MOLD FILLING BEHAVIOR OF TITANIUM MELT IN THIN-WALLED AND COMPLICATED CAVITIES IN HYPERGRAVITY FIELD

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Abstract:

The mold filling process of titanium alloy in the thin-walled and complicated cavities in hypergravity field is the subject of this paper. The obtained results indicate that the filling process of the melt in the thin-walled and complicated cavity at different mould rotational speeds is quite complex. The free surface of the melt in the thin-walled ribs moves forward in a near planar way parallel to the gravity direction under different mould rotational speeds. The mold filling process with higher filling rotational speed, 300rpm and 500rpm shows that the free surface in the thin-walled ribs and backward filling in the radial runners are in the same vertical plane. Besides, the speed of backward filling in the radial runner is equal to that in the thin-walled ribs. The free surface during the backward filling process at the rotational speeds of 300rpm and 500rpm is a series of arc surfaces, while the free surface during backward filling with 150rpm is not obvious, for the free surface during the forward filling process occupies nearly the whole radial runner.

1 Introduction

Hyper-gravity technology is a technology that intensifies the heat transfer process by producing a steady and adjustable centrifugal field [1, 2]. The application of hyper-gravity technology in foundry industry started with the centrifugal casting patent developed by A. G. Erchart and granted in 1809 [3]. Vertical centrifugal precision casting is the mere application of hyper-gravity technology in foundry industry, which is the most effective means for near-net shape-forming of the big-size titanium alloy castings with a thin-walled and complicated geometry structure.

Recently, scientific and technological workers have paid more and more attention to vertical centrifugal precision casting technique [4, 5]. Therefore, it has become the hotspot of research and engineering application. The American PPC Company had already produced a large TiAl-based engine diffuser with an external diameter of 61cm and the width of 6.25cm [6]. W.J. Richards et al determine the presence of ace coatings materials in thick cross sections of fracture critical aero structural titanium investment castings by neutron radiography which has resulted in the ability to detect inclusion [7, 8].

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In China, Nan Hai and Xie Chengmu et al successfully developed a wax pattern for the thin-walled and complicated titanium alloy castings and obtained a rim-like Ti-6Al-4V alloy casting with dimension of 630×300×130mm. The casting whose minimum wall thickness is 2.5mm can meet all designed requirements by non-destructive testing, chemical analysis and mechanical property test etc [9, 10]. Chen et al dedicated themselves to studying low-cost preparation technology for ceramic shell molds and successfully produced the Ti-Al-Zr alloy aerospace engine intake components [11, 12]. Wu's numerical and experimental study on the solidified structure of a thin-walled and complicated titanium alloy casting indicated that technological parameters and casting wall-thickness exert an important effect on the solidified structure of different parts of the casting [13, 14].

However, to the best of our knowledge, very little has been done on the research into the mold filling behavior of titanium melt in a thin-walled and complicated cavity, which plays a significant role in the analysis of subsequent solidification and defects formation, such as the misrun, inclusion, cold shut, shrinkage etc. Based on this, the present work is concerned with the mold filling behavior of titanium melt in a thin-walled and complicated cavity under vertical centrifugal casting process.

