



ARCHIVES

of

FOUNDRY ENGINEERING

DOI: 10.1515/afe-2016-0102

ISSN (2299-2944)

Volume 16

Issue 4/2016



Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

157 – 162

Prediction of Shrinkage Porosity in Femoral Stem of Titanium Investment Casting

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Received 30.06.2016; accepted in revised form 16.08.2016

Abstract

Design of gating system is an important factor in obtaining defect-free casting. One of the casting defects is a porosity caused by internal shrinkage in solidification process. Prediction of the internal shrinkage porosity in the femoral stem of commercially pure titanium (CP-Ti) is investigated based on the gating system design. The objective of this research is to get the best gating system between three gating system designs. Three gating system designs of the femoral stem were simulated in an investment casting method. The internal shrinkage porosity occurs on the largest part and near the ingate of the femoral stem. The gating system design that has ingates cross section area: 78.5; 157; and 128.5 mm² has the least of the internal shrinkage porosity. This design has the most uniform solidification in the entire of the femoral stem. An experiment is conducted to validate the simulation data. The results of internal shrinkage porosity in the three gating system designs in the simulation were compared with the experiment. Based on the comparison, the trend of internal shrinkage porosity at the three gating system designs in the simulation agrees with the experiment. The results of this study will aid in the elimination of casting defect.

Keywords: Femoral stem, Shrinkage porosity, Commercially pure titanium, Investment casting

1. Introduction

One of the methods in titanium casting is an investment casting process. The investment casting is used widely in biomedical, aerospace and automotive industries for manufacturing of complex metal shapes [1]. This method suitable to produce a complex shape in a good quality, however it has complex, time-consuming and expensive process. Numerical simulation of the investment casting can be considered to reduce cost and time in design preparation. There are many problems in numerical simulation of the investment casting. For example, complex shape causes uneven heat dissipation during cooling. Finally, the uneven heat dissipation effects on non-linear and non-uniform shrinkage distribution [2].

Using of numerical simulation can assist in casting process. The numerical simulation software usually uses finite-different method (FDM) and finite-element method (FEM) for casting analysis. Commonly, the first method is used in thermal transfer, solidification and metallic filling flow in many casting simulations, while the second method can treat complicated boundary condition and performs well in accuracy [3]. The casting simulation should be used when economically justified for at least one of the three reason: quality enhancement, yield improvement and rapid development [4]. For example, optimizing gating system design and predicting shrinkage porosity of dental parts was done using MAGMASOFT. Four kinds of runner system for simulation and computational efficiency was analyzed by the component-wise spitting method and the explicit finite difference method [5]. ProCAST software can predict the shrinkage porosity of Ti Al alloy. This research investigated effect

of temperature gradient of the mold, pressure and pouring temperature on the shrinkage porosity [6].

Many researchers focused their research on the gating system in titanium casting. Effect of sprue design on roughness and porosity in the titanium dental casting was investigated. The sprue design variation made in number of main sprue and their positions. Based on this research, the double-sprue design is more effective than the single main sprue design in decreasing the internal porosity and smoothing surface of the titanium crown casting [7]. A numerical simulation to optimize the runner and the gating system of the titanium dental casting was reported by Wu et al. [8]. The cast crown with free of porosity and smooth surface was obtained from the first casting trial by using integrated scanning, rapid prototype pattern and casting procedure. Wu et al. [9] demonstrated the numerical simulation of titanium prostheses and implant casting. Optimization of the gating system design and casting parameters reduce the defect level.

