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Analysis of filling process of Ti6Al4V alloy melt poured in permanent mold during centrifugal casting process①

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[Abstract] Ti6Al4V hip joint was foundered and the filling process of the melt poured in permanent mould during the centrifugal casting process was analyzed and the mathematical model of the filling process was established. Furthermore, the mathematical model was validated with a wax-model experiment. Calculating results show that the centrifugal field has an important influence on the filling process and the melt fills the mould with variational cross-sectional area and inclined angle. The cross-sectional area is in inverse proportion to the filling speed and its decreasing speed becomes fast with increasing rotating speed. The tangential value of the melt cross-sectional free-surface inclined angle is in direct proportion to the filling speed and the inclined angle increases with the filling length. Change curves of the cross-sectional inclined angle and area were obtained by the wax-model experiment when the rotating speeds were 60, 90 and 120 r/min respectively, which shows that the mathematical model is consistent with the experimental results.

[Key words] flow status; Ti6Al4V alloy; cross-sectional area; permanent mold; centrifugal casting
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1 INTRODUCTION

Titanium alloys have attracted a great deal of attention because of their potential attractive properties for high-temperature structural materials. At the same time, for their excellent corrosion, oxidation resistance and low density, Ti6Al4V based alloys are being applied to a number of aerospace fields[1~5].

In 1957, Levental first produced hip joint and the materials were developed. Symposon applied titanium board to brain surgical operation in 1961. Many titanium and titanium alloys have been applied to dentistry and other fields in Japan and some countries in Europe. Some researchers have given their efforts to research the forming character of Ti6Al4V based alloys. For example, the properties and forming characteristics have been evaluated by Suzuki et al[6]. Moreover, several forming methods applied to the alloys have been discussed, such as Powder Metallurgy (PM), Rapid Solidification (RS) and investment casting. In China, PM, investment casting and permanent mold casting formation methods[7~10] have been studied by researchers in Institute of Metal Research, Institute of Powder Metallurgy, Harbin Institute of Technology and Institute of Aeronautical Materials, and so on.

On the basis of the analysis of Ti6Al4V alloy hip joint, we believe that the centrifugal field has important influence on the formation of inner defects. In this paper, the flowing status during centrifugal filling process has been analyzed to conclude the flow characters in centrifugal field.

2 MATHEMATICAL MODEL

Ti6Al4V (mass fraction, %) hip joint (see Fig. 1) designed horizontally in rotating permanent mold are founded in Induction Skull Melting (ISM) furnace. The rotating speed is 300 r/min. The pressure in vacuum chamber and melting power are respectively about 0.1 Pa and 235 kW.

We know that the melt fills the mould with high speed in centrifugal field during ISM process and the full-filling time is short. The thickness of the solidified layer has been calculated with Chvorinov formula and the result shows that the maximum value (at mould entrance) is less than 0.8 mm. It can be concluded that the solidified layer has no important influence on the filling process until the mould is full-filled. So, the mathematical model is established by neglecting the influence of the solidified layer.

The mould is defined as column whose radius and length are r and L ($L \gg r$) respectively. Rotating speed of the mould is ω, rad/s, and the horizontal original filling speed is v_0, m/s. Distance from entrance to rotation axis is L_0, as seen in Fig. 2. For simplifying the mathematical model, the following assumptions are made:

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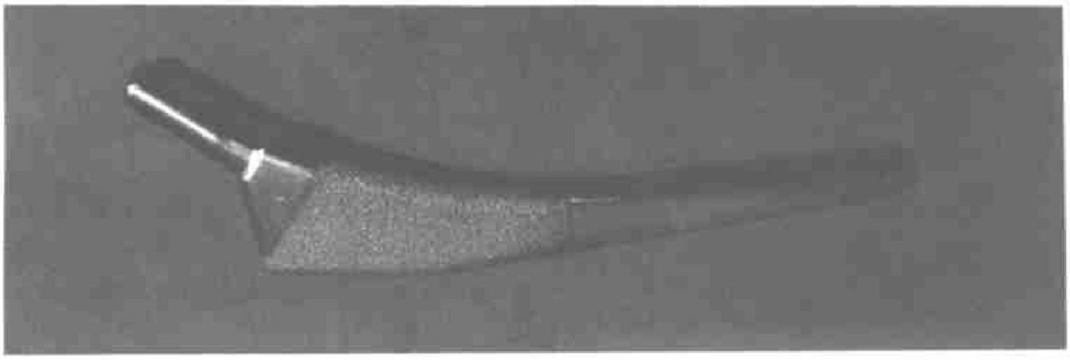

