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Shape model of multi-pass spray deposition plate①

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Abstract: Multi-pass spray deposition shows apparent advantages in preparing large scale plates with rapid solidification. Shape model is promoted to obtain excellent shape. Three dimensional mathematical models considering motion of atomization cone and substrate, deposition distance and atomization parameters were used to predict deposited plate's shape. The results can be used to optimize the process parameters.

Key words: spray deposition; mathematical models; plate shape **Document code**: A

1 INTRODUCTION

Spray deposition can be used to produce equiaxed fine grain microstructures without segregation thus leading to excellent mechanical properties. It shows flexibility in dimensions of parts compared to powder metallurgy and high ratios of property to cost compared to casting, and has become a new manufacturing technology and attracted more and more attentions[1~3]. It is necessary to improve control accruacy for lower cost. Many researchers devote to establishing process model for different preforms[4~6], but there is no model for plate billets. In this paper a 3-D plate shape model is promoted for multi-pass spray deposition process.

2 MATHEMATICAL MODEL

There are many factors which influence preform shape, including metal melt flow rate, capturing rate, atomizer and substrate motion. Capturing rate depends mainly on droplet solid fraction before impacting, solid fraction on deposit surface and impacting angle. Cai's research[7] showed that the capturing rate climbed close to 1 when the impaction angle was close to 90°. This model treats capturing rate as 1 because the spray axis is vertical to substrate.

2.1 Motion description

Multi-pass spray deposition equipment[8~10] is shown in Fig. 1. Atomizer and substrate move perpendicularly, and driven by brace mechanism (Fig. 2). The motion can be formulated as

$$u = \omega l_1 \sin\theta \times \left[1 + l_1 \cos\theta / \sqrt{l_2^2 - l_1^2 \sin^2\theta}\right] \quad (1)$$

where u is the speed of atomizer or substrate, ω is the angular velocity, l_1 and l_2 are lengths of two shanks respectively, and θ is motion phase which can be expressed as

$$\theta = \int_0^t \omega(t)\mathrm{d}t \quad (2)$$

where t is motion time. When ω is constant, θ can be expressed as

$$\theta = \omega t + \varphi \quad (3)$$

where φ is initial motion angular phase. Displacement (S) can be expressed as integral of velocity to time, and given as follows:

$$S = \int_0^t u(t)\mathrm{d}t \quad (4)$$

When angular velocity is constant, S can be depicted as

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$$S = l_1\cos(\omega t + \varphi) + \sqrt{l_2^2 - l_1^2\sin^2(\omega t + \varphi)} \quad (5)$$

2.2 Mass distribution in spray cone

The mass in close-coupled atomizing nozzle spray cone can be treated as uniform distribution in the zone of r_{50}[6]. r_{50} is the radius where the axial gas velocity is half that of axis. Bewley[7] indicated the gas velocity can be formulated as

