INFLUENCE OF GATE SHAPE AND DIRECTION DURING CENTRIFUGAL CASTING ON ARTIFICIAL LUMBAR DISC MODEL OF Cp-Ti

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Abstract
Shape and direction of gate in centrifugal casting affected the microstructures and defects in castings. The purpose of this research was to determine the effects of gate shape and direction in centrifugal casting toward on porosity, density, roughness, and microstructures on the artificial lumbar disc model. The main shapes of the gate were circular and rectangular cross-section. The circular cross-section gate shape was used for two different directions of artificial lumbar discs; vertical, and horizontal. Furthermore, the rectangular cross-section gate shape consisted of three different directions; oblique clockwise, oblique counter-clockwise and perpendicular towards the mold. The rotational mold was conducted at a speed of 60 rpm. The results showed that the rectangular cross-section gate shape with the oblique direction same with the rotation of the mold produced artificial lumbar disc model that had the smallest porosity area among the other directions. It was the best shape and direction of the gate among the others which had the smallest porosity area (0.68%), highest density (4.517 g/cm^3), and smoothest roughness (8.76 μm). In the sub-surface, the microstructure of α-case was formed. The thickness and hardness of the α-case in this design were 50-100 μm and 760 VHN, respectively. Hence, the rectangular cross-section gate shape with the oblique direction same with the rotation of the mold was appropriate to be applied in the manufacture of an artificial lumbar disc model.

Keywords: Gating system, Foundry, Centrifugal casting, Artificial lumbar disc model

1 Introduction

Centrifugal casting has several advantages such as accurate dimensions, smooth surface finish, limited gas porosity, faster solidification, and effective cost rather than the traditional gravity casting method [1, 2]. These advantages are caused by the distribution of the liquid metal into the mold which is using forces generated from the centripetal acceleration of a rotating mold. The centrifugal force is a function of radius, metal density, and rotational speed [1]. The rotational speed that directly controls the pressure distribution affects the shrinkage cavity. In general, increasing centrifugal force can decrease defects [3].
The gating system is an essential element in the casting process, which affects the molten metal flow behavior [4]. The purpose of gating system design in centrifugal casting is to get the product

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with minimal defects such as porosity. Porosity can occur due to the trapped gas or shrinkage during the cooling process [5-7]. Shrinkage control is carried out to produce defect-free products [8]. Modifications and trial errors of gating system design are less efficient and high cost to acquire good quality products. Therefore, computer simulation is sufficient to be used to plan the gating system design. The simulation results show the suitability with experimental data such as liquid solidification, porosity area, trapped gas, and filling behavior occurred in the foundry process [6, 9-11].

The direction, position, and cross-section of gating system design on centrifugal casting are made to get products with minimal shrinkage porosity. Gate shapes that often used are circular [4], rectangular [10, 12-14], and hexagonal [10] cross-section with perpendicular direction to the mold. The circular cross-section of the gate shape has a higher molten metal filling speed rather than the rectangular or hexagonal [10]. Viscosity increases rapidly in rectangular and hexagonal cross-section which has a closer gate wall distance to the cross-section center than a circular one. This condition affects porosity, which tends to be more numerous [10].

The internal porosity can be reduced by adjusting a high rotational speed (≥180 rpm) [15]. On the other hand, it can reduce the mechanical properties of the product. In the gating system, decreasing cross-sectional area towards the mold cavity increased the pressure that will affect the tensile strength [16]. On the contrary, increasing cross-sectional area towards the mold cavity reduced turbulence [16]. Research of gate shape and direction on centrifugal casting is still needed to make the best design so that liquid metal can enter the mold cavity with higher pressure and low turbulence. Changing geometry, shape, and number of the gate can be the solution affected higher pressure and low turbulence [13]. On the other hand, researches on the oblique direction of gating system design are still unavailable.

However, the final products of centrifugal casting still have porosity even though circular, rectangular, or hexagonal cross-sections of gate were used. Gate design with the oblique of clockwise or counter-clockwise directions, which purposed to increase the speed of molten metal in entering the mold, has not been applied. The study was conducted to determine the effects of shape, direction, and position of gate design toward on porosity, density, microstructure, hardness, and surface roughness of the artificial lumbar disc model. Artificial lumbar disc model in this research is prepared for the spinal implant. Porosity, density, and hardness controls of the product must be carried out so that the product strength is adequate. The surface roughness of the product must be adjusted with the bioactive area [17].