Fig. 1 Ti6Al4V hip joint

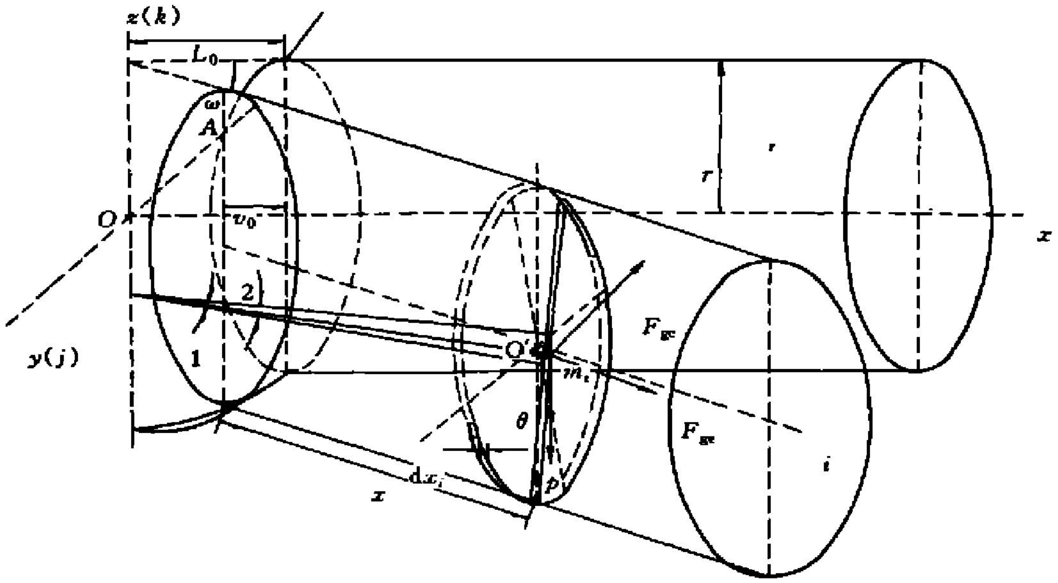

Fig. 2 Schematic diagram of flowing status analysis

1) Filling process is continuous; 2) melt flows constantly; 3) dynamical viscosity coefficient μ_{ta} and density ρ_{ta} of melt are both constants; 4) melt can not be compressed; 5) resistance existing during the filling process is negligible.

2.1 Cross-sectional inclined angle

Points consisting of free surface can be regarded as higher speed ones because of the resistance of wall. So in the same cross-section, center point should have the maximum speed. Particle $m_i(x, y, z)$ is a point on the maximum speed trochoid, which is chosen to study the moving rule. Following relation should be satisfied:

$$\boldsymbol{F}_{gc} + \boldsymbol{F}_{ge} + \boldsymbol{P} + \boldsymbol{F}_n = 0 \tag{1}$$

in which, $\boldsymbol{F}_{gc}$ —Coriolis force; $\boldsymbol{F}_{ge}$ —Inertial centrifugal force; $\boldsymbol{P}$ —Gravity; $\boldsymbol{F}_n$ —Composition of forces acting on particle m_i, including gravitation, repulsive force, surface tension, and so on, its direction should be the same as free surface normal, so $\boldsymbol{F}_n \times \boldsymbol{n}_s = 0$ ($\boldsymbol{n}_s$ is normal vector of the free surface).

Expression of $\boldsymbol{F}_n$ can be obtained:

$$\boldsymbol{F}_n = M_i(\omega \times (\omega \times \boldsymbol{x}_r) - 2\omega \times \boldsymbol{v}_r - \boldsymbol{g}) \tag{2}$$

in which, M_i —Mass of particle; $\boldsymbol{x}_r$ —Radius vector of moving relative to rotating axis origin; $\boldsymbol{v}_r$ —Speed vector of moving relative to rotating axis origin; ω —Rotating speed.