A soundness casting indicates the porosity in the casting product. Density measurement is one of the methods to determine the porosity [10]. The porosity, one of the most frequent defect occurring in metal casting, is still of a serious problem recently. Both the shrinkage during solidification and entrapped gas in product cause the porosity [11]. The shrinkage porosity was divided as micro-or macro shrinkage [3]. This defect is quite sensitive to casting geometry, running process parameters and gating-system design [9]. Volumetric shrinkage upon solidification causes the porosity. The volumetric shrinkage creates the shrinkage porosity if casting parameters are not properly controlled which it tends to be distributed in the last areas to solidify. The shrinkage porosity was quantitatively predicted using an essential feeding criterion [12]. The shrinkage porosity of Ti-Al alloy significantly improve by forming the vertical temperature gradient of $3^{\circ}\text{C}/\text{mm}$ on the mold, while the pressure on the molten metal alloy and the increasing of pouring temperature have no apparent effect on the reduction of the shrinkage porosity [6]. Shrinkage characteristic control is an important factor for producing defect-free castings [13]. Another research about titanium casting shrinkage explains that estimation of titanium casting shrinkage is about 1.55% [14].

Design of gating system is a critical factor causes the shrinkage porosity in titanium casting. Traditionally casting technicians often relied on practical experience, trial and error methods to determine gating system design for obtaining the soundness casting. Alternatively, numerical simulation software for modeling in casting process is more often used in foundry [15]. Titanium is an expensive material, trial and error method by real casting of this material will time consuming and more costly. The objective of this research is to compare the effect of the three gating system designs on the internal shrinkage porosity of the titanium femoral stem investment casting.

2. Methodology

The commercially pure titanium (CP-Ti) was used in this simulation. The femoral stem was designed particularly for Indonesian as can be seen in Fig. 1(a). Three gating system designs as can be seen in Fig. 2-4 were designed with investment mould. Sprue design (Fig. 1(b)) was fixed in all designs, but ingate

design was independent. The ingate was fixed in total cross section area, but its number, dimension, and location were independent variables. There are three gating systems that total cross section area of each gating system was 364 mm^2 as was shown in Fig. 2-4. There were three cavities in each the investment mold. The "A" gating system design has three ingates (cross section area: $78.5; 157; 128.5\text{ mm}^2$) which the biggest ingate in the largest part of the femoral stem. This design is hoped the liquid metal can fulfill the largest part of the femoral stem. The "B" gating system design has four ingates (cross section area: $78.5; 78.5; 78.5; 128.5\text{ mm}^2$) which two ingates in the largest part of the femoral stem casting. Similar to the "B" gating system design, there are four ingates (cross section area: $128.5; 78.5; 78.5; 78.5\text{ mm}^2$) in the "C" gating system design, but the femoral stem position is inversed. The four ingates both in the "B" and "C" gating system design are expected to strive for uniformity of liquid metal spread in the cavity.

The investment casting process of the femoral stem with the three gating system designs were simulated by the Solid Cast 7.0.2 software. Thermal conductivity and specific heat capacity are 31 W/m-K and 965 J/kg-K respectively [1]. The solidification range is estimated $1660\text{-}1667^{\circ}\text{C}$ [16] while latent heat of fusion is 391 kJ/kg [9]. Pouring temperature and filling time are 1700°C and 4s. The mould was made in investment casting method with thermal conductivity, specific heat and density were 1.73 W/m-K , 836.8 J/kg-K , 2082.34 kg/m^3 respectively (Solid Cast).

Sprue design at each molding is shown in Fig.1(b). Three designs of the femoral stem ingate were shown in Fig.2-4, and total cross section area was 364 mm^2 for every design. The design of casting and gating system in 3D model was converted into a standard STL format. These designs were meshed with node size $1 \times 1 \times 1\text{ mm}$. The shrinkage porosity is indicated by material density parameter. Material density was determined as 0.99 because below of this value was minimum value for detectable shrinkage porosity in the casting. Volumetric shrinkage porosity is computed by multiplying the shrinkage porosity cross area in the top view of cavity by average of shrinkage porosity thickness in the front view of each cavity using Image J.