2 Material and Methods

2.1 Used Material and Mold

This study used commercial pure titanium (Cp-Ti) with 99.72 wt% Ti; 0.17 wt% Fe; and 0.11 wt% gaseous element. Analysis of composition used EDS (Quanta x50 SEM Series). Cp-Ti was melted at a temperature of 1700°C, then poured in an artificial lumbar disc model shell mold. The shell mold was made from the zirconium-based ceramic material consisted of 8 layers. The filling time of the centrifugal casting when pouring was constant with the molten metal pouring rate of about 0.12 kg/s. Furthermore, the mold was rotated at 60 rpm when molten metal was poured. The above processes were carried out in the vacuum furnace (Flash caster, Japan).

The schematic product geometry and product of artificial lumbar disc model can be seen in **Fig.1**. The outer diameter of the product was 30 mm, then the radius of the ball-on-socket was 13 mm with 2 mm of depth.

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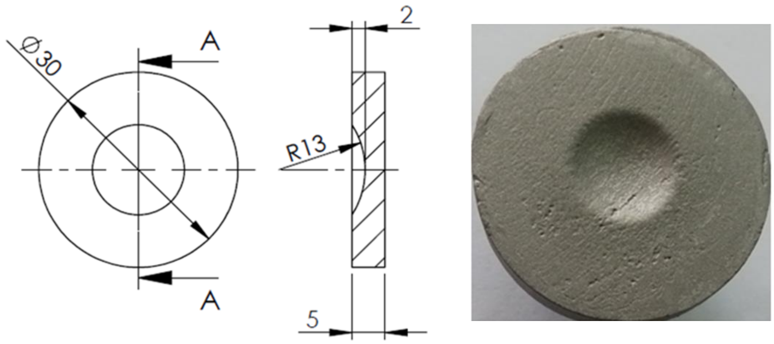
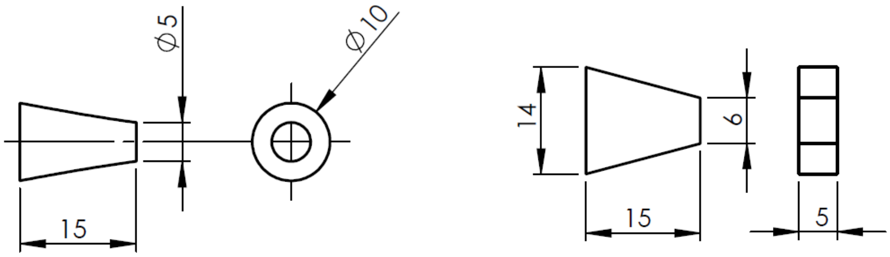


a. b.

Fig. 1 The schematic geometry of product (a) and product (b) of artificial lumbar disc model

2.2 Gate Shape and Direction

The shape and geometry of gate can be seen in **Fig.2**. The main shapes of gate design were circular (**Fig. 2.a**) and rectangular cross-section (**Fig. 2.b**). The geometry of gate cross-section area decreased gradually to increase the pressure of molten metal when entering the mold. The length of each gate types was 15.0 mm. The circular cross-section area was 78.5 mm^2 then decreased gradually until 19.6 mm^2 when entering the mold. While the rectangular cross-section area was 70.0 mm^2 then decreased gradually until 30 mm^2 when entering the mold.



a. b.

Fig. 2 The gates shape and geometry

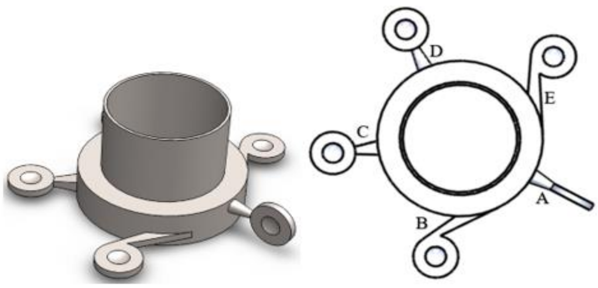


Fig. 3 The gates position and direction of artificial lumbar disc model

The gate position and direction was shown in **Fig. 3**. The circular cross-section design was used for two different directions of artificial lumbar discs, namely vertical “A” and horizontal “D”. The

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direction of this design was perpendicular toward the mold. The rectangular cross-section design consisted of three different directions, namely oblique clockwise “B”, perpendicular “C”, and oblique counter-clockwise “E” toward the mold. All positions of the mold on the rectangular gate design were horizontal. The oblique direction of the clockwise and counter-clockwise was 45^o toward the mold.