$$u(0, z) = u_0 \times \exp(-z/\lambda) \quad (6)$$

$$\lambda = 3.04 \times 10^{-4} u_0^{1.24} \quad (7)$$

$$u(r, z) = u(0, z) \times [1 - (r/(0.004 + 0.268z))^{1.5}]^2 \quad (8)$$

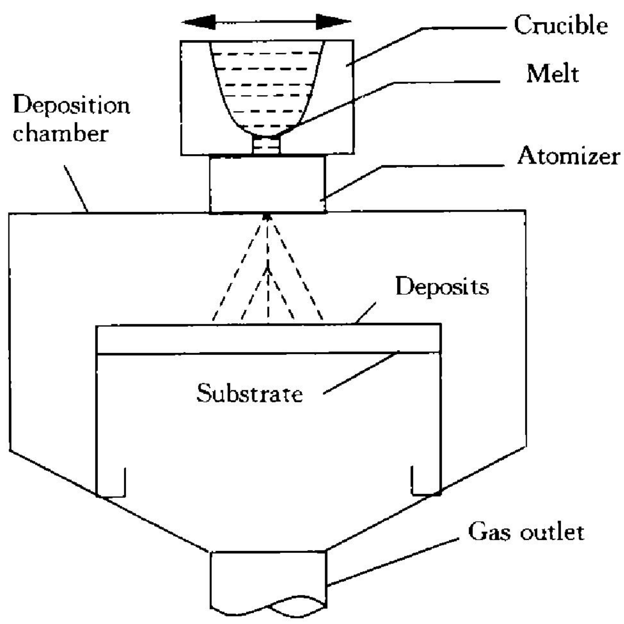


Fig.1 Diagram of multi-pass equipment for plate buildup

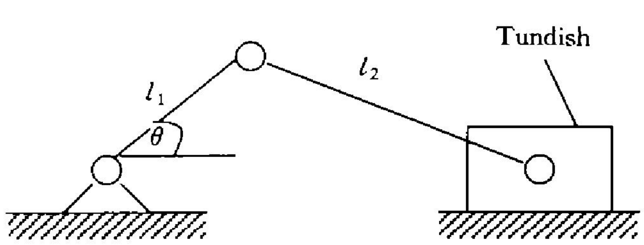


Fig.2 Schematic diagram of atomizer and substrate motion mechanism

where u_0 is the initial gas velocity, z is the axial distance from the gas outlet, and r is the radius. The radical velocity is much smaller than the axial velocity, so it can be neglected.

r_{50} can be calculated in relation with z:

$$r_{50} = (0.004 + 0.268z)(1 - \sqrt{2}/2)^{2/3} \quad (9)$$

The thickness growth rate throughout deposition zone can be formulated as follows:

$$dL/dt = \dot{D}/(\pi r_{50}^2) \quad (10)$$

where L is the deposit thickness, $\dot{D}$ is the mass deposition rate, and t is the time.

The above mathematical description establishes the relation between the deposit shape and the process parameters.

3 NUMERICAL EVALUATION

Thickness of each point increases at a different rate due to continuous relative motion of spray cone and substrate. The following method is used to calculate the deposit thickness: the substrate is divided into small grids, the increment of thickness at each grid point for each time interval is calculated and added up to one another. The spray cone is regarded as static at an interval, and the incremental rates for the grid points of the covered grids are the same. Whether a grid point is covered is judged according to whether the four center points of adjacent grids are covered. The division of grids and judging rule for deposition is charted in Fig. 3. The calculating method is charted in Fig.4.

The parameter values used in computation, such as deposition distance and motion speed, are not optimum for microstructure, but this will not affect the assessment for this model. The values of parameters are listed in Table. 1.