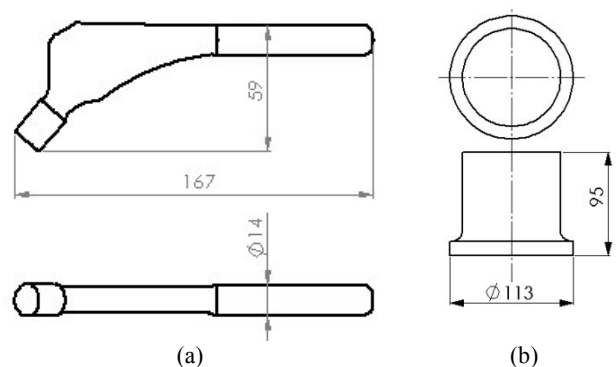


Fig. 1. Design of (a) femoral stem and (b) sprue (mm)

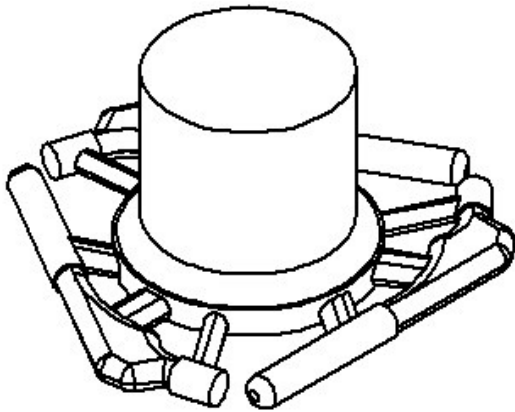


Fig. 2. Gating system design "A" type of the femoral stem casting

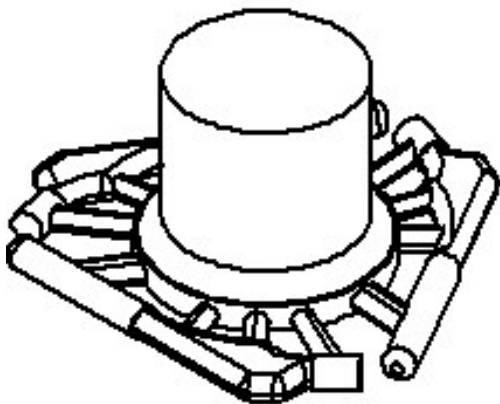


Fig. 3. Gating system design "B" type of the femoral stem casting

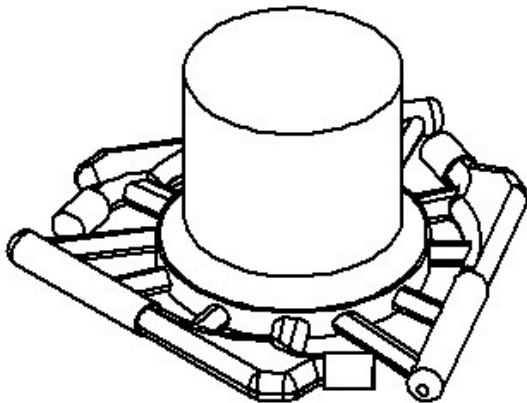
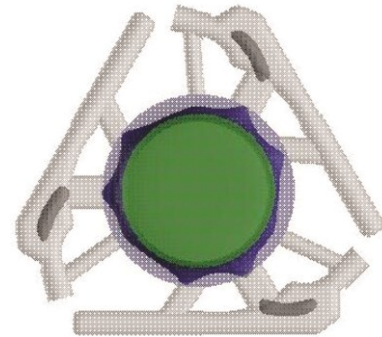


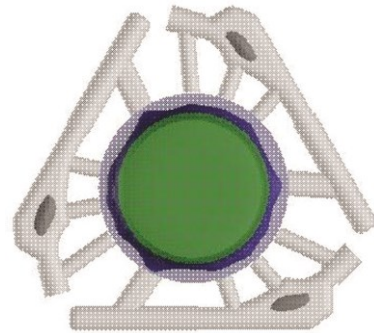
Fig. 4. Gating system design "C" type of the femoral stem casting

