PREPARATION OF ROUND BILLETS BY SPRAY FORMING TECHNOLOGY①

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ABSTRACT The pattern of making round billets by spray forming technology was studied by means of numerical method combined with experiment. The results show that during the atomization deposition process, the shape of the deposit reaches a stable state after a primary transient state, and then the round billet grows in the mode of equi-diameter. The basic condition to reach the stable state is that the withdraw velocity of the collector, v, is smaller than $a\cos\Phi$, where a is the atomization density along the atomization axis, and Φ is the atomization angle. With the other technological parameters being constant, round billets with different diameters can be made by adjusting the withdraw velocity. Additionally, the ratio of gas flux to melt flux (G/M) also directly affects the shaping of round billets in the atomization deposition process.

Key words spray forming round billets numerical method ratio of gas flux to melt flux

1 INTRODUCTION

The spray forming technology is a new technology for making materials. It has been developed on the basis of the conventional rapid solidification powder metallurgy[1]. The materials prepared by the spray forming technology not only maintain the advantages of the conventional rapid solidification powder metallurgy, but also reduce many intermediate processes, cut down the production cost and depress the oxidation degree. Recently, this new technology has drawn wide attentions from the industrial circles[2-4].

The key is to develop technologies for preparing deposits of certain shapes[5,6]. In this paper, by combining the numerical method with experiment, the pattern of making round billets by spraying forming technology was studied, and the effects of the key technological parameters on the shaping of round billets were revealed.

2 GROWTH MATHEMATICAL MODEL OF ROUND BILLETS IN SPRAY DEPOSITION PROCESS

2.1 Establishment of mathematical model

In order to establish the growth mathematical model of round billets in the spray deposition process, two coordinates are introduced as shown in Fig.1(a): one is (R_r, Θ_r, Z_r) for describing the shape of the deposit, the other is (r_r, θ_r, z_r) for describing the distribution function of atomization density. Fig.1(b) shows the angle between the central axis of atomization and the normal growth direction of point P on the deposit. This model has several assumptions[7]:

(1) The distribution function of atomization density presents a Gauss distribution with the atomization axis as the symmetrical axis, and is given by

$$M(r_s) = a\exp(-br_s^2) \quad (1)$$

where a is the atomization density along the

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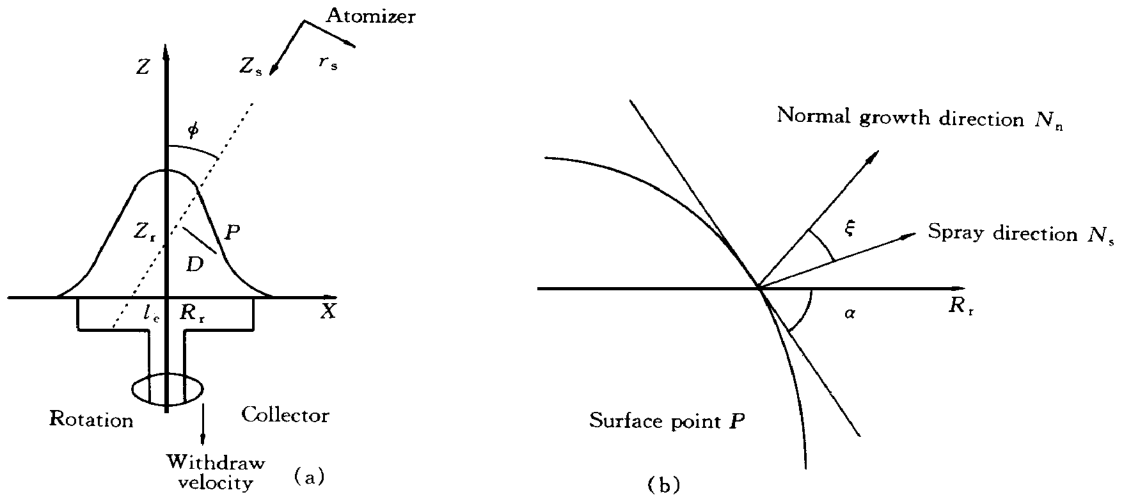


Fig.1 Coordinate systems used in formulation
(a) —Cal-coordinate system; (b) —Geometric rod system

atomization axis, b is a distribution coefficient of the distribution function of atomization density.

(2) All the melt droplets reaching the deposit surface will be deposited completely, namely the deposition coefficient is 100%.

(3) When the atomization included angle of the atomizer is very small, it can be believed that the flying direction of the melt droplets is parallel to the nozzle axis.