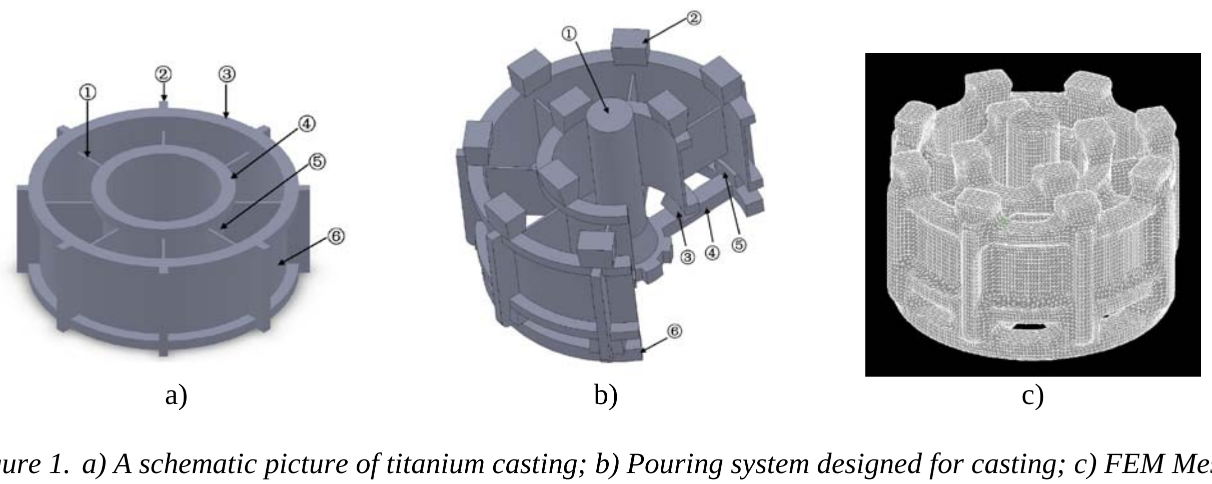
2 Numerical settings

2.1 Geometric model

Fig.1a shows the schematic diagram of the thin-walled casting with a complicated geometry structure. The casting is an axial symmetry casting with the minimum wall thickness of 3mm and the maximum wall thickness of 16mm. It consists of the following parts: 1-eight thin-walled ribs; 2-eight thick-walled ribs; 3-two thick-walled inner circular rings; 4-two thick-walled outer circular rings; 5-one thin-walled inner circular ring and 6-one thin-walled outer circular ring. The dimensional size of the casting is: Φ159mm×110mm. Fig.1b presents the pouring system designed for casting. It consists of: 1-a sprue in the centre, 4-a radial runner at the bottom, 6-an external ring-like runner at the bottom, 5-eight ingates located at the external ring-like runner and 3-four ingates located at the radial runner. In addition, 12 risers are set on the top of the casting to keep feeding of the casting (shown in Fig.1b and Fig. 2).

2.2 FEM mesh generation

First, 3D modeling software Solidworks 2009 was adopted to draw the three-dimensional geometry of the thin-walled and complicated TC4 casting with its pouring and feeding system and export the geometry structure in *.step format. Then, import the *.step file into MeshCAST, the grid processing system of ProCAST. After generating the surface mesh (in *.sm format), the shell for investment casting based on the surface mesh with the command "Create New Shell" in MeshCAST was created. The thickness of the shell is set to be 5mm. Finally, the FEM volume mesh has been generated, shown in Fig.1c. The total number of Nodes is 299658 and the total number of Elements is 1361368.



a) b) c)

Figure 1. a) A schematic picture of titanium casting; b) Pouring system designed for casting; c) FEM Mesh of Casting and its pouring system.

2.3 Boundary condition and parameter setting

The casting material used in the present work is Ti-6Al-4V alloy whose chemical composition is 6wt% Al, 4wt% V. The mould is made of ceramic ZrO_2 with about 6wt% Y_2O_3. In the present paper, ProCAST commercial software with the finite element method was selected to study the melt filling process of the thin-walled and complicated cavity during the vertical centrifugal precision casting process. The filling states at different rotational speeds are investigated and the casting is actually cast at 300rpm. The thermal-physical properties of casting and mould materials employed in simulation are summarized in Table 1. Boundary conditions and heat transfer coefficients are shown in Table 2.

3 Results and discussion

3.1 Filling process of melt in the thin walled cavity with complicated geometry shape

Fig. 2 presents the process of filling titanium melt in the thin-walled and complicated cavity under actual operational conditions. The simulated results show that the melt filling process of the cavity is very complex. First, the titanium melt moves forward and fills the radial runner along the side of the runner opposite to the direction of the rotational mould under effect of the coriolis force (shown in Fig. 2a). After it has reached the end of the runner, the melt moves upward and fills the cavity through the outer ingate (shown in Fig. 2b). At the same time, the melt fills the thin-walled outer circular ring from below to up in the direction opposite to the rotating mould(shown in Fig. 2c). When the melt has reached the top of the cavity, the melt moving backwards fills the radial runner and the thin-walled ribs (shown in Fig. 2d). During the backward filling of the radial runner, the melt subsequently flows through the inner ingate, and then fills the thin-walled ribs. The melt moving from the inner ingate and the outer ingate converges and then fills the rest of the cavity including the inner thin-walled annular cavity until the filling process has finished.

3.2 Morphology of the free surface in the radial runner

Fig.3 presents the morphology of the free surface in the radial runner when the mould rotational speed is 300rpm. The mould filling process of the titanium

Table 1. Thermo-physical data used in the simulation.

	Ti-6Al-4V	Mold
Density, ρ (kg m^{-3})	4430	2000
Thermal conductivity, λ (Wm^{-1} K^{-1})	14.1	156
Specific heat capacity, c_p (Jkg^{-1} K^{-1})	930	672
volumetric latent heat, L(Jm^{-3})	1580×10^6	
Liquidus temperature, T_l (°C)	1720	
Solidus temperature, T_s (°C)	1710	
Viscosity, μ (m^{2}s^{-1})	4×10^{-5}	

Table 2. Boundary conditions and initial conditions.