Expressions of $\boldsymbol{x}_r$ and $\boldsymbol{v}_r$ should be as follows for the maximum speed particle:

$$\boldsymbol{x}_r = x_i(t)\boldsymbol{i} + x_i(t)\cdot \mathrm{tg}\angle 1\boldsymbol{j} + x_i(t)\cdot \mathrm{tg}\angle 2\boldsymbol{k} \tag{3}$$

$$\boldsymbol{v}_r = v_i(t)\boldsymbol{i} + v_i(t)\cdot \mathrm{tg}\angle 1\boldsymbol{j} + v_i(t)\cdot \mathrm{tg}\angle 2\boldsymbol{k} \tag{4}$$

$\angle 1$, $\angle 2$ —Respectively the angle offsets on $\boldsymbol{j}$ and $\boldsymbol{k}$ directions in which m_i moves relatively to rotating axis origin;

$x_i(t)$, $v_i(t)$ —Filling length and speed of m_i in i direction.

Because $x \gg r$, $\mathrm{tg}\angle 1 \approx \mathrm{tg}\angle 2 < \frac{r}{x}$ and $\frac{r}{x} \to 0$ should be satisfied. As a result, the following relation can be obtained:

$$\boldsymbol{x}_r = x_i(t)\boldsymbol{i}, \quad \boldsymbol{v}_r = v_i(t)\boldsymbol{i} \tag{5}$$

Similar relations can also be obtained in $\boldsymbol{j}$ and $\boldsymbol{k}$ directions. Integrating them, contrail equation of the maximum speed particle can be expressed as follows:

$$\left.\begin{aligned} x_i(t) &= C_1 e^{\omega t} - C_2 e^{-\omega t} \\ y_i(t) &= -2C_1 e^{\omega t} - 2C_2 e^{-\omega t} + C_3 t + C_4 \\ z_i(t) &= -(g/2)t^2 + C_5 t + C_6 \end{aligned}\right\} \quad (6)$$

in which, C_1, C_2, C_3, C_4, C_5 and C_6 —Integral constants.

If α_i, β_i and γ_i are respectively the angles that $\boldsymbol{F}_n$ departures in $\boldsymbol{i}$, $\boldsymbol{j}$ and $\boldsymbol{k}$ directions, they can be expressed as

$$\cos\alpha_i = \frac{F_{ge}}{F_n},\ \cos\beta_i = \frac{F_{gc}}{F_n},\ \cos\gamma_i = \frac{M_i g}{F_n} \quad (7)$$

Change of inclined angle must be determined first if we want to describe flow status of melt during the filling process. The cross-section where the maximum speed particle lies on is chosen. Cross-sectional structure should be irregular because of flowing characteristic of melt and resistance of inner mould surface. Cross-section is predigested as a normal arc and $\theta_i(t)$ is the angle between projection of $\boldsymbol{F}_n$ on jok plane and rotating axis (k axis). Furthermore, followings are defined: 1) angle between melt cross-section dx_i and rotating axis is just the angle between normal direction of the maximum speed contrail point on free surface and rotating axis; 2) angle defined above is between the normal on straight side and rotating axis. So, inclined angle $\theta_i(t)$ of melt cross-section can be expressed as

$$\mathrm{tg}\,\theta_i(t) = \frac{F_{gc}}{M_i g} = \frac{\omega(v_0 + \omega L_0)}{g} e^{\omega t} + \frac{\omega(v_0 - \omega L_0)}{g} e^{-\omega t} \quad (8)$$

$\boldsymbol{F}_{gc}$ is produced by Coriolis force because of the influence of centrifugal field, and increases with the increase of distance from cross-section to rotating axis. As a result, cross-sectional inclined angle increases gradually. $\theta_i(t) \to \pi/2$ when $\omega \to \infty$ and $|h_m(t)| \to r$. It is shown that melt free surface tends to be vertical at the end of mould when rotating speed is high enough. The same result can be obtained when mould length is long enough.

