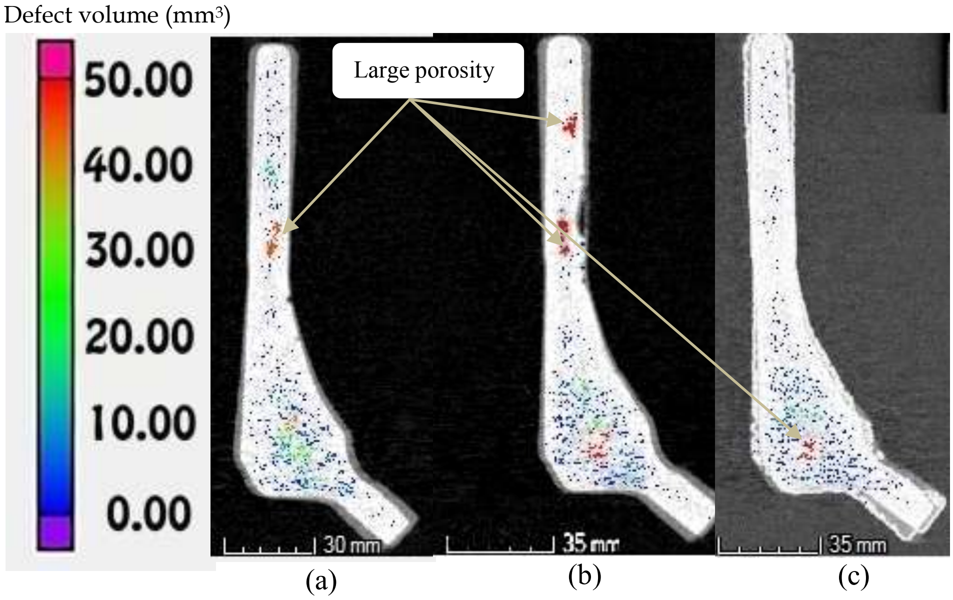



**Figure 6.** Middle slice longitudinally on the neutron tomography of the femoral stems (a) first design (b) second design (c) third design

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.

## References

[1] Wong J Y, Bronzino D R and Peterson J D 2013 *Biomaterials principles and practices* (Boca Raton: CRC Press)
[2] Nogueira F, Fais L M G, Fonseca R G and Adabo G L 2010 The influence of short-heating-cycle investments on the quality of commercially pure titanium castings *J. Prosthet. Dent.* **104** 265–72
[3] Rahmati S, Farahmand F and Abbaszadeh F 2010 Application of rapid prototyping for development of custom – made orthopedics prostheses : An investigative study *Int. J. Adv. Des. Manuf. Technol.* **3** 11–6
[4] Ramos M and Simões J A 2009 CAD-CAM-RTV – lost-wax casting technology for medical implants *Rapid Prototyp. J.* **15** 211–5
[5] Vekariya R and Ravani R 2013 Investment Casting Process uzing fuzzy logic modelling *Int. J. Mech. Eng. Robot. Res.* **2** 232–41
[6] Atwood R C, Lee P D, Curtis R V and Di Silvio L 2005 Multiscale modeling of titanium *investment* cast dental prostheses *Mater. Sci. Eng. C* **25** 255–62
[7] Wu M, Sahm P R, Augthun M, Spiekermann H and Schädlich-Stubenrauch J 1999 Numerical *study* of porosity in titanium dental castings *J. Mater. Sci. Mater. Med.* **10** 519–25
[8] Magnitskiy A 1970 Casting properties of titanium alloys *Cleating-House Fed. Sci. Tech. Inf. Springf.* 5 and 92
[9] Jiang W, Fan Z, Chen X, Wang B and Wu H 2014 Combined effects of mechanical vibration and wall thickness on microstructure and mechanical properties of A356 aluminum alloy produced by expendable pattern shell casting *Mater. Sci. Eng. A* **619** 228–37
[10] Wits W W, Carmignato S, Zanini F and Vaneker T H J 2016 Porosity testing methods for the quality assessment of selective laser melted parts *CIRP Ann. - Manuf. Technol.* **65** 201–4
[11] Jiang W, Fan Z, Liu D and Wu H 2013 Influence of gas flowrate on filling ability and internal quality of A356 aluminum alloy castings fabricated using the expendable pattern shell casting with vacuum and low pressure *Int. J. Adv. Manuf. Technol.* **67** 2459–68
[12] Just P, Rost J, Echelmeyer T L, Ebert and Roscher M A 2016 A method to quantify coating thickness and porosity of electrodes for lithium-ion-batteries *Meas. J. Int. Meas. Confed.* **89** 312–5
[13] Khademzadeh S, Carmignato S, Parvin N, Zanini F and Bariani P F Micro porosity analysis in additive manufactured NiTi parts using micro computed tomography and electron microscopy *J.Mater Design* **90** 745–52
[14] Tudisco E, Hall S A, Charalampidou E M, Kardjilov N, Hilger A and Sone H 2015 Full-field Measurements of Strain Localisation in Sandstone by Neutron Tomography and 3D-Volumetric Digital Image Correlation *Phys. Procedia* **69** 509–15

[15] Abdullah M Z, Ashaari N A, and Aziz M A 2009 Development of a neutron tomography system for industrial applications *Meas. J. Int. Meas. Confed.* **42** 1017–26
[16] Abd el Bar W, Mahmoud I I, Konber H A and Mongy T 2015 Image reconstruction technique using projection data from neutron tomography system *Alexandria Eng. J.* **54** 1057–66
[17] Pugliesi R, Andrade M L G, Dias M S, Siqueira P T D and Pereira M A S 2015 Study of pixel damages in CCD cameras irradiated at the neutron tomography facility of IPEN-CNEN/SP *Nucl. Instruments Methods Phys. Res. Sect. A.* **804**, 59–63
[18] Pereira M A S, Schoueri R, Domienikan C, de Toledo F, Andrade M L G and Pugliesi R 2013 The neutron tomography facility of IPEN-CNEN/SP and its potential to investigate ceramic objects from the Brazilian cultural heritage *Appl. Radiat. Isot.* **75** 6–10
[19] Kichanov S E, Kozlenko D P, Ivankina T I, Rutkauskas A V, Lukin E V and Savenko B N 2015 The Neutron Tomography Studies of the Rocks from the Kola Superdeep Borehole," *Phys. Procedia* **69** 537–41
[20] du Plessis A and Rossouw P 2015 X-ray computed tomography of a titanium aerospace investment casting *Case Stud. Nondestruct. Test. Eval.* **3** 21–26
[21] Sutiarso, Akbar F, Gunawan and Indradjaja A 2012 Neutron tomography application in Batan Serpong for internal structure investigation of archeological object *Conference of science and materials technology* 181–4
[22] Monroe R 2005 Porosity in castings *AFS Trans.* **5** 1–28
[23] Lu S, Xiao F, Zhang S, Mao Y and Liao B 2014 Simulation study on the centrifugal casting wet-type cylinder liner based on ProCAST *Appl. Therm. Eng.***73** 512–21

**Acknowledgment**
This work was supported by Applied Research Grant in Research, Technology and High Education Ministry of Indonesia.