Boundary conditions and initial conditions	Expression
Pouring velocity	1 m/s
Pouring temperature	1750°C
Ambient temperature	205°C
Vacuum degree	0.1Pa
Heat transfer coefficient between the metal and mould interface	h=100w/m^{2}k
Heat transfer coefficient mould and air	air cooling

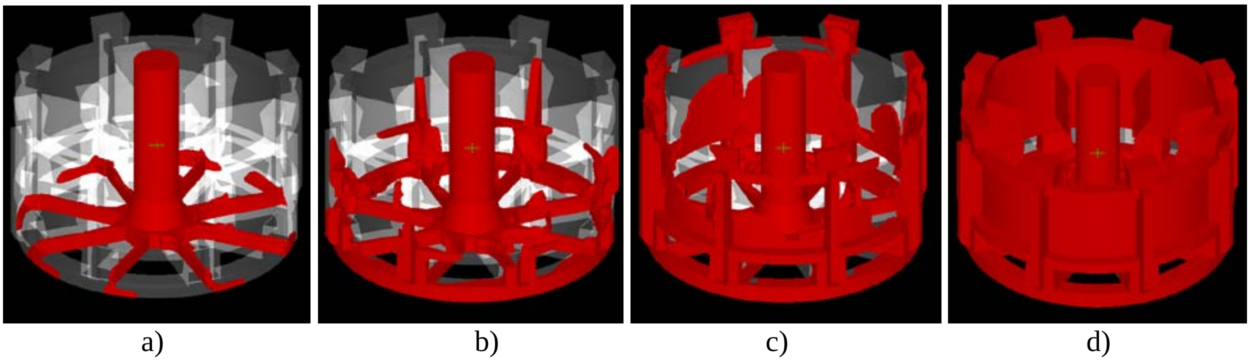


Figure 2. Melt filling state in the cavity during vertical centrifugal casting process: a) t=0.16s; b) t=0.26s; c) t=0.42s; d)t=0.61s.

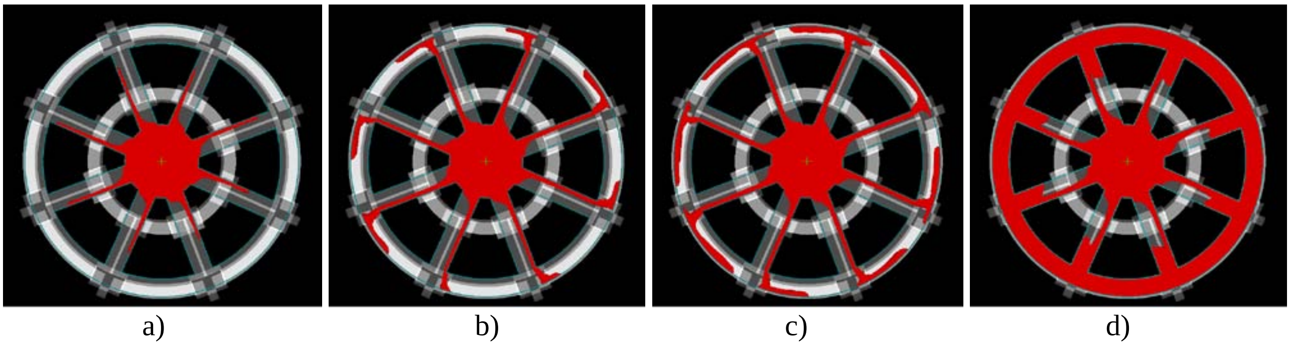


Figure 3. Melt free surface in the radial runner at 300rpm: a) t=0.14s;b) t=0.16s; c) t=0.17s; d) t=0.61s.

alloy in the radial runner consists of forward and backward filling. During vertical centrifugal casting process, the forces exerted on the molten titanium alloy are gravity forces, the coriolis and centrifugal force. The centrifugal force is much larger than the gravity force. In the forward filling process, the ratio of the coriolis and the centrifugal force is far larger than 1. Thus, the coriolis force plays a leading role in changing the melt moving direction during the forward filling process. Therefore, the titanium melt flows along the mould wall opposite to the rotational direction of the rotating mould. While the melt reaches the end of the radial runner, it begins the backward filling process. The filling phenomenon of the melt in the radial runner is consistent with the filling process in the two dimensional cavity [15]. Fig. 4 and Fig. 5 show the morphology of the free surface in the radial runner when the mould rotational speed is 150rpm and 500rpm respectively. A comparison of the filling process under different mould rotational speeds shows that the morphology of the free surface during the backward filling process with higher rotational speed is a series of arc-like surface with the same radius, while the morphology of the free surface during backward filling at 150rpm is not obvious, for the free surface during the forward filling process occupies nearly the whole radial runners. The ratio of the coriolis force and the centrifugal force is deeply related to the mould rotational speed. So, when the mould rotational speed is 150rpm, the effect of the coriolis force becomes much weaker, and consequently the filling process at 150rpm is quite different from that at 300rpm and 500rpm. During the backward filling process under hypergravity field conditions, the pressure arisen from the centrifugal force is the main power that makes the melt move from the outer to the rotating shaft. And the driving force is the same at the same radius. Thus, free surfaces during the backward filling process at higher rotational speeds are a series of arc surfaces with the same radius. The difference between backward filling at 300rpm and the one at 500rpm is that the backward filling speed of the melt is higher when the mould rotational speed is 500rpm.