2.2 Cross-sectional area and laminar flow criterion

Filling speed near inner surface of mould will decrease due to viscosity of the melt. A micro-flown cube is chosen in the melt along the main flowing direction (center axis of the mould), and cross-sectional areas of melt are s_0 and s_i respectively. Because of the continuous filling process, the inflow flux through s_0 should be equal to the simultaneous outflow through s_i according to conservation of mass. So

$$\rho_0(t)\,\overline{v_0(t)}\,s_0(t) = \rho_i(t)\,\overline{v_i(t)}\,s_i(t) \quad (9)$$

$\overline{v_0(t)}$ and $\overline{v_i(t)}$ are respectively the average speed in two cross-sections and superpose with cross-sectional center of gravity when filling time is t. Melt can't be compressed during the filling process, so $\rho_0(t) = \rho_i(t) =$ const. On the basis of speed distribution rule of laminar flow, $\overline{v_0} = v_0/2$ and $\overline{v_i} = v_i(t)/2$ should be satisfied. So, average speed $v_m(t)$ on arbitrary cross-section should be equal to $\overline{v_i}$, and $v_m(t) = v_i(t)/2$. Cross-sectional area $s_i(t)$ can be expressed as

$$s_i(t) = \frac{2\pi v_0 r^2}{(v_0 + \omega L_0)e^{\omega t} + (v_0 - \omega L_0)e^{-\omega t}} \quad (10)$$

Because cross-section is defined as arc, its area $A_i(t)$ is

$$A_i(t) = r^2[\pi - \arccos h_w(t) + h_w(t)\sqrt{1 - h_w^2(t)}] \quad (11)$$

in which, $h_w(t) = \dfrac{h_i(t) - r}{r}$, defined as relative height and $-1 \leqslant h_w(t) \leqslant 1$;

$h_i(t)$ is height of arc cross-section, which changes with the filling time.

Comparing formula (10) with (11), $s_i(t)$ is equal to $A_i(t)$:

$$\frac{2\pi v_0}{(v_0 + \omega L_0)e^{\omega t} + (v_0 - \omega L_0)e^{-\omega t}} = \pi - \arccos h_w(t) + h_w(t)\sqrt{1 - h_w^2(t)^2} \quad (12)$$

Formula (12) can be calculated with different methods.

3 RESULTS AND DISCUSSION

3.1 Filling process description

Based on the expression of filling length, we can know that the filling speed increases gradually when the filling length increases. Cross-sectional area decreases when filling speed increases, because the flux is unchanged for different cross-sections. Change of cross-sectional area with the filling length is shown in Fig. 3. Entrance length and speed are $L_0 = 0.12$ m and $v_0 = 1$ m/s, and rotating speeds are 100, 200, 300, 400 and 500 r/min respectively. Change of inclined angle under different rotating speeds is shown in Fig. 4. Inclined angle increases with the increase of

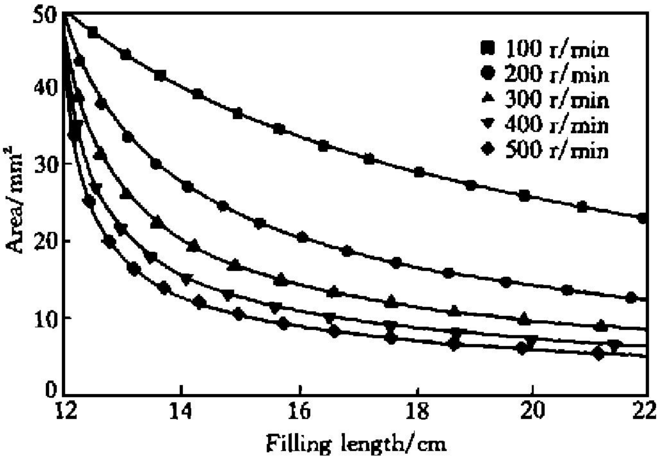

Fig. 3 Change of cross-sectional area with filling length

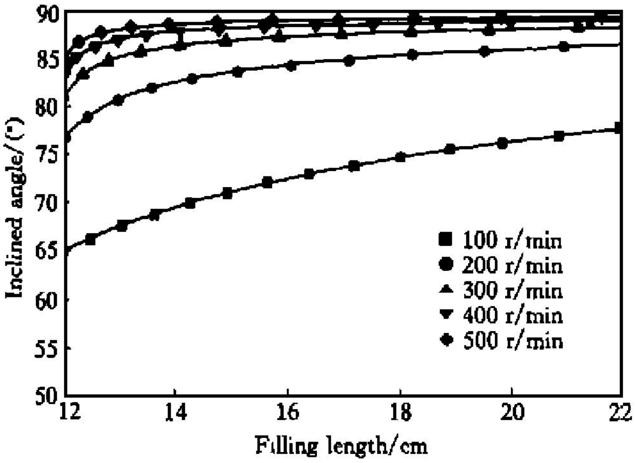

Fig. 4 Change of inclined angel with filling length

filling length and tends to be 90° at the end of mould. At the entrance, melt will be apart with the mould at different positions (with different inclined angles) when the rotating speed changes and the angle increases with the increase of rotating speed. In Fig. 4, angles at the entrance are respectively 65°, 77°, 81°, 83° and 85°.