(4) When the rotation frequency of the collector is relatively high, the shape of the deposit is of axial symmetry, and the tangent plane of the deposit top is parallel to the collector.

Let the initial eccentric distance be l_e at the beginning of the atomization deposition; it represents the distance from the center of the collector to the intersection point of the atomization axis and the collector. The withdraw velocity of the collector is kept at v. Let D be the vertical distance of an arbitrary point P on the deposit to the atomization axis, and $f(R_r, t)$ be the Z value of point P at t moment, then

$$D^2 = (R_r \sin\Theta)^2 + \frac{[R_r\cos\Theta - \tan\phi \cdot f(R_r, t) +}{(1+\tan\phi)\cdot} \rightarrow$$

$$\leftarrow \frac{vt\tan\phi - l_e]^2}{(1+\tan\phi)} \qquad (2)$$

where R_r is the radius of point P. Let $M(D)$ be the atomization density at point P, then

$$M(D) = a \cdot \exp(-bD^2) \qquad (3)$$

There exists a critical boundary between the melt droplets and the deposit surface in the atomization deposition process, i.e. a region $|\xi| \geqslant \pi/2$, in which there are no liquid droplets to reach. Therefore, we define

$$F(\xi) = \begin{cases} 1, & \cos(\xi) \geqslant 0 \\ 0, & \cos(\xi) \leqslant 0 \end{cases} \qquad (4)$$

Then the surface growth rate, G, at point P is given by

$$G(R_r, f(R_r, t), t) = F(\xi)\, M(D)\, N_s \cdot N_n \qquad (5)$$

The average growth rate at point P after each cycle becomes

$$\overline{G}(R_r, f(R_r, t), t) = \frac{1}{2\pi}\int_0^{2\pi} F(\xi)\, M(D)\, N_s \cdot N_n \mathrm{d}\Theta \qquad (6)$$

When the growth of the round billet reaches the stable state, its diameter does not change any more, and the growth rate of the top surface should be equal to the withdraw velocity of the collector, namely

$$\frac{\mathrm{d}Z_r}{\mathrm{d}t} = \frac{G}{\cos\alpha} = v \qquad (7)$$

Substituting Eq.(6) into Eq.(7) yields

$$\frac{1}{2\pi\cos\alpha}\int_0^{2\pi} F(\xi)\ M(D)\ N_s \cdot N_n d\Theta = v \tag{8}$$

If the origin of the coordinate (R_r, Θ_r, Z_r) is located at the intersection point of Z_r and Z_s, then Eq.(2) can be reduced to

$$D^2 = (R_r\sin\Theta)^2 + [R_r\cos\Theta - \tan\phi \cdot f(R_r)]^2\cos^2\phi \tag{9}$$

At the center of the top surface, we have $R_r = 0$ and $\alpha = 0$. Substituting these conditions and Eq.(9) into Eq.(8) and integrating gives

$$a\cos\phi \cdot \exp[-b\sin^2\phi \cdot f^2(0)]2\pi = 2\pi v \tag{10}$$

Simplification of Eq.(10) gives

$$f^2(0) = (\frac{1}{b\sin^2\phi})\ln(\frac{a\cos\phi}{v}) \tag{11}$$

The non-negativity of Eq.(11) decides that the condition of the existence of stable state in the growth process of the round billet is

$$\frac{a\cos\phi}{v} \geqslant 1$$

namely

$$v \leqslant a\cos\phi \tag{12}$$

Solving Eqs.(8) and (7) through programming, the growth process of the deposit can be simulated.

