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MACROSEGREGATION IN VERTICAL CENTRIFUGAL THIN-WALLED AND COMPLEX TC4 CASTINGS

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Abstract. This study investigated the macrosegregation in the thin-walled and complicated TC4 castings manufactured by a VCC (vertical centrifugal casting) process. The segregation mechanism and the effect of macrosegregation on the microstructure have also been studied. The results show that there is a trend of segregation in complicated casting produced by vertical centrifugal casting process. The macrosegregation at the thick-walled parts of the casting with complicated geometry shape is much obviously than that at the thin-walled parts of the casting. The cooling rate of the casting is the main factor to the formation of macrosegregation. The cooling rates at the thick-walled parts are much lower than that at the thin-walled parts, and the elements diffuse much more sufficiently at the thick-walled parts and the phase segregation occurs, therefore, there ultimately existed slightly elemental macrosegregation at thick-walled parts.

1. INTRODUCTION

Macrosegregation, which is one kind of normal segregation, is the spatial non-uniformity in the chemical composition on the scale of a solidified casting. It makes the microstructures at different positions of the casting diverse greatly, and thus affects the uniformity of the castings [1-3]. The presence of macrosegregation sets limitations on the size and the composition of the billet to be cast in a productive and economical way. So the importance of macrosegregation in the production of cast products cannot be overemphasized. The macrosegregation will be more serious in centrifugal casting due to the centrifugal force, which is much higher than the gravity. In the centrifugal casting, the densities of the elements in the melts are different, and because of the different centrifugal force on the particles, therefore, the phase distribution is diverse with the radiuses of the casting and the macrosegregation generates [4-6]. B. Balout et al. [4] pointed out that the macrosegregation of the ZA8 alloy casting produced by the vertical centrifugal casting process was related to the melt pouring temperature, the mold preheat temperature, the alloy composition and the melt cooling rate. When the melt cooling rates are high, the macrosegregation is diminished or even disappeared if the cooling rate is high enough. Chen et al. [5] studied the macrosegregation in the centrifugal ZL27 alloy castings which shows that when the pouring time is longer and the mold preheat temperature is lower, the macrosegregation decreases and the manganese added in the ZL27 alloy can also reduce the macrosegregation.

However, the studies on macrosegregation in centrifugal casting only are limited to the big size castings ingots, and there are few studies on the castings with thin wall and complicated structure, especially for the titanium alloy castings. Now the study on thin-walled and complicated titanium castings with big size and complicated shape is the trend of aerospace industry [7-9], to study the

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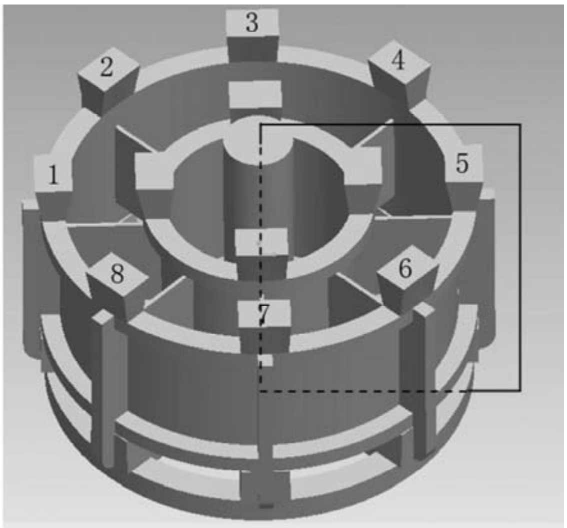
macrosrgregation of big size thin-walled and complicated castings will do great benefits to improve the casting characteristics, and therefore enhance the strength of the national defense and science and technology.

2. EXPERIMENTAL AND NUMERICAL PROCEDURES

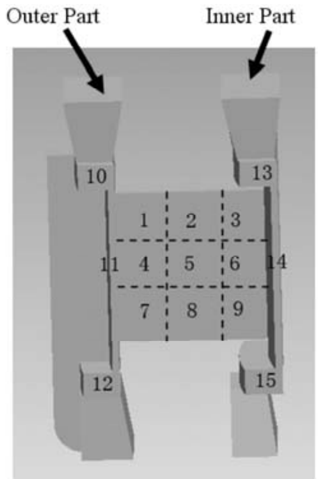
2.1. Casting experiments and examination of specimens

The alloy used in this experiment is the $\alpha+\beta$ type Ti-6Al-4V alloy. The raw material is melted in the ISM (Induction skull melting) furnace, in which the vacuum degree is 0.1 Pa. When the temperature reaches a certain value, the melt was poured into the rotating investment mould, which was preheated to 150 °C. After pouring, the mould is naturally cooled in the furnace. The rotation speed of the mould is 300 rpm. The schematic diagram of the thin-walled and complex Ti-6Al-4V alloy casting is shown in Fig. 1a.