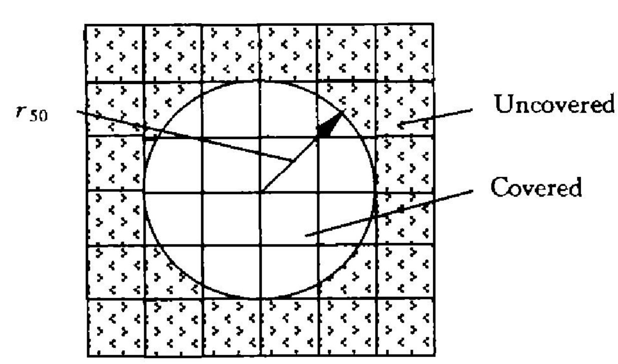


Fig.3 Substrate grids division and judging rule for deposition

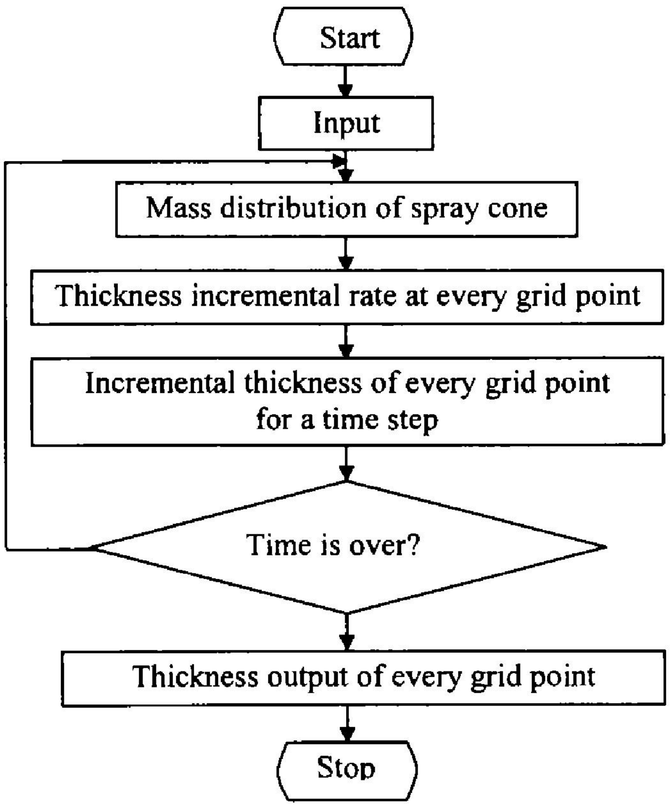


Fig.4 Flow diagram for computation

Table 1 Parameters used in computation

Initial deposition distance	500 mm
Net deposition rate	30 g/s
Deposit density	2.7 g/cm^{-3}
Plate dimension	300 mm × 300 mm
Grid dimension	10 mm × 10 mm
Time step for computation	0.01 s

