ANALYSIS OF OVERFLOW CRITICAL VALUE FOR TiAl BASED ALLOY MELT DURING PROCESS OF CENTRIFUGAL CASTING①

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ABSTRACT The method combining theoretical analysis with experimental verification was adopted, and the pressure distribution of TiAl based alloy melt poured in permanent mould during the process of centrifugal casting was analyzed. The expression of extra pressure item Δp and the relations between the maximum angular velocity $\omega_{0\max}$ and melt height H, pouring basin diameter D_0 were concluded. It provided theoretical guide for actual casting process. The analytical results showed that the pressure item affecting castings consists of static pressure and extra pressure during the process of centrifugal casting. The static pressure was determined by melt height, while the extra pressure was controlled by metal liquid density and rotating angular velocity. The pouring basin height and diameter should follow certain functional relation. Also, it showed that the value of maximum angular velocity decreased with increasing metal liquid height and pouring basin diameter.

Key words angular velocity TiAl base alloy pressure distribution centrifugal casting

1 INTRODUCTION

TiAl based alloys have attracted a great deal of attention because of their potentially attractive properties for high-temperature structural applications. For their excellent corrosion, oxidation resistance and low density, the TiAl based alloys are being considered for a number of aerospace applications[1-5]. Since 1980, the upsurge of studying and developing on the alloys has occurred in many countries, characterizing by development of intermetallic compounds used as structural materials and extensive applications of intermetallic compounds served as functional materials.

Some researchers in foreign countries have given effort to study the forming properties of TiAl based alloys. The properties and formation of TiAl based alloys have been elaborated by Froes *et al*[6], and several formation methods applied to TiAl based alloy have been concluded, such as powder metallurgy (PM) and rapid solidification (RS), and so on. Ti-47Al-2Cr-2Nb (mole fraction, %) alloy automotive exhaust valves have been poured in permanent molds by Jones[7], and the conditions of static pouring, die casting and injection have been compared by experiments. They have concluded that, in the future, the permanent mold centrifugal casting is very possible to be the productive method for large quantity TiAl alloy castings. In our country, the Powder Metallurgy Research Institute has done some works about powder metallurgy, and many papers have been published[8,9].

During the process of melting TiAl alloy, if the centrifugal angular velocity is not chosen correctly, TiAl based alloy melt will overflow from pouring basin and the static pressure in the melt within mould chamber will disappear. Not only materials will be wasted, but also the vacuum chamber seal rings are destroyed and equipment life become shorter because of the metal liquid

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overflowing. In this paper, with the ISM equipment introduced from Germany, the pressure distribution during the process of permanent mold centrifugal casting has been analyzed. At the same time, results in this paper have also been verified by experiments.

2 PROCESS ANALYSIS

In this paper, Ti-48Al-2Cr-2Nb (mole fraction, %) alloy is poured into permanent mould under the centrifugal condition with induction skull melting (ISM) method. The vacuum chamber pressure is about 1.08 Pa. During the process of centrifugal casting, the platform and metal turn around the center axis with angular velocity ω (rad/s). The pouring basin structure of the pouring system is defined as column, and its height and diameter are respectively H and D_0, adopting side gate into head, shown as Fig. 1. At the beginning of rotation, TiAl alloy liquid will move outward because of the centrifugal force. Immediately it becomes unity with the mould and forms a relative balance with the basin.

Suppose that the metal liquid fills the mold completely during the process of centrifugal casting, then the pressure distribution in static fluid can be expressed as following:

$$\mathrm{d}p = \rho_t (X\mathrm{d}x + Y\mathrm{d}y + Z\mathrm{d}z) \tag{1}$$

where X, Y, Z are respectively the projections that unit mass power acts on x, y and z axes. They can also be regarded as the projections of gravity acceleration g on x, y and z axes. Some isotonic surfaces that consist of isotonic points exist in fluid. For these surfaces, p is constant, so $\mathrm{d}p = 0$. Because fluid density ρ_t is not equal to 0, the isotonic surface differential equation can be obtained:

$$X\mathrm{d}x + Y\mathrm{d}y + Z\mathrm{d}z = 0 \tag{2}$$

By analyzing the forces acting on the mass point m, we can know that besides gravity, it also suffers a centrifugal inertia force. It equals the product of mass and centripetal acceleration, and its direction is opposite to centripetal acceleration. The forces acting on unit mass m include:

$$X = \omega^2 r\cos\alpha = \omega^2 x$$

$$Y = \omega^2 r\sin\alpha = \omega^2 y$$

$$Z = -g$$

where r is the distance from mass point m to axis, just the radius that it is on; x, y are the projections of r on x, y axes.