Fifteen specimens with different wall thickness were cut from different positions of the thin-walled and complicated Ti-6Al-4V alloy casting (shown in Fig. 1b). The specimens were prepared by grinding, polishing, cleaning, and etching with a reagent composed of a mixture of 5 ml of HNO_3, 10 ml of HF, and 50 ml of H_2O. The microstructure was examined under an optical microscope (OLYMPUS SZX7). The element distribution of different specimens was determined by the line scanning (Energy Dispersive Spectrometer, EDS) in the S-570SEM type scanning electron microscope.



(a) Schematic diagram of the casting and its gating system



(b) Schematic of specimen position

Fig. 1. Schematic diagram of Ti–6Al–4V alloy thin-walled and complicated casting.

2.2. Computer simulations and boundary conditions

The effects of cooling rate under different casting conditions on element distribution were undertaken by a ProCAST software (version 2009). The mould thickness is 5 mm. 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. The mold material is SAND_Zircon.

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

	Casting(TC4)	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
Velocity	2 m/ s
Pouring temperature	1750 °C
Ambient temperature	20 °C
Heat transfer between the metal and mould interface	$Q_{cm} = h_r(T_{mold} - T_{metal})$
Heat transfer coefficient between the metal and mould interface	h = 100w/m^{2}k
Heat transfer coefficient mould and air	air cooling

3. RESULTS AND DISCUSSION

3.1. Elements distribution

Fig. 2 are the distribution diagrams of alloying elements along the radius in the thin and thick-walled parts of TC4 thin-walled casting whose chemical compositions are 6 wt.% Al and 4 wt.% V. As shown in Fig. 2 with the rectangle markers, the element distributions of thin-walled parts have specific laws of its own, that is, the content of Ti element keeps uniform even at different distance from the rotating shaft, while the content of Al gets lower, but the fluctuation range is very small. In the meantime, the content of V rises with the rise while the distance from the rotating shaft is bigger.

The distribution of alloying elements at different parts of the casting with distinct wall-thickness shows significant deviation. Specifically speaking, for Al element which is shown in Fig. 2b, obvious Al distribution changing trend can be observed with the changing trend of the casting wall-thickness, the thinner the walled part is, the lower the Al content is, vice versa. While the distribution of V just has the same trend as Al element. With different distance from the rotating shaft, the significant deviation of elements distribution can be observed also as shown with triangle marks. The smaller the distance is, higher content of V and Al are, vice versa.

3.2. Segregation mechanism of thin-walled centrifugal castings

3.2.1. Element density

The elementary segregation of centrifugal casting is influenced by the density difference among the elements and molten steel [10-12]. In Fu et al. study [6], they also reported that element distribution in centrifugal castings is greatly related to the element density. The element whose density is bigger than molten melt decreases continuously as the distance departing from the casting surface increases. In contrast, the content of the element whose density is lower than molten melt increases slowly. In the meantime, there is no obvious segregation for the element whose density is close to molten steel.

In the Ti-6Al-4V alloy, the density of titanium is 4.51 g/cm^3, the density of aluminum is 2.7 g/cm^3, and that of V is 5.96 g/cm^3. However the density of the Ti-6Al-4Valloy is 4.4 g/cm^3. The density of titanium element is similar to that of the TC4 alloy, so there is scarcely any segregation of the titanium element and there is slight aluminum segregation for its density is smaller than the TC4 alloy. As the density of V is much higher than the TC4 alloy, its distribution is increasing with the increment of the distance from the rotating shaft. Moreover, the rotational speed of the mould is 300 rpm and the centrifugal force acted on the running melt is relatively smaller, so the segregation of the whole casting is not serious.