2.2 Calculation results

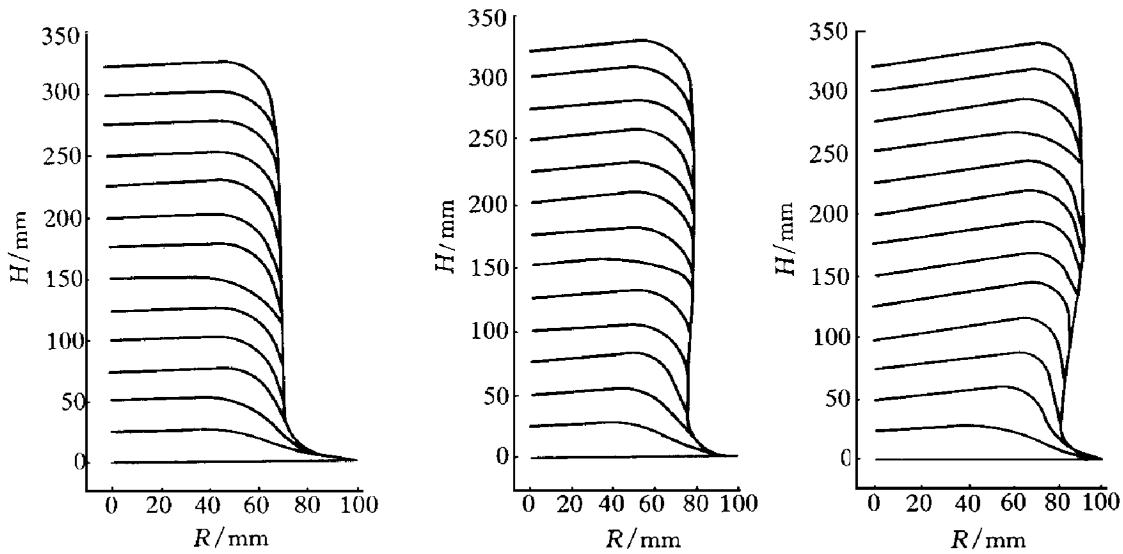
A bell-shaped deposit was prepared on the self-made SF-200 type spray forming equipment with the self-made free-fall type atomizer in the mode of vertical spray and non-eccentricity. The atomization pressure and the melt flux are constant, the initial receiving distance is 530 mm and the withdraw velocity of the collector in the deposition process is zero. The atomization density at the center of the spray axis, a, is calculated to be 5 mm/s and the corresponding distribution coefficient of atomization density, b, is calculated to be 0.001 mm^{-2}, thus

$$M(r_s) = 5\exp(-0.001\ r_s^2) \tag{13}$$

Based on the mathematical model established above, the growth process of the deposit was calculated by the method of finite difference under the following conditions: $\phi = 30°$, $l_e = 45$ mm, $f = 30$ r/min, and $v = 1.0$, 0.8, 0.6 mm/s. The calculation results are shown in Fig.2. Corresponding to different withdraw velocities, the diameters of the deposits are 142, 159, 181 mm, respectively.

3 EXPERIMENTAL

3.1 Experimental procedure



(a) $v = 1.0$ mm/s (b) $v = 0.8$ mm/s (c) $v = 0.6$ mm/s

Fig.2 Calculated shapes of round blanks at different withdraw velocities

The test material is a hypereutectic Al-Si alloy with the composition(mass fraction, %) of Si 22.5 ~ 23.5, Fe 4.6 ~ 5.2, and balance Al. The atomization gas is nitrogen gas.

The tests were carried out with PF-200 equipment in the mode of oblique spray (ϕ = 30°). The initial eccentric distance is 45 mm, and the atomization distance is 530 mm. In the tests, the melt flux was controlled at 41 g/s by adjusting the liquid level in the tundish and the temperature of the melt was kept at 750 ±5 ℃. The gas pressure and flux were changed so as to find the technological conditions for obtaining optimum shaping and density; the withdraw velocity of the collector was changed so as to find the relationship between the diameter of the round billet and the withdraw velocity.

3.2 Results and discussion

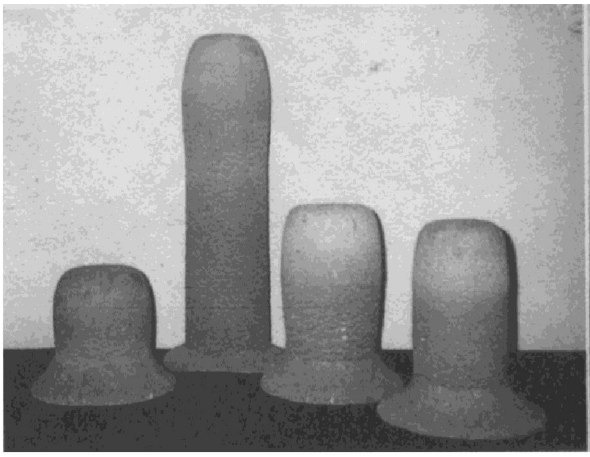
Table 1 shows the effects of atomization gas pressure and flux on the shaping and density of the deposits.