Fig.1 Schematic diagram of pressure analyzing

If the expressions of forces are taken into Eqn.(2), the isotonic surface equation is obtained:

$$\omega^2 x\mathrm{d}x + \omega^2 y\mathrm{d}y - g\mathrm{d}z = 0$$

After integrated, it becomes

$$\frac{\omega^2 r^2}{2} - gz = C_1$$

It is obvious that the isotonic surfaces are a cluster of paraboloids rotating around z axis. When metal liquid does not overflow, the volume that is closed by free surface and bottom is equal to that of static liquid. That is

$$\pi\left(\frac{D_0}{2}\right)^2 H_0 = \int_0^{2\pi}\int_0^{\frac{D_0}{2}} r\left(\frac{\omega^2 r^2}{2g} - \frac{C_1}{g}\right)\mathrm{d}\alpha\mathrm{d}r$$

So, $C_1 = \dfrac{\omega^2 D_0^2}{16} - H_0 g$, and the free surface equation is

$$z = \frac{\omega^2 r^2}{2g} - \frac{\omega^2 D_0^2}{16g} + H_0 \qquad (3)$$

and when $r = 0$, $z = H_0 - \frac{\omega^2 D_0^2}{16g}$.

Take the expressions of powers into Eqn. (1), get

$$dp = \rho_l(\omega^2 x dx + \omega^2 y dy - g dz)$$

integrate it, get

$$p = \rho_l(\frac{\omega^2 r^2}{2} - gz) + C_2 \qquad (4)$$

According to the boundary conditions that when $r=0$, $z = H_0 - \frac{\omega^2 D_0^2}{16g}$ and $p = p'_0$ (p'_0 is outside pressure). Substitute them into Eqn. (4), we have

$$p'_0 = \rho_l[-g(H_0 - \frac{\omega^2 D_0^2}{16g})] + C_2$$

then $C_2 = p'_0 + \rho_l g H_0 - \frac{\rho_l \omega^2 D_0^2}{16}$ can be obtained. Take it into Eqn.(4) again, we have

$$p = \frac{\rho_l \omega^2 r^2}{2} - \rho_l g z + p'_0 + \rho_l g H_0 - \frac{\rho_l \omega^2 D_0^2}{16} \qquad (5)$$

Eqn.(5) is just the pressure distribution formula in pouring basin for constant angular velocity. Theoretically, when $r = D_0/2$ and $z = 0$, higher ω produces higher pressure on castings. Because of the limitation of pouring basin height H, if $z > H$ when $r = D_0/2$, metal liquid will overflow from the pouring basin and materials are lost. z will obtains its maximum value z_m at the interface where metal liquid meets mold. Then, according to Eqn. (3) we can know that

$$z_m = \frac{\omega^2 D_0^2}{16g} + H_0 \qquad (6)$$

It is obvious that z_m only concerns with ω when the size of mold has already been determined.

The relations between the metal height and the pouring basin diameter and height can be obtained according to the external conditions that $z_m = H$ when $r = D_0/2$, and $z=0$ when $r=0$,

$$H_0 = \frac{H}{2} \text{ and } \frac{H}{D_0^2} = \frac{\omega^2}{8g}$$

To prevent metal from overflowing, $z_m \leqslant H$ must be satisfied, so

$$\frac{\omega^2 D_0^2}{16g} + H_0 \leqslant H \qquad (7)$$

Now, the maximum angular velocity (it is just at $z_m = H$) ω_{max} that prevents metal from overflowing can be obtained as

$$\omega_{max} = \frac{4\sqrt{(H - H_0)g}}{D_0} \qquad (8)$$

We can know that the maximum angular velocity ω_{max} is in direct proportion to the quadratic root of the difference between the pouring basin height and the static metal height $(H - H_0)$, and is inversly proportional to the pouring basin diameter D_0.