The Gate shape and direction of artificial lumbar disc model was simulated using Solid Cast 7.0.2 software to predict the porosity occurred. The parameters used in the simulation refer to the research that has been done before [5, 18].

2.3 Observations and Tests

The observations carried out in this research included porosity, and microstructures. The porosity phenomena were analyzed using dye penetrant and a stereo zoom microscope (SZ-PT, Olympus, Japan). Porosity calculations that used visual inspection with millimeter blocks were carried out by comparing the area of porosity with the total area of the product. The number of pores was determined by counting manually. The microstructure characterization was analyzed using a metallurgical microscope (PME 3, Olympus, Japan) and SEM (Quanta x50 SEM Series). Preparation was done with #180 to #8000 sandpapers to obtain a smooth surface, then metal was polished. While to uncover the microstructure (etching process), a Kroll reagent was used.

The tests carried out in this research included hardness, surface roughness, and density. The hardness was obtained from the outer of the sub-surface to the inner of a cross section spanning sample using a microhardness tester (HMV-M3, Shimadzu, Japan). The distance among each test points of hardness test was 50 μm with a load of 2 N, then hold for 5 s. Surface roughness (Ra) testing was carried out in five places in the upper surface of each product using a profilometer (Surfcorder SE 1700, Fowler). The Ra tester was calibrated on the standard specimen (Ra being 3.0 μm). The density calculation was done by dividing the weight with the volume of product. The weight was measured by using analytical balancing (Sartorius AG Gottingen LC 12018, Germany)

3 Results

3.1 Porosity

The casting product was shown in **Fig. 4.a.** All gates design allow the molten metal flows properly so that there are no defects on the surface of the product. The simulation result using Solid Cast software (**Fig. 4.b**), shows there is porosity that can be seen through different colors. The product with the circular cross-section gate shape on the vertical direction (A) only has a few porosities. However, the horizontal direction (D) has the most porosities. While the rectangular cross-section gate design with oblique clockwise (B), and perpendicular (C) appear to have almost the same porosity, while oblique counter-clockwise (E) has the smallest porosity.

The porosity location of all products on the experiment results is spreading, as shown in **Fig. 5**. The porosity in all gate design is found in the middle area between the thickness of the products. Internal shrinkage porosity (**Fig. 5.F**) is found with irregular shapes in different sizes (50-200 μm). The internal shrinkage porosity that occurs has a crack tail. Crack tail (**Fig. 5.G**) occurs in transgranular (1) and intergranular (2) of grains.

The percentage of porosity area can be seen in **Table 1**. Product with the circular cross-section gate design on the vertical direction only has a few porosities (0.69%) compared to the total area

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of the product. The porosity tends to congregate with a size of about 50-150 µm. However, the horizontal direction has the most porosities (1.29%). The porosity in this design tends to congregate with a size bigger than in vertical direction (about 50-200 µm).

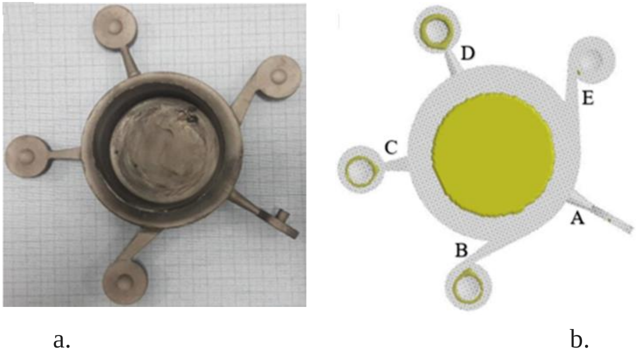

Fig. 4 The casting product (a) and simulation result (b)

Table 1 The porosity area of various gate shape and direction

Type	Total Area (mm²)	Porosity (mm²)	Percentage (%)
A	10920	75	0,687
B	10920	254	2,326
C	10920	88	0,806
D	10920	141	1,291
E	10920	74	0,678