Fig.3(a) presents the photographs of the round billets of different specifications prepared by the atomization deposition process. The maximum length and diameter of the round billets can reach 700 mm and 180 mm, respectively. Fig.3(b) presents the photographs of the central cross-sections of two round billets, from which it can be seen that there exist some porosity in the parts near the substrate. This is due to the very rapid solidification rate in these parts which makes feeding by melt flow very difficult, thus forming fine solidification porosity. When the round billets reach their stable states, sequential solidification is realized except the several millimeters near the external surface, thus the deposits have high densities which in general can reach over 95 %.

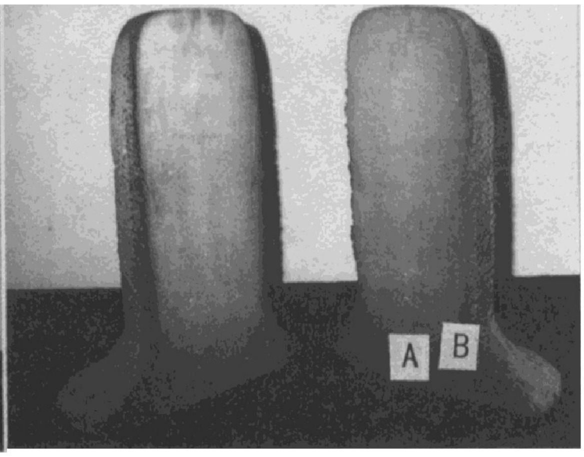
Table 1 Effects of atomization parameters on shaping and density of deposit

Gas pressure / MPa	Gas flux / ($g \cdot s^{-1}$)	G/M ratio	Shaping of billet	As-cast density / %
0.5	32.3	0.79	Poor	-
0.7	45.2	1.10	Ordinary	82
0.8	51.7	1.26	Good	95

Fig.4 shows the relationship between the diameter of round billet and withdraw velocity under the experimental conditions adopted in this work. It indicates that at the same withdraw velocity of the collector, the diameter of the actual deposit is always smaller than the calculated one. This is due to the fact that some atomized droplets collide elastically with the deposit surface, thus making the actual deposition efficiency lower than 100 %. But it can also be concluded from the tests that round billets of desired di-



(a) Profile



(b) Cross section

Fig.3 Photographs of billets made by atomization deposition process

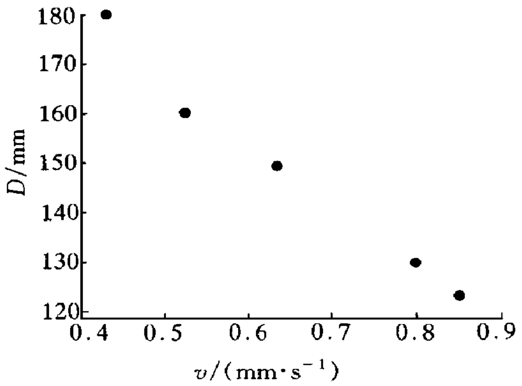


Fig.4 Relationship between diameter of round billets and withdraw velocity

ameters can be produced by adjusting the withdraw velocity of the collector under the conditions that all the other technological parameters are definite. This is of great importance to the practical applications of the spray forming in the industry.

4 CONCLUSIONS

(1) The numerical method in combination with experiments shows that when the technological parameters are suitably selected, the shape of the deposit passes a primary transient stage, and finally reaches a stable state, then the round billet will grow in the mode of equi-diameter. The basic condition for reaching the stable state is that the withdraw velocity of the collector satisfies $v \leqslant a\cos\phi$.

(2) Round billets of different diameters can be produced by adjusting the withdraw velocity of the collector with the other technological parameters being definite.

(3) The ratio of gas flux to melt flux (G/M) directly affects the shaping and density of deposit. For the test Al-Si alloy in this work, when $G/M = 1.26$, the density of the as-cast deposit can reach above 95 %.

REFERENCES

1 Singer A R E. Metals and Materials, 1970, 4: 246.
2 Evans R, Leatham A G and Brooks R G. Powder Metall, 1985, 28: 13.
3 Leatham A G. In: Second International Conference on Spray Forming. Swansea, UK, 1993: 129.
4 Higginbotham G J S. In: Second International Conference on Spray Forming. Swansea, UK, 1993: 259.
5 Shaw Lee and Spiegelhauer Claus. The International Journal of Powder Metallurgy, 1997, 3: 31.
6 Seok H K *et al*. In: Third International Conference on Spray Forming. Cardiff, UK, 1996: 287.
7 Liu Jiang and Shi Likai. Rare Metals, (in Chinese), 1997, 21: 12.
8 Mathur P, Apelian D and Lawley A. Acta Metall, 1989, 37: 429.

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