So, the filling process in centrifugal field can be described. Melt fills the mould with a certain original speed. During the filling process, melt flows along the back wall with changeable speed. The speed becomes higher when the filling length increases. Cross-sectional area and inclined angle also change because of the increasing filling speed. Cross-sectional area decreases when the filling length increases, while the inclined angle increases. Both of them change more rapidly near the entrance. With the increase of rotating speed, the changes become more obvious. Inclined angle tends to be 90° if the mold is long or the rotating speed is high enough. In addition, inclined angle at the entrance is different when the rotating speed changes.

When the melt reaches the end of mould, the mould will be full-filled first at the end because of centrifugal force. Immediately, melt returns to fill the mould. The mould will be fully filled until the moving melt reaches the entrance. When the rotating speed is 300 r/min, the filling process at different filling times is shown in Fig. 5.

3.2 Experimental validation

Filling process of the melt is validated by pouring wax into the permanent mold because it is very difficult to control the filling of Ti6Al4V alloy melt during ISM process. The mould radius, length and entrance length are respectively 10, 30 and 12 cm. The rotating speeds are 60, 90 and 120 r/min respectively, which are less than that in actual casting process. Wax-models are shown in Fig. 6. The area and inclined angle of the wax model cross-section have been measured every 3 cm, as seen in Fig. 7. It is obvious that the measuring value is consistent with the calculating result basically, which shows that the mathematical model is correct.