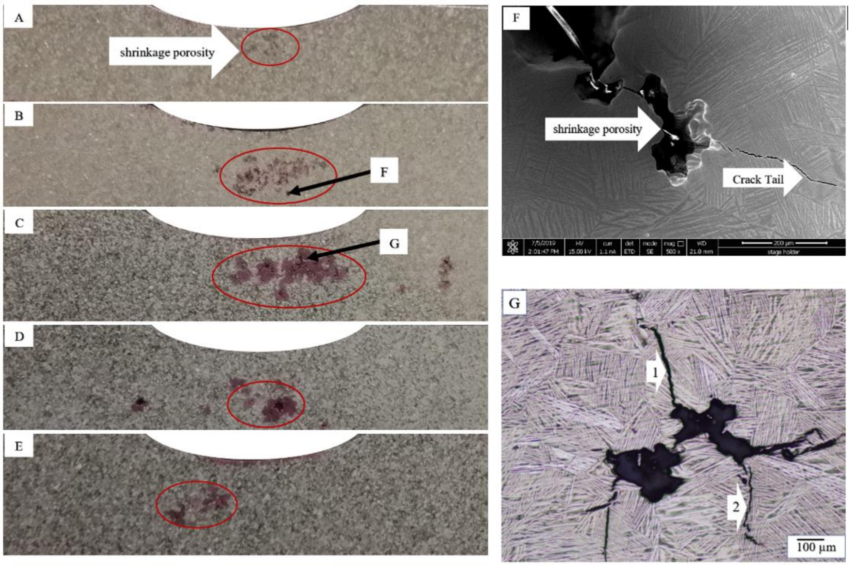

Fig. 5 The location of shrinkage porosity on product (A – E) with various types of gate shape and direction; and enlargements of shrinkage porosity (F and G in products B and C)

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Furthermore, the rectangular cross-section gate design with oblique clockwise, perpendicular and oblique counter-clockwise have 2.33%, 0.81%, and 0.68% porosities area respectively compared to the total area of the product. The porosity on the rectangular cross-section with oblique clockwise spreads with a size of about 50-150 μm. While on the perpendicular and oblique counter-clockwise direction has a size of about 50-200 μm.

3.2 Density

The products density with various types of gate design is shown in **Fig. 6**. The density of product with the circular design for vertical direction is 4,515 g/cm^3. While product with a horizontal direction has a density of 4,511 g/cm^3. Furthermore, the density of product with the rectangular cross-section with oblique clockwise, oblique counter-clockwise and perpendicular towards the mold are 4,510 g/cm^3, 4,511 g/cm^3, and 4,517 g/cm^3 respectively.

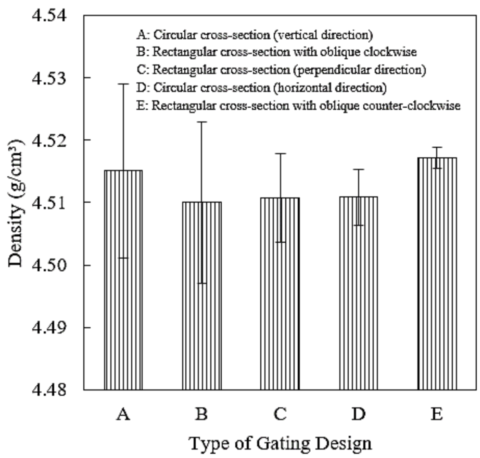

Fig. 6 The density of product with various types of gate shape and direction

3.3 Hardness and Microstructure

Fig. 7 shows the results of the hardness test. The product with a circular design for vertical and horizontal directions gate design have the same trend of hardness. The hardness with the circular design for vertical direction is 671 VHN on sub-surface, then drops significantly to 412 VHN at 250 μm from the surface. While product with a horizontal direction has a hardness of 732 VHN on sub-surface, then drops significantly to 362 VHN at 350 μm from the surface. Both products have relatively the same hardness (around 340 VHN) at a distance of 350 to 1.250 μm from the surface.

The types of α morphologies and equiaxed prior β grains were found in the microstructure of product in all kinds of gate design (**Fig. 8**). It is supported by the previous research result [19]. The types of α-morphologies are known as α-case (a), prior β grain boundaries (b), widmanstaten α (c) and fine acicular α (d) at different locations. The morphologies of grain are similar with the previous research [20]. The microstructure of the outer edge has lamellar shaped with a random, tight, and small arrangement.