3. Results and Discussion

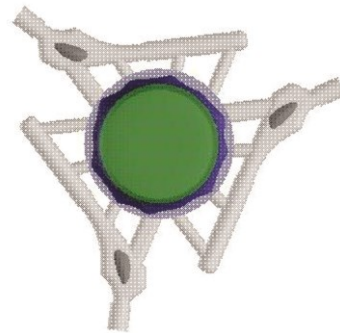
Solidification time of liquid titanium at 0.5 minutes after mold filling for each design can be seen in Fig. 5. The dark area inside the casting represents the location of liquid titanium that not yet completely solidified. It occurred in the largest part of each design. The last area which not yet solidified completely in the "A" design turned to ingate part, while it occurred in the middle of the femoral stem at the other designs.



(a)



(b)



(c)

Fig. 5. Solidification time of each design at 0.5 minutes after mold filling in (a) the "A" design (b) the "B" design (c) the "C" design

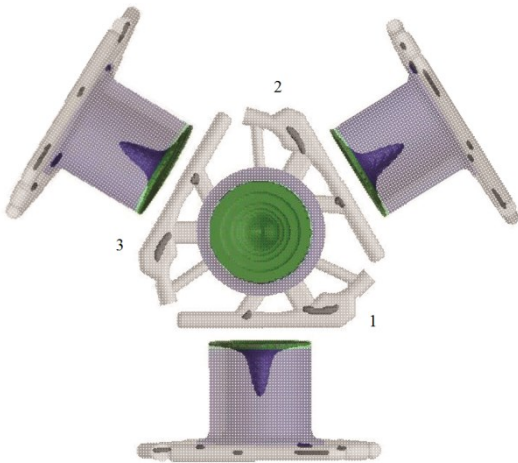


Fig. 6. Top view of the shrinkage porosity (dark area) in the "A" design with front view for each cavity

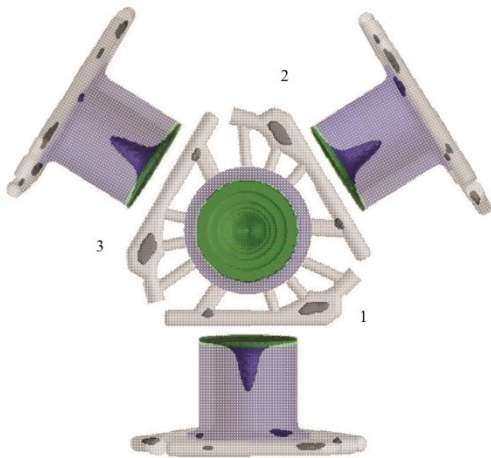


Fig. 7. Top view of the shrinkage porosity (dark area) in the "B" design with front view for each cavity

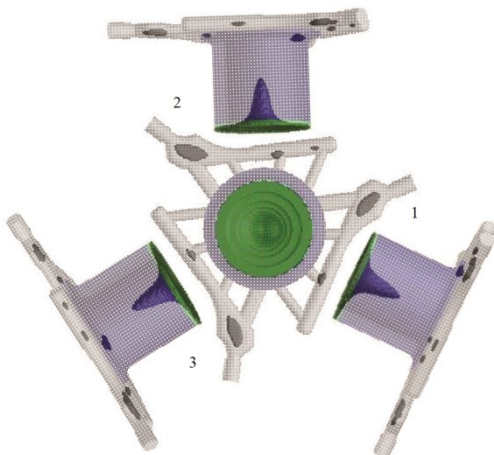


Fig. 8. Top view of the shrinkage porosity (dark area) in the "C" design with front view for each cavity

The shrinkage porosity occurs in the femoral stem casting simulation at the all of the gating system designs. The shrinkage porosity of the three designs is shown in Fig 6-8. A Dark area indicates the shrinkage porosity in the femoral stem and sprue. There are three cavities of femoral stem signed by number 1, 2 and 3 for each design. The shrinkage porosity takes place in near of ingate for all gating system designs. In the "A" design, the shrinkage porosity occurs at a part of the ingate and the casting while it occurs only in the casting at the other designs.