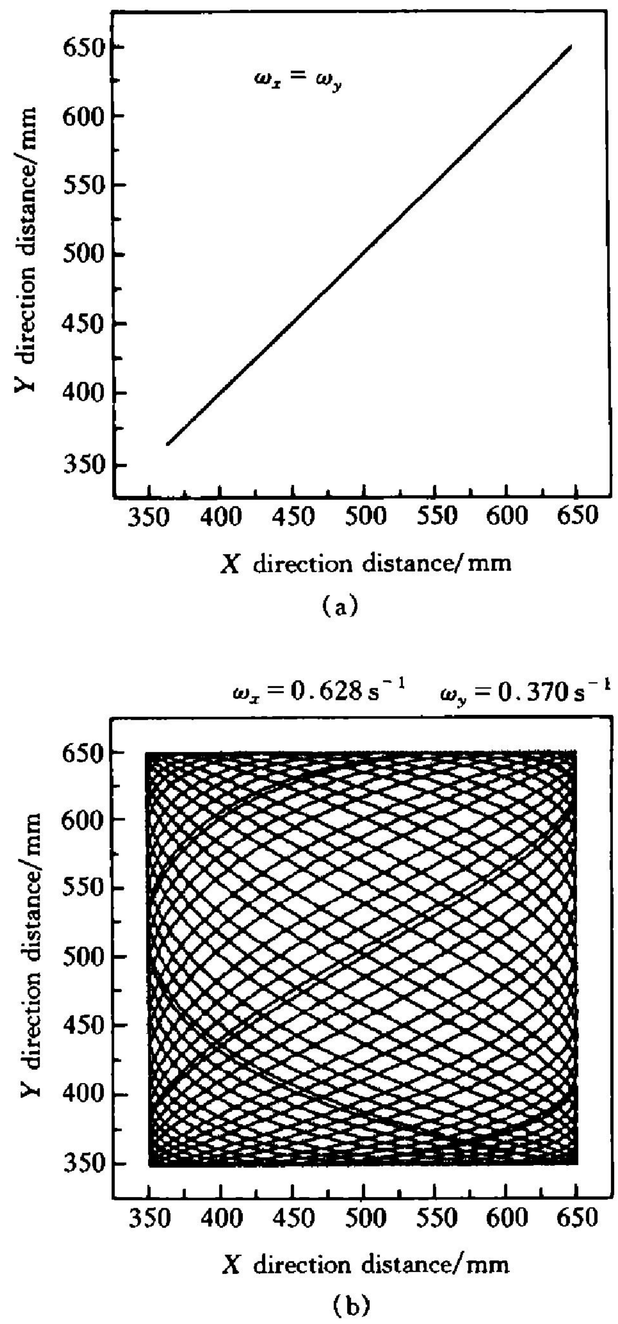


Fig.5 Influence of angular velocity on footprint

4 RESULTS AND DISCUSSION

4.1 Influence of annular velocity

The annular velocity (ω) of the crank determines the motion speed of the substrate and/or the spray cone. The spray cone's trace projected on the substrate is controlled by the motion speed ratio of them and their initial location. The velocity ratio plays a key role on the trace. It is obvious that short cycle of motion will do harm to uniform thickness. The motion trace for several annular velocity ratios with identical initial angle of 0 is shown in Fig.5, where atomizer and substrate move in X-axis and Y-axis respectively. If trace repeats quickly as Fig.5(a), it is hard to obtain uniform plate, while trace such as Fig.5(b) may be candidate for good shape.

3-D surface appearance corresponding to Fig.5(b) is shown in Fig.6. The deposition rate near the edges of plate is higher than that near the center of plate, which results from the motion speed difference. With the progress of deposition, the thickness incremental rate will differ from each other more and more, because there is shorter deposition distance for thicker zone besides the above-mentioned speed factor. This phenomenon lead to worse shape with increasing time, as shown in Fig.6.

In order to improve the thickness equality, a method of accelerating near the edges is used to minimize the speed difference. Supposing that atomizer or substrate accelerates in a distance of 50 mm from the edges, namely $\omega_{edge} = n\omega_{inner}$, it is found that when $n = 1.6$, the plate shape is improved, as shown in Fig.7.

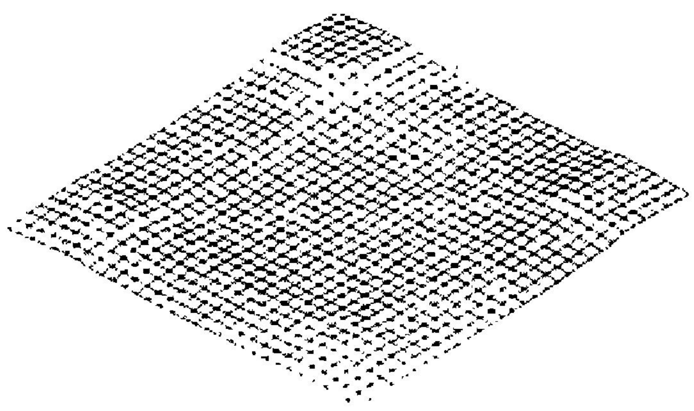


Fig.6 Plate shape corresponding to Fig.5(b) (100 s, viewpoint(1, 1, 1))

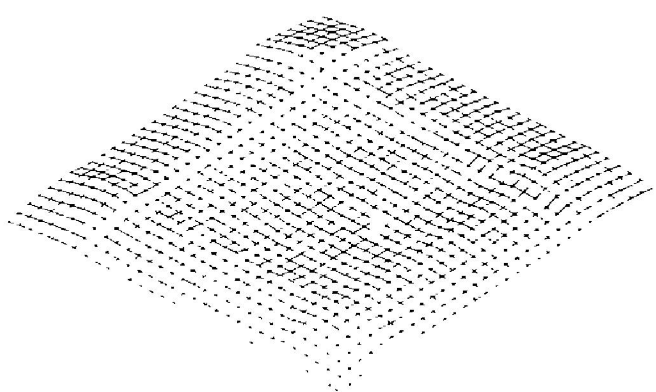
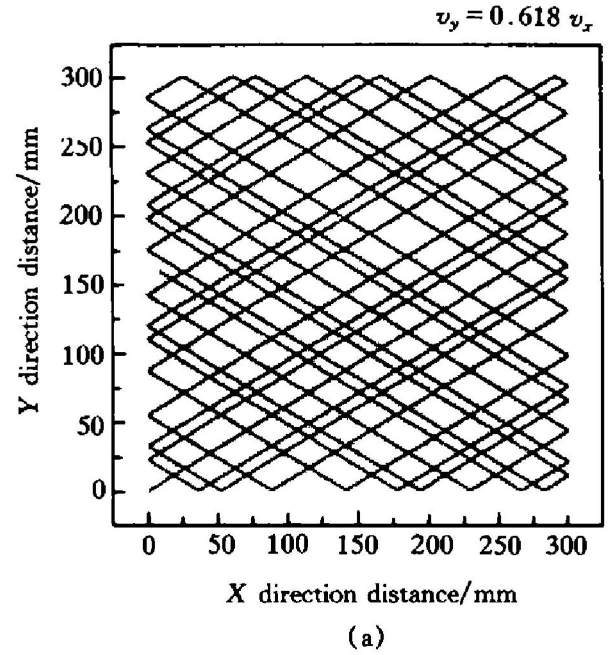