In the sub-surface, the microstructure of α-case is formed. The thickness of α-case is about 50-100 μm and 250-300 μm with circular cross-section on vertical (**Fig. 8.A**) and horizontal (**Fig. 8.D**) direction respectively. The α-case on the horizontal direction has a crack (e) for about 150-300 μm length. While the rectangular cross-section with oblique clockwise (**Fig. 8.B**), perpendicular to the mold (**Fig. 8.C**), and oblique counter-clockwise (**Fig. 8.E**) are 200-250 μm, 150-200 μm, and 50-100 μm respectively. The α-case on rectangular cross-section with oblique clockwise has a crack (e) for about 150-300 μm length.

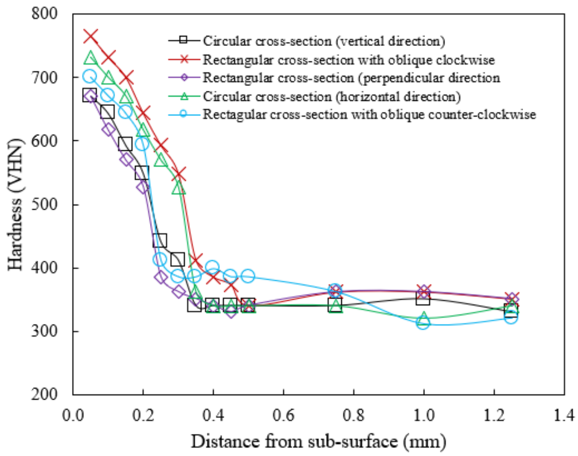

Fig. 7 The hardness of product with various types of gate shape and direction

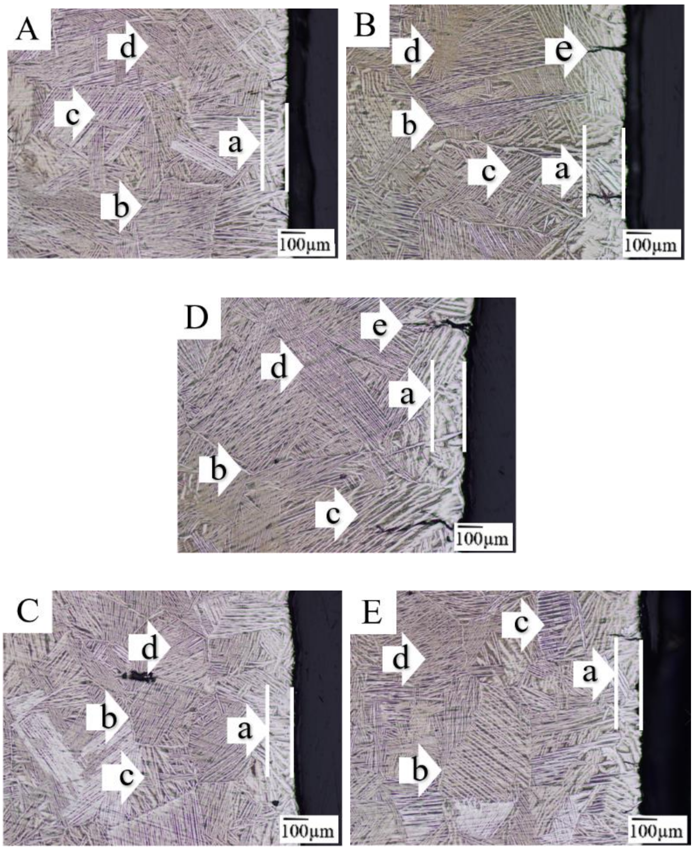

Fig. 8 The microstructures in the subsurface of the product

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Furthermore, the hardness of the product with the rectangular cross-section with oblique clockwise, oblique counter-clockwise, and perpendicular towards the mold also have the same trend in reducing the hardness. The hardness of product with oblique clockwise drops from 766 VHN in the sub-surface until 412VHN at the 350 µm from the surface. Then oblique counter-clockwise at the hardness of 701 VHN drops until 412 VHN at the 250 µm. Lastly, the perpendicular towards the mold also drops significantly from 671 VHN to 386 VHN in the distance of 250 µm from the surface. All products have relatively the same hardness (around 340 VHN) at a distance of 350 to 1.250 µm from the surface.