Table 1.

Shrinkage porosity in each specimen

Design Code	Specimen	Shrinkage porosity (mm ³)	Average of shrinkage porosity (mm ³)
A	1	870	714
	2	589	
	3	684	
B	1	1187	1306
	2	1182	
	3	1548	
C	1	1337	1697
	2	1454	
	3	1941	

Volumetric internal shrinkage porosity of the "A" design is smaller than the others as described in Table 1. The volume internal shrinkage porosity in the "A" design is 714 mm³ while in the "B" and "C" designs are 1306 and 1697 mm³ respectively. The shrinkage porosity results in the each specimen are not exactly same but have a resemblance.

Shrinkage occurs during solidification process while the density increases. During solidification, the liquid metal volume declines in terms of the atoms drawing nearer and reaching to fixed lattice positions resulting in shrinkage. There are three stages of shrinkage; shrinkage of liquid metal until liquidus, shrinkage during solidification, shrinkage from solidification to room temperature [13]. If there are many internal sites as a nucleation of shrinkage, the internal shrinkage will occur and appears as porosity [17]. Micro shrinkage defect is an irregular shape with dendrites, small cavity and usually can not be seen by naked eye. It may be seen after machining of product [18]. Macro shrinkage occurs if there is significant amount of solid material covered the liquid metal, which is strong enough to restrain the depression of the contracting liquid [19]. In a good gating system design, the shrinkage occurs in riser or additional dimension of casting. For this condition, a good product will be achieved although the porosity is not only caused by shrinkage but also by oxide layer and nonmetallic inclusion in the liquid metal [17].

The shrinkage porosity occurs in all of the three gating system designs of the femoral stem casting. Based on Table 1, the shrinkage porosity in the "A" design is smaller than that in the other designs. Temperature gradient between the surface and

middle of casting has a significant effect on the porosity formation [6]. The result of the shrinkage porosity indicates that the gradient temperature between the surface and the middle of casting in the "A" design is the smallest. The ingates in the "A" design hold the temperature in the surface of casting and result in the smallest gradient temperature between the middle and the surface of the femoral stem.

Solidification time of 0.5 minutes in the both "B" and "C" gating system designs indicated that liquid titanium at the ingate solidified completely while it not yet occurs in the center of the femoral stem. This condition is caused by modulus in the center of the femoral stem is larger than that at the ingate. The ingate in these designs was designed as riser of casting and solidification was directed to the ingate. Based on the results of this simulation, the "A" gating system design showed better design because it has the lowest shrinkage porosity and its porosity occurs at near of the ingate.

The other factor caused internal shrinkage porosity is uniformity in liquid metal solidification. Liquid metal from the ingate will spread to the entire of the cavity and solidify. The more uniform of solidification results in the smaller porosity which is caused by internal shrinkage porosity. For this research, the uniformity in solidification is influenced by the position, number and size of ingates. Three ingates in the "A" gating system design which the greatest dimension is in the largest part of the femoral stem give the best uniformity. The sprue does not be considered because it was made same for all the gating system design. The best combination of these ingate parameters will result in the uniformity in liquid metal solidification. Therefore, reaching uniform solidification is a key issue in controlling the position of the casting defects [20]. Based on these results, the "A" design has more uniform in solidification of liquid metal and has the smallest porosity.