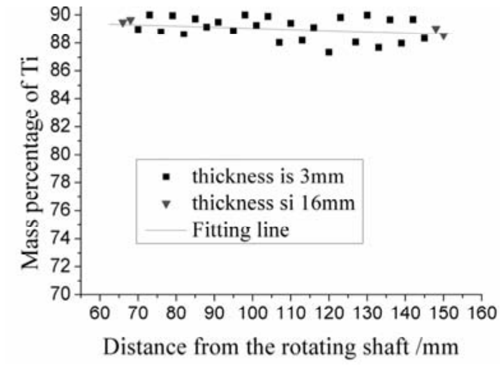
3.2.2. Cooling rate

The temperature and cooling rate as a function of time and position through the section which obtained by the ProCAST software are presented in Figs. 3a and 3b for the given initial pouring and mold temperatures. The cooling rate is given by the following equation,

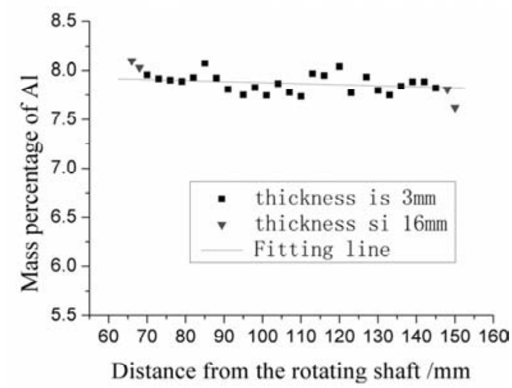
$$C = \frac{\Delta T}{\Delta t} = \frac{T_l - T_s}{t_l - t_s}, \qquad (1)$$

where C is the cooling rate, T_l is the liquidus of the TC4 alloy, T_S the solidus of the TC4 alloy and Δt solidification time of the alloy.

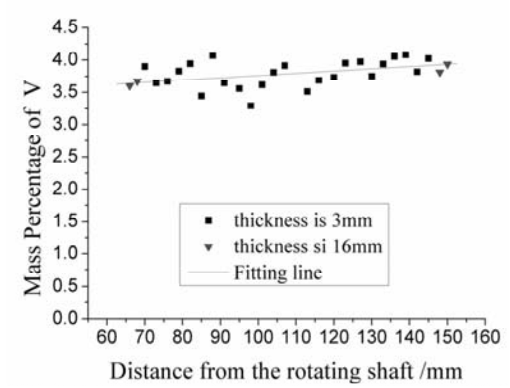
It can be seen from the figure that the cooling rate at the thin-walled parts are very big and temperature changes greatly with the time changes. At the beginning, the cooling rates and the temperature of the metal decreases quickly with time going on, and the temperature variation becomes much smaller as the solidification process proceeds. This behavior is attributable to the temperature difference between the mold and the



(a) Ti

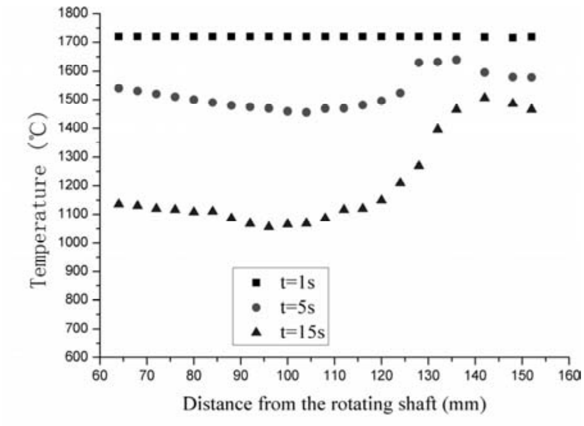


(b) Al

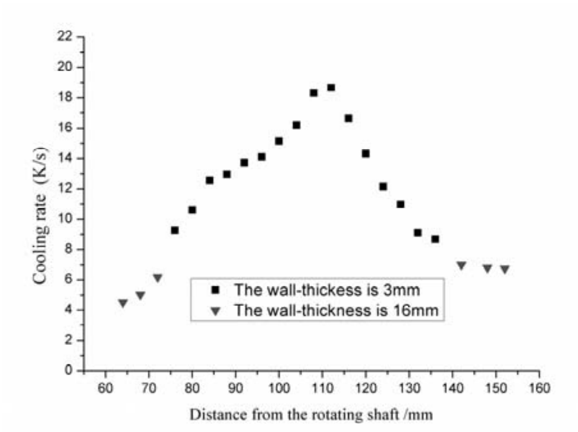


(c)

Fig. 2. Distribution of elements along radius direction.



(a) Temperature distribution



(b) Cooling rate distribution

Fig. 3. Temperature and cooling rate distribution of the casting.