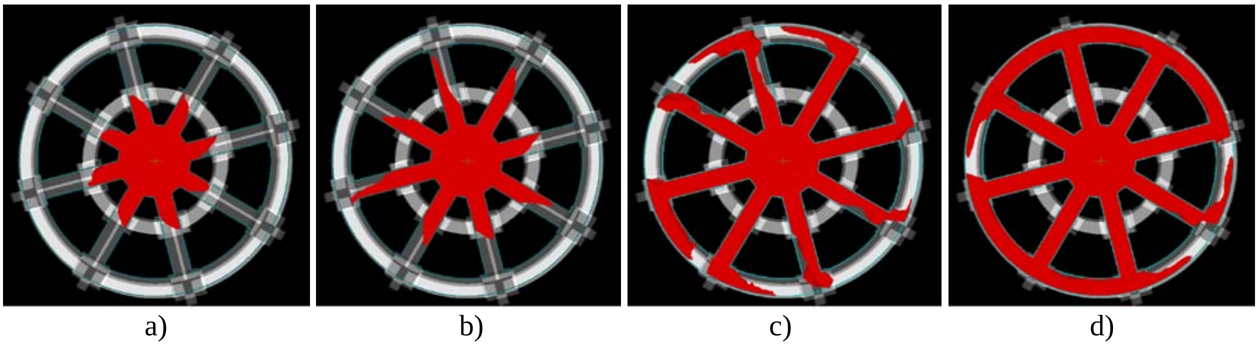


Figure 4. Melt free surface in the radial runner at 150rpm: a) t=0.16s; b) t=0.19s; c) t=0.28s; d) t=0.36s.

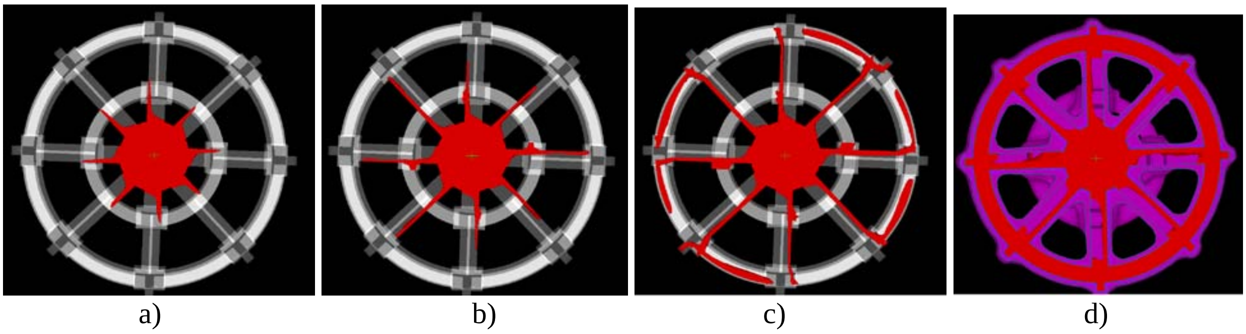


Figure 5. Melt free surface in the radial runner at 500rpm: a) t=0.13s; b) t=0.14s; c) t=0.16s; d) t=0.55s.