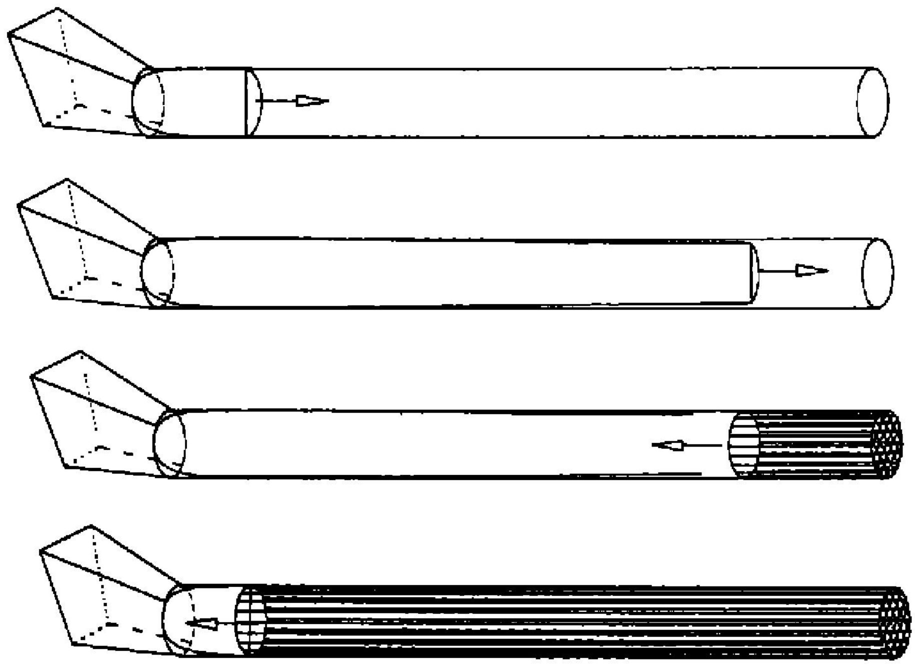

Fig. 5 Filling process of false joint-bone when rotating speed is 300 r/min

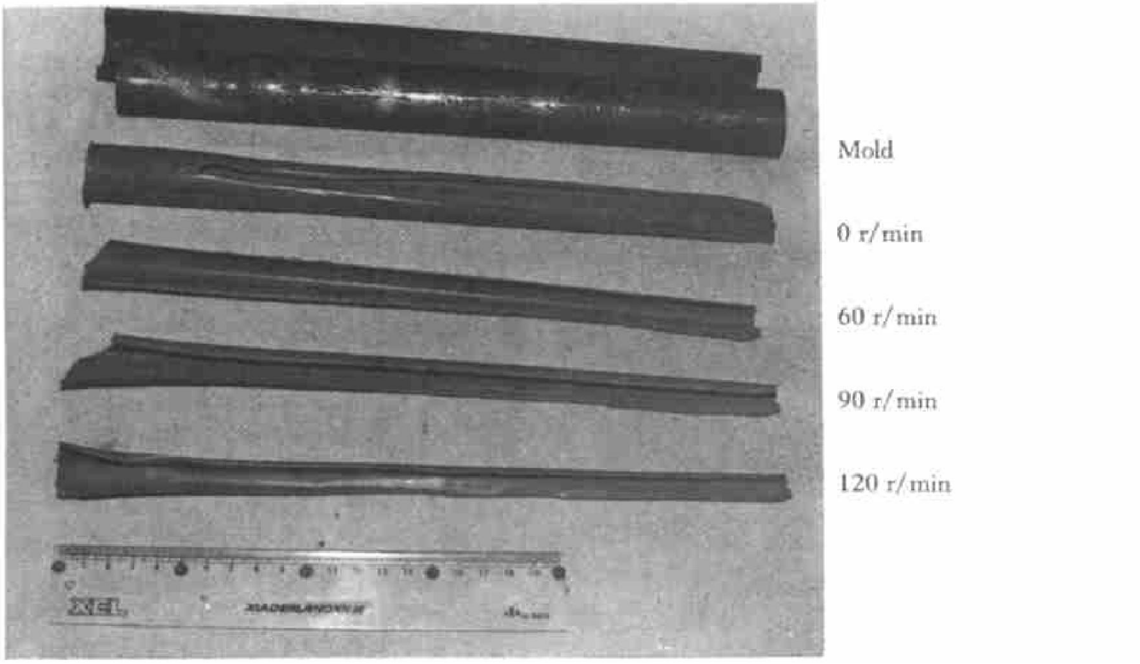

Fig. 6 Wax models formed under different rotating speeds

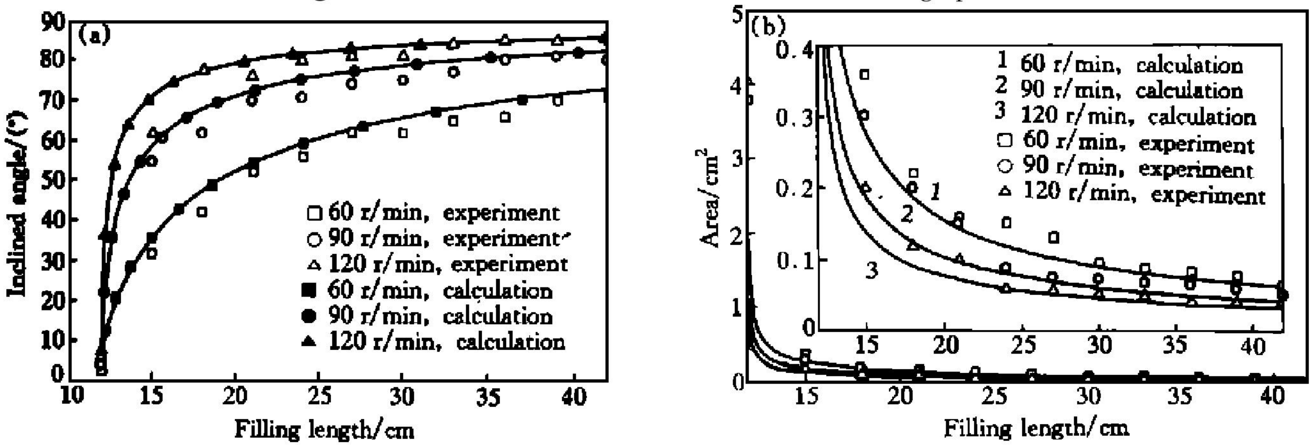

Fig. 7 Comparison of calculating value and experimental result
(a) —Cross-sectional inclined angle; (b) —Cross-sectional area

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