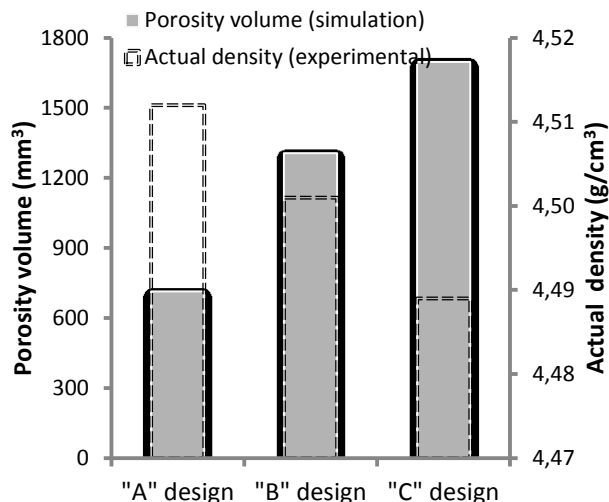


Fig. 9. Comparison between simulation and experimental in the femoral stem casting

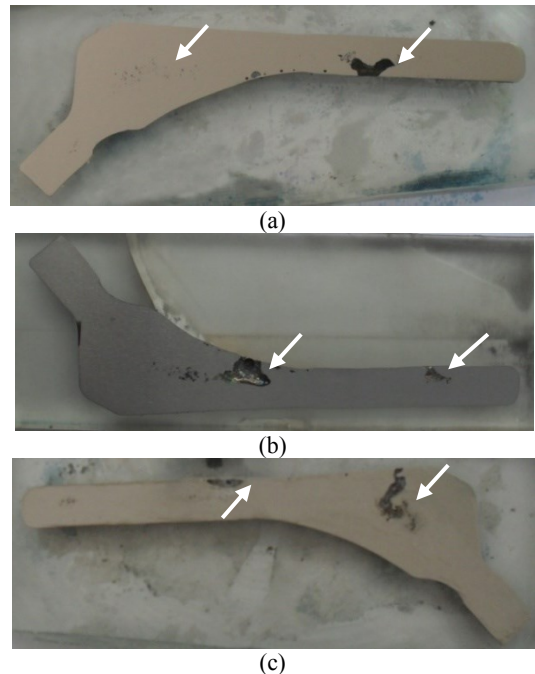


Fig. 10. Longitudinal middle slice of the femoral stem in the experimental results (a) "A" design (b) "B" design (c) "C" design, the narrows indicate the porosity

Validation of these simulations was carried out by measurement the actual density based on an Archimedean principle in casting experiment as can be seen in Fig. 9. Three femoral stems for each gating system design were casted and their actual densities were measured. The actual density of "A", "B" and "C" designs are 4.512; 4.501 and 4.489 g/cm³ respectively while the porosity volume are 714; 1306 and 1697 mm³ respectively. The actual density in the experiment casting decreases from "A" to "C" design but the porosity volume in the casting simulation increases. The shrinkage porosity is inversely proportional to the actual density, or if the actual density is high, the shrinkage porosity is low. Based on the actual density and porosity volume data, the "A" design is the best gating system.

The porosity defect was investigated in the experimental casting of the three gating system designs as shown in Fig.10. There are porosities in all of the femoral stems. These porosities occur at the almost similar location with the simulation results. The porosity take place in the near of ingate and in the biggest part of the femoral stem. As before, The "A" gating system design makes the liquid metal fills the cavity more uniform than that in the both "B" and "C" gating system designs.

3. Conclusion

Three designs of gating system in casting of the femoral stem were simulated in this research. The internal shrinkage porosity was predicted to determine the best design of the gating system in this casting. The gating system has a variation not only in number and position of the ingate but also on the position of the femoral

stem. The best gating system based on the internal shrinkage porosity is the "A" design. More uniform solidification of liquid metal in the femoral stem causes decreasing of the internal shrinkage porosity. Further execution, the optimal design will be proposed based on this result.

Acknowledgements

This work was supported by Applied Research Program No. 046/K6/KM/SP2H/RISET TERAPAN/2016 in Research, Technology and High Education Ministry of Indonesia

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