3.4 Surface Roughness

The surface roughness (Ra) of products are ranged from 8.76 to 11.07 µm (**Fig. 9**). The Ra of the product with circular cross-section on vertical and horizontal direction are 8.94 µm and 10.57 µm. While the Ra of the product with the rectangular cross-section with oblique clockwise, oblique counter-clockwise and perpendicular towards the mold are 11.07 µm, 8.76 µm, and 9.36 µm respectively. The product with rectangular cross-sections with oblique counter-clockwise has the smoothest surface among the others.

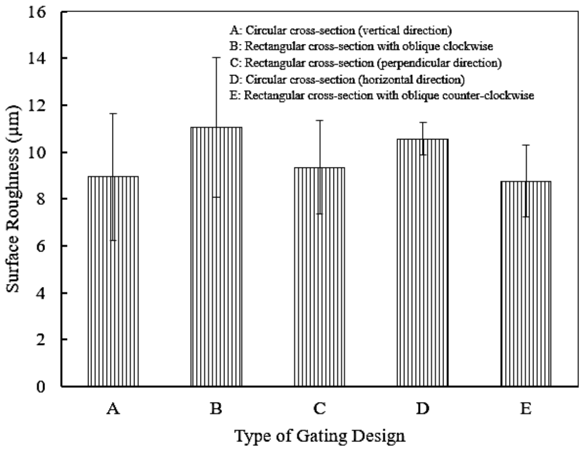

Fig. 9 The surface roughness of product with various types of gate shape and direction

4 Discussion

Product with the circular cross-section gate shape on the vertical direction has less porosities, higher density, and smoother surface than the horizontal one. This condition caused by the vertical direction has a smaller vortex space compared to the horizontal during the pouring process. The bigger diameter of the vortex flow runner in the casting product will directly proportional with the average flexural strength [4]. The porosities in both designs congregate with an irregular spherical shape with a crack tail (**Fig. 5.F**). The size of porosity in the vertical direction of the product is smaller than the horizontal one.

The vertical and horizontal direction of products has relatively the same trend of hardness. The α-case is formed on the sub-surface of the region. The α-case has a thickness of 50-300 µm with a hardness of 760 VHN. This is confirmed with the results of a study [21]. The α-case on the horizontal direction is thicker and harder than the vertical one. This condition happens because the vertical position that has a small vortex space may have a higher cooling rate compared to the horizontal one during the solidification process. Higher cooling rate makes the α-case thinner that prevents oxygen diffusion to occur [22].

The rectangular cross-section gate shape with an oblique counter-clockwise direction has the smallest porosity area, highest density, and smoothest surface among other directions. The direction of this gate is aligned with the rotation of the mold. The molten metal becomes easier and faster to enter the mold cavity when pouring; then it freezes immediately. Losses friction between the molten metal and the gate wall become small. This design has the thinnest α-case (with no crack) among other directions.

Furthermore, the design with the oblique counter-direction of the rotation of the mold has the largest porosity area, lowest density, and roughest surface, among other directions. The molten metal is difficult to get in the mold cavity when the direction of gate is opposite toward the mold rotation. This condition happens because there are minor and major losses exist in the gate wall. These major losses are caused by friction along the molten metal flow against the gate wall, while minor losses are caused by sharp turns. Major and minor loses cause fluidity to decrease rapidly, so porosity will be easier to occur [10]. This design has the thickest α-case among other directions, so there is crack. The α-case layer is hard and brittle with a high-stress concentration [21], so cracking happens easily.

The microstructure formed tends to be similar, which consists of some α morphologies types and equiaxed prior β grains. The different morphologies nucleate, including the α grain boundary, make prior β grains remain observable. The microstructure on the subsurface is transformed from fine grain to slightly become coarse one in the inner area. This transformation of grain is similar with the previous research [3].

5 Conclusion

The conclusions of this research are:

1. Product with the circular cross-section gate shape on the vertical direction has less porosities, higher density, and smoother surface than the horizontal one.
2. Product with the rectangular cross-section with the oblique counter-direction of the rotation of the mold has the largest porosity area, lowest density, and roughest surface among other directions.
3. The rectangular cross-section gate shape with oblique same with the mold rotation produces an artificial lumbar disc model with the smallest porosity area (0.68%), the highest density (4,517 g/cm^3), and the thinnest α-case (50-100 µm).
4. The rectangular cross-section gate shape with oblique direction same with the mold rotation can be applied to the manufacture of artificial lumbar disc model.

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