Taking into account of the location of casts during the actual casting process, when the angular velocity is ω and the height of metal/mould interface is z_m, the pressure p_m that acts on castings center axis ($r = D_0/2$, the depth from liquid surface is $z = h$, h is the distance from the cast center axis to pouring basin bottom) is

$$p_m = \frac{\rho_l \omega^2 D_0^2}{16} + \rho_l g(H_0 - h) + p'_0 \qquad (9)$$

It is obvious that p_m is similar to z_m, when the size of mold has already been determined, also only concerns with ω. Its maximum value p_{max} is obtained when $z_m = H$, it is just that $\omega = \omega_{max}$,

$$p_{max} = \rho_l g(H - h) + p'_0$$

Comparing with gravity casting, the difference Δp exists between the centrifugal side pressure p_m and static pressure p_s, p_s is determined by the height difference between the metal liquid and casting center axis:

$$p_s = \rho_l g(H_0 - h) + p'_0$$

Now, the pressure difference Δp can be obtained:

$$\Delta p = p_m - p_s = \frac{\rho_l \omega^2 D_0^2}{16} \qquad (10)$$

We can know that the side pressure p_m produced during the process of centrifugal casting consists of two parts: one is the static pressure p_s, the other is the extra pressure Δp due to the centrifugal casting.

The free surface will contact with the pouring basin bottom diameter D' when angular velocity is ω'. If angualr velovity is higher than ω', melt will depart at the bottom diameter. Taking $z = D'/2$, $z = h'$ and $p = p'_0$ into Eqn. (5), ω' can be obtained. The value of ω' is

$$\omega' = 4\sqrt{\frac{g(H_0 - h')}{(D_0^2 - 2D'^2)}}$$

At this time, the static pressure has no influence on the solidification castings even when melt does not overflow. This results in pressure decreasing in melt within the mould chamber and produces bad effects on the solidification structure.

3 RESULTS AND DISCUSSION

From the results above, we can know that the surface of TiAl based alloy liquid looks like paraboloid during the process of centrifugal casting. When $H = 20$ cm, $H_0 = 10$ cm and $D_0 = 10$ cm, the surfaces with a series of angular velocities are shown as Fig.2.

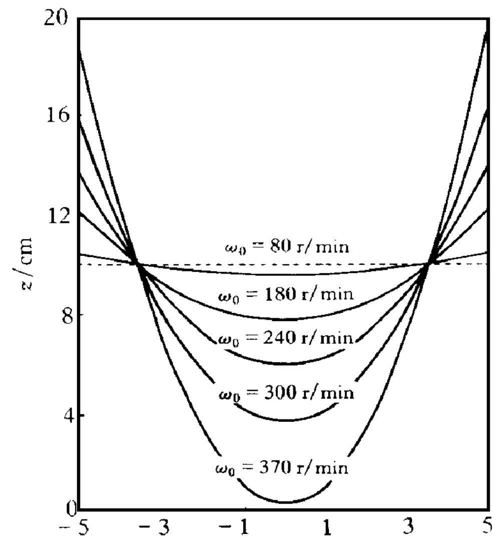

Fig.2 Free surfaces with different angular velocities

From the results showed in Fig.2, we can know that the maximum allowable angular velocity is about 370 r/min when the factors are determined. According to the measuring data showed in Fig.3, we can know that the calculating results are approximately corresponding with experiments.

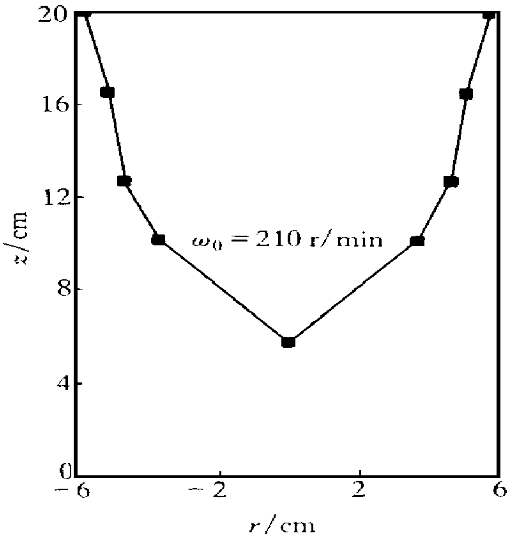

Fig.3 Measuring free surface when ω_0 = 210 r/min

With a certain angular velocity, because of the centrifugal force, the pressure of melt on sides increases. So, melt will fill the mould with higher pressure. Melt near the sides moves upside, while that on center axis moves to sides to supply. With higher angular velocity, the central point of free surface becomes lower, while sides becomes higher. It is more distinct when the angular velocity increases. The static pressure on castings will increase with the increasing of melt height, whose increasing follows parabola rule. Melt will overflow and mould bottom outcrop if the angular velocity is higher enough.