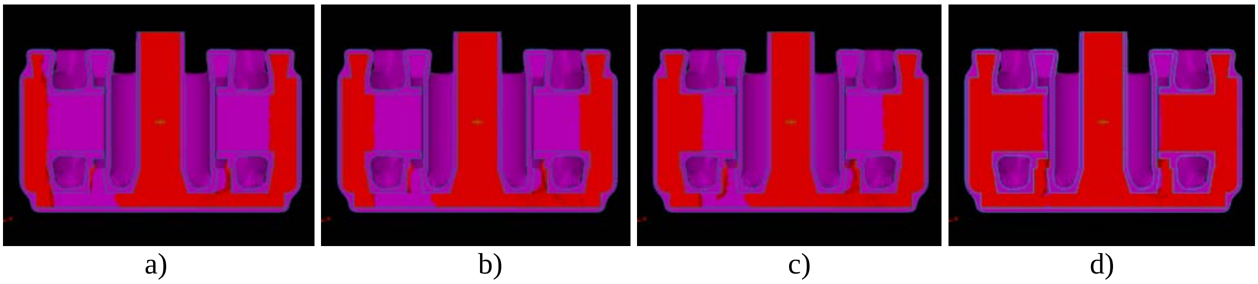


Figure 6. Melt free surface in the thin-walled ribs at 300rpm: a) t=0.53s; b) t=0.57s; c) t=0.59s; d) t=0.66s.

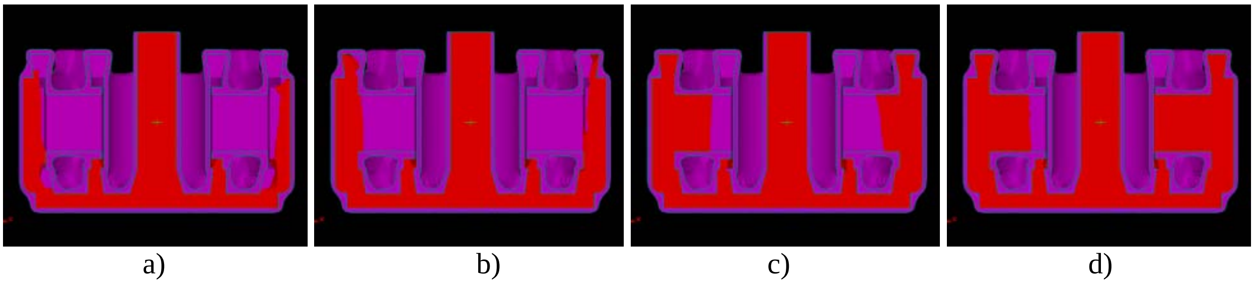
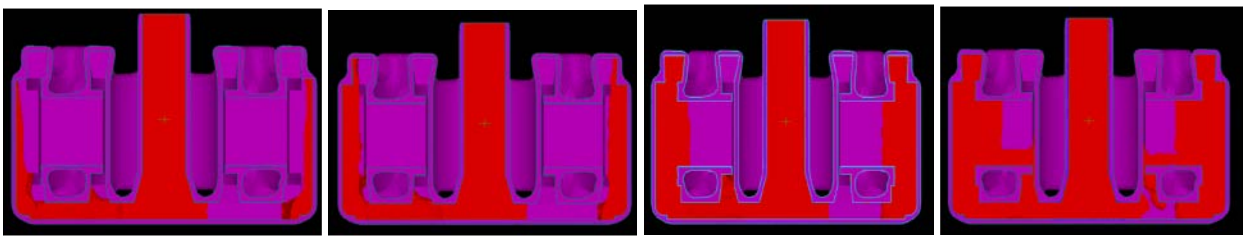


Figure 7. Melt free surface in the thin-walled ribs at 150rpm: a) t=0.46s; b) t=0.63s; c) t=0.70s; d) t=0.72s.



a) b) c) d)

Figure 8. Melt free surface in the thin-walled ribs at 500rpm: a) t=0.23s; b) t=0.31s; c) t=0.56s; d) t=0.63s.

3.3 Morphology of the free surface in the thin-walled ribs

Fig. 6, Fig. 7 and Fig. 8 are the mould filling processes of the titanium melt in the thin-walled rib cavity at different time at 300rpm, 150rpm and 500rpm. The results show that the free surface of the melt in the thin-walled rib moved forward in a planar mode perpendicular to the radial ingate at different mould rotational speeds. The comparison drawn between the filling state in the thin-walled ribs and the filling state in the radial runner indicates that the free surface in the thin-walled ribs and backward filling free surface in the radial runners are in the same vertical plane at 300rpm and 500rpm. But the filling process in the radial runner at 150rpm is different, as the free surface during the forward filling process in the radial runner occupies nearly the whole radial runner. Considering another aspect, the melt filling at 500rpm converged in the thin-walled ribs.

4 Conclusion

(1) The melt filling process of the thin-walled and complicated cavity at different mould rotational speeds is quite complex.
(2) The backward filling speed in the radial runner is equal to that in the thin-walled ribs when mould rotational speeds are 300rpm and 500rpm.
(3) The filling process in the radial runner at 150rpm is different since the free surface during the forward filling process occupies nearly the whole radial runner.

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