Fig.7 Plate shape with higher angular velocity at edge, viewpoint(1, 1, 1) ($t = 200$ s, $\omega_{outer} = 1.6\omega_{inter}$)

Ignoring the decrease of line velocity to zero near the edges, the footprint in case of constant line speed are given in Fig.8. Long motion cycle is beneficial to good shape. 3-D shape corresponding to Fig.8(b) is shown in Fig.9.

4.2 Influence of other factors

For a given motion mechanism, the start location φ can be varied to change the deposit shape, as shown in Fig. 10 with other process parameters identical to that of Fig. 5(b). It is found that the footprint is sensitive to the change of φ. For related situation, when the difference



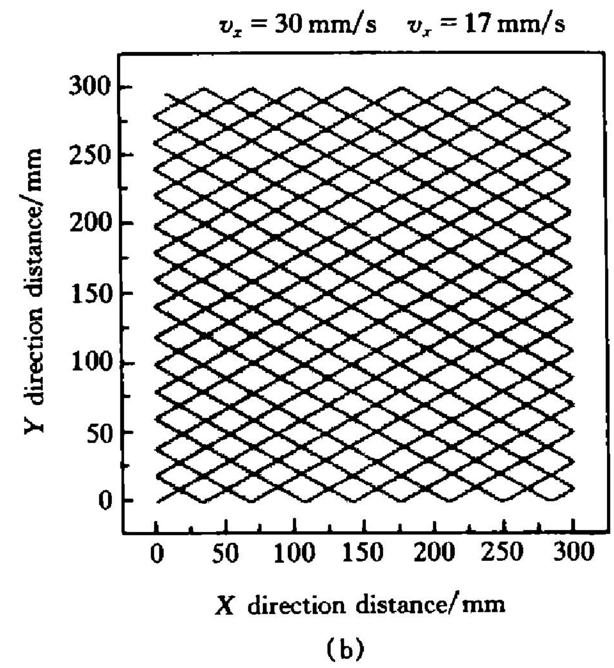


Fig.8 Footprint in case of uniform speed

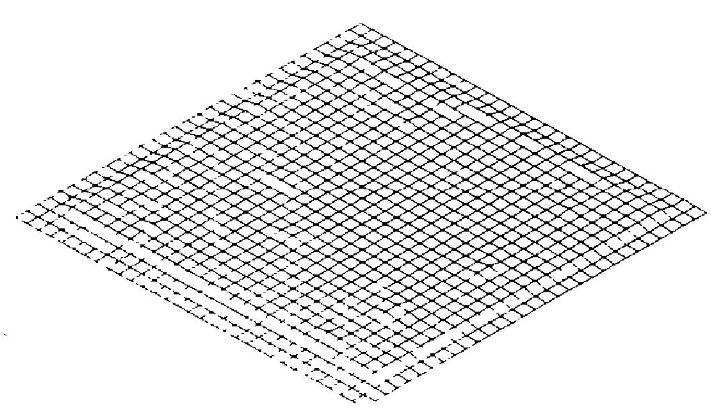


Fig.9 Plate shape corresponding to Fig.8(b)