During the actual pouring process, the major restricting reasons are the pouring basin height H and diameter D_0, as well as melt height H_0. When factors above have already been determined, the shape of free surface is decided by angular velocity. The chamber pressure is about 1.08 Pa when TiAl based alloy is melted with ISM method, so the outside pressure can be neglected. We can know that on the same height, the pressure distribution centers around axis and increases from center to sides which follows parabola rule. With the increasing of angular velocity, pressure area which is equal to environmental pressure appears firstly on central axis, and increases with the higher angular velocity.

It is very important to adopt reasonable pouring system and melt volume during the process of casting. Not only can maximum pressure be obtained, but also materials lose can be avoided during centrifugal casting. The melt height is the static height H_0 before the platform begins to rotate. The interfaces melt height z_m increases from H_0 to the pouring basin height H which follows parabola rule with the change of angular velocity. Accordingly, the value of pressure p_m of melt on sides increases from static pressure to maximum. The difference Δp between the centrifugal pressure and static pressure also follows parabola rule, and is parallel to p_m. The relations among them are shown in Fig.4.

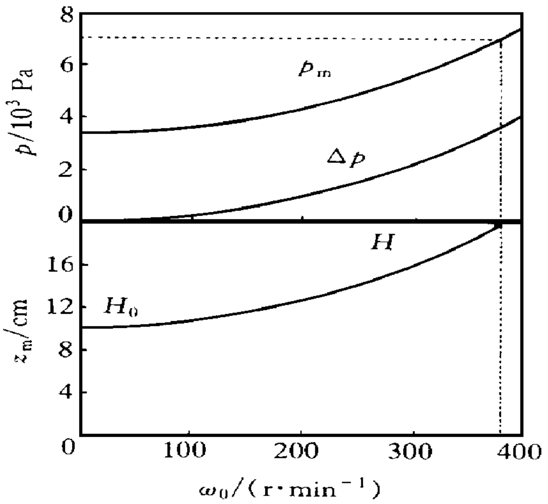

Fig.4 Relations between ω_0 and z_m, p_0

The melt height and pressure on sides increases with the increasing of angular velocity. The pressure reaches its maximum value when the melt height is equal to the pouring basin height. During the actual process, not only the vaccum chamber is destroyed, but also materials are lost if melt overflows. So, it is very important to choose reasonable angular velocity.

The maximum allowable angular velocity $\omega_{0\max}$ and maximum pressure $p_{\max}$ according to the relations shown in Fig.4 can be obtained. It can be expressed by the dotted line in Fig.4. The point of intersection between the curve z_m and the middle axis is just the pouring basin height H, and the point of intersection between the line parallel to vertical axis line drawing out from this point and the horizontal axis just expresses the maximum allowable angular velocity $\omega_{0\max}$. The vertical coordinate of the point of intersection with the curve p_m is the maximum side pressure $p_{\max}$ when the maximum angular velocity has been adopted. The $\omega_{0\max}$ and $p_{\max}$ values shown in Fig.5 are respectively 375 r/min and 7×10^{-3} Pa when $H = 20$ cm, $H_0 = 10$ cm and $D_0 = 10$ cm, and the result is identical with experiments.

If the pouring basin dimension is different, the maximum allowable angular velocity is also different. The pouring basin dimensions and angular velocity both have important influences on obtaining maximum pressure and avoiding the lose of materials during the casting process. Reasonable angular velocity should be chosen according to the pouring basin dimension. The relations between the maximum angular velocity $\omega_{0\max}$ and melt height H_0, pouring basin diameter D_0 are shown in Fig.5 when H is 20 cm. The maximum angular velocity decreases with the increasing of pouring basin diameter when the melt height is constant. It also decreases with the increasing of melt height when the pouring basin diameter is constant.

4 CONCLUSIONS

(1) The pressure produced during the process of centrifugal casting for TiAl alloy consists of two parts, one is the static pressure p_s, the other is the extra pressure.

(2) During the process of centrifugal casting, to prevent the TiAl based alloy melt from overflowing and keep high melt static pressure in mould chamber, the following conditions should be satisfied: $\frac{\omega^2 D_0^2}{16g} + H_0 \leqslant H$. The maximum angular velocity is $\omega_{\max} = \frac{4\sqrt{(H - H_0)g}}{D_0}$.

(3) The maximum angular velocity decreases when the pouring basin diameter or melt

Fig.5 Relations between melt height H_0 and pouring basin diameter D_0, maximum angular velocity $\omega_{0\max}$ when $H = 20$ cm

height increases.

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