Manufacturing of Herringbone Gear Model by 3D Printing Assisted Investment Casting

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Abstract. 3D printing technology and investment casting are used to manufacturing of a herringbone gear. Four kinds of gating system are designed and the numerical simulation of the four gating systems are executed. It is determined that the optimal casting mode of herringbone gears is the top casting system. Subsequently, the investment mold is made with PLA material by 3D printing technology and the mold shell is made of gypsum. Finally, experiment is performed to verify the validation of the top gating system. The results show that the combination of 3D printing technology and investment casting can effectively improve casting accuracy and production efficiency.

1. Introduction
Investment casting is a manufacturing process in which a wax pattern is coated with a refractory material. Once the material is hardened, its internal geometry takes the shape of the casting. The wax is melted out and molten metal is poured into the cavity where the wax pattern is. Upon cooling, the metal solidifies and the mold shell is broken out, leaving behind an exact duplicate of the desired part. This manufacturing technique is also known as the lost wax process and suitable for refractory metal and complex thin-wall parts[1]. But it needs to use the mold to manufacture the investment mold traditionally. The production process is complex and the manufacturing cost is high [2].

However, combination of 3D printing technology and investment casting has achieved good results[3-4]. By comparison with the traditional investment casting, the investment casting using SLS technology has the characteristics of low cost, short cycle and flexible process [5]. Also, in order to analyze and explore the suitability of 3D Printing to make the multi-unit fixed bridge base, total of 50 fixed bridge models composed of 6 units in the same anterior teeth area are made. Half is designed and made with 3D Printing, and another half is made with the traditional manual method. And the experimental results prove the validity of 3D printing [6]. In the field of automobiles, the technical line, key process and application effects of the 3D printing wax model-plaster mold investment casting are analysed [7]. Furthermore, based on 3D printing moldless casting, the gating system of compressor cylinder castings is arranged reasonably. And the casting process yield could reach more than 80%. Also, the development period could be shortened more than 70% [8]. Also, by means of casting process simulation and 3D printing technology, the final casting of the automobile supercharger impeller with typical complex surface is obtained after shell baking, pouring and sand blasting [9]. Also, in the field of aerospace, aimed at lightweight, high strength, thermal resistance, and high-efficiency forming of spacecraft structure, casting technology of high-strength and heat-resistant
magnesium alloy cabin is investigated [10]. Moreover, the molten pattern for the investment casting of the cabin is prepared by using the selective laser sintering (SLS) 3D printing method. And three kinds of gating systems are designed. Subsequently, the rapid investment casting of the magnesium alloy cabin is achieved [11].

In this paper, 3D printing technology is used to make the investment mold. And, the top gating, lower side gating, upper side gating and bottom gating systems are designed. Also, mold flow analysis is executed based on numerical simulation. Subsequently, the optimal gating system is obtained to make the qualified castings.

2. Investment mold manufacturing
The three-dimensional model of herringbone gear is shown in Figure 1. The radius, width, thickness, pitch and modulus of herringbone gear are 50mm, 20mm, 2mm, 4mm and 1mm, respectively. Then, the herringbone gear is printed with Polylactic acid (PLA) by means of FDM technology. However, complex shape may lead to insufficient pouring of liquid metal during filling, even shrinkage cavity, which has a great impact on casting performance. Therefore, it is necessary to execute the simulation of the casting process by CAE software [12,13]. In this experiment, ZL104 aluminium alloy is used to make the melting die, and the casting temperature is 750°C. And mold shell is made of high temperature resistant gypsum because of its good fluidity, low thermal conductivity, high dimensional accuracy [14,15]. Figure 2 shows the model of the herringbone gear based on 3D printing.

3. Numerical simulation
The filling process of the top gating system is analysed with the parameters shown in Table 1. And the finite element model is established which consist of about 36000 elements (Figure 3).

| Parameters                  | Values |
|-----------------------------|--------|
| Shell mold temperature (°C) | 750    |
| Filling temperature (°C)    | 750    |
| Filling velocity (cm/s)     | 15     |

Figure 1. 3D model of herringbone gear
Figure 2. Sample of herringbone gear
Figure 3. FEM of Herringbone Gear with top gating system
3.1. Analysis of top gating system
Figure 4 shows the filling process of top gating. And the entire gating system is placed above the mold cavity, then the molten metal falls from the ingate to the bottom of the mold. So the solidification sequence is not easy to produce defects. Based on filling time, filling sequence, solidification time, solidification sequence and entrainment sequence of molten metal, the position of most likely defects on the top gating system is obtained, as shown in Figure 5 (red region). Figure 6 gives shrinkage and porosity of the part with the residual mold melting number (RMM). And the shrinkage is concentrated in the gating system other than the herringbone gear.

3.2. Analysis of lower side gating system
The molten metal filled laterally downward from the part. Figure 7 shows the probable defects at two position: one is the area between the outer surface and the flow path, and another is the surface of mounting hole. Figure 8 shows the probable shrinkage on the inner surface of the mounting hole.
3.3. Analysis of upper side gating system
The molten metal filled laterally upward from the part. Figure 9 shows the probable defects in the area between the outer surface and the flow path. Figure 10 shows the probable shrinkage on the inner surface of the mounting hole.

3.4. Analysis of bottom gating system
The molten metal filled the mold cavity from the bottom of the casting. Figure 11 shows the probable defects in the area between the outer surface and the flow path. Figure 12 shows the probable shrinkage on the inner surface of the mounting hole.

Based on the Figure 5 -12, the top gating system is the optimal choice for herringbone gear casting. For the lower side, upper side, and bottom gating system, during the filling process, shrinkages appear on the inner surface of the mounting hole probably.

4. Experimental Validation
Experiment is performed to verify the validation of the top gating system. The gypsum and water are blended in a ratio of 100:46 (g) and fully stirred. Then the mold is placed in a cast bell full of gypsum slurry, as shown in Figure 13.
Figure 13. Gypsum casting mold

The gypsum casting mold needs about two hours to be air-dried. Then, the casting mold is put in resistance furnace when the internal temperature up to 100°C. And, in order to avoid gypsum cracking, the casting mold is kept warm for 10 minutes after the internal temperature rises to 400°C. Subsequently, the temperature of the resistance furnace is heated to 600°C and keep warm for 1 hour, and then to 750°C for 2 hours. The complete gypsum cavity is obtained as shown in Figure 14 after the investment mold made of PLA is completely vaporized. Also, the gypsum casting mold after casting is shown in Figure 15, the casting obtained after removing the shell is shown in Figure 16 and the final herringbone gear is shown in Figure 17. Casting quality of the herringbone gear is good and there are no obvious casting defects such as shrinkage cavity and porosity.

Figure 14. The gypsum cavity after investment mold vaporized

Figure 15. The gypsum casting mold after casting

Figure 16. Casting with sprue gate and riser

Figure 17. The final herringbone gear
5. Conclusions
3D printing technology and investment casting are used for manufacturing of a herringbone gear. And some valuable conclusions are obtained:

(1) Based on numerical simulation, it is determined that the best casting mode of herringbone gears is the top casting mode.

(2) The combination of 3D printing technology and investment casting can effectively improve casting accuracy and production efficiency.

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