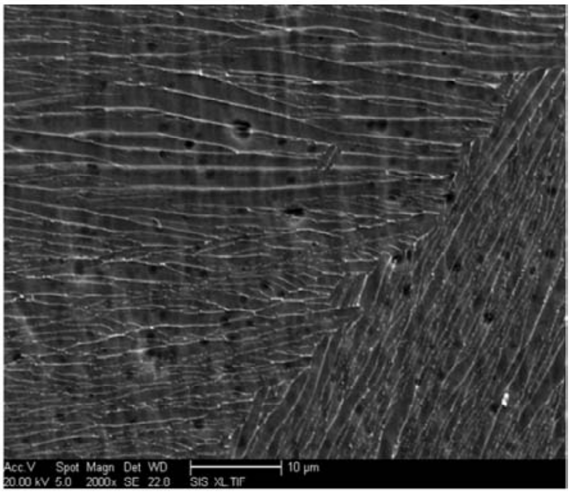
melt. At the commencement of the pouring and solidification, the mold temperature is markedly lower than that of the melt, so the heat escapes rapidly at the beginning of cooling. In the sequel, with solidification continued, the primary solidification crystals come into being and the internal heat transfer decreases, which in turn lead the variation in temperature and cooling rate decrease.

In Direct-Chill Cast, Nadella et al. [3] pointed out that the macrosegregation can be very tiny when the casting speed is large enough. This phenomenon can be explained by the large cooling rate at the high casting speed. Thus the casting macrosegregation is closely related to the cooling rate of the castings. In general, when the cooling rate is high, the macrosegregation is very tiny. From Fig. 3, we can see that the cooling rates at the thin-walled parts of the vertical centrifugal casting with complicated shape are very big, so the macrosegregation of the alloying elements are very tiny for this casting.

3.3. Effect of macrosegregatiom on microstructures

The element segregation will certainly result in the microstructure non-uniform and make the mechanical property of different parts vary from each other. In this part, the interlamellar spacing of the TC4 alloy casting was studied. Fig. 4 is the typical lamellar structures at different parts of the titanium

(a) 81mm from the shaft, wall thickness is 3mm



(b) 142mm from the shaft, wall thickness is 16mm

Fig. 4. Typical lamellar structure of the titanium alloy casting.

alloy casting, Fig. 4a is the image with wall thickness of 3 mm at the position of 81 mm from the rotating shaft, and Fig. 4b is the image of 16 mm at 142 mm from the shaft. The EDS analysis showed that the white phases are β phases and the white ones are α phases.

The interlamellar spacing is measured by the transversal method. Under this experimental condition, the interlamellar spacing at the thin-walled parts is between 2.4 μm and 2.9 μm, while at the thick-walled parts is much bigger, which reaches about 5 μm~6.5 μm. Fig. 5 is the α/β interlamellar spacing distribution along with the distance from the rotating shaft when the wall-thickness is 3 mm. The interlamellar spacing decreases with the distance from the rotating shaft. According to the cooling rate distribution (shown in Fig. 3b), we can

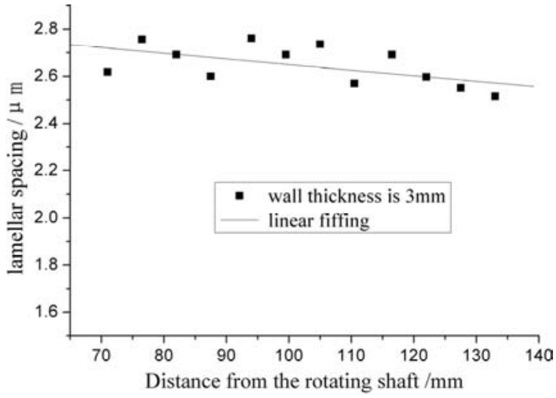


Fig. 5. Interlamellar spacing of thin-walled specimens.

obtained that the interlamellar spacing of this TC4 alloy thin-walled casting become finer as the cooling rate (*C*) increases. The cooling rate is the critical factor for the macrosegregation.

4. CONCLUSIONS

(1) The elemental distribution has been obtained and there is a trend of segregation in vertical centrifugal casting process. The mold rotating speed is low in the present study, so the elemental macrosegregation is not serious.
(2) The cooling rate of the casting is the main factor that affects the formation of macrosegregation. When the thickness of the casting is small, the cooling rate is high and the element does not have enough time to diffuse, so the segregation is not obvious. But when the casting thickness is big, the cooling rate is relatively low, so the element diffuses sufficiently and forms phase segregation, thus the element segregation is much more serious than in the thin-walled parts of casting.
(3) It can be differed from the present study that the macrosegregation in the vertical centrifugal castings can be fully diminished if the melt cooling rate is high enough whenever the rotating speed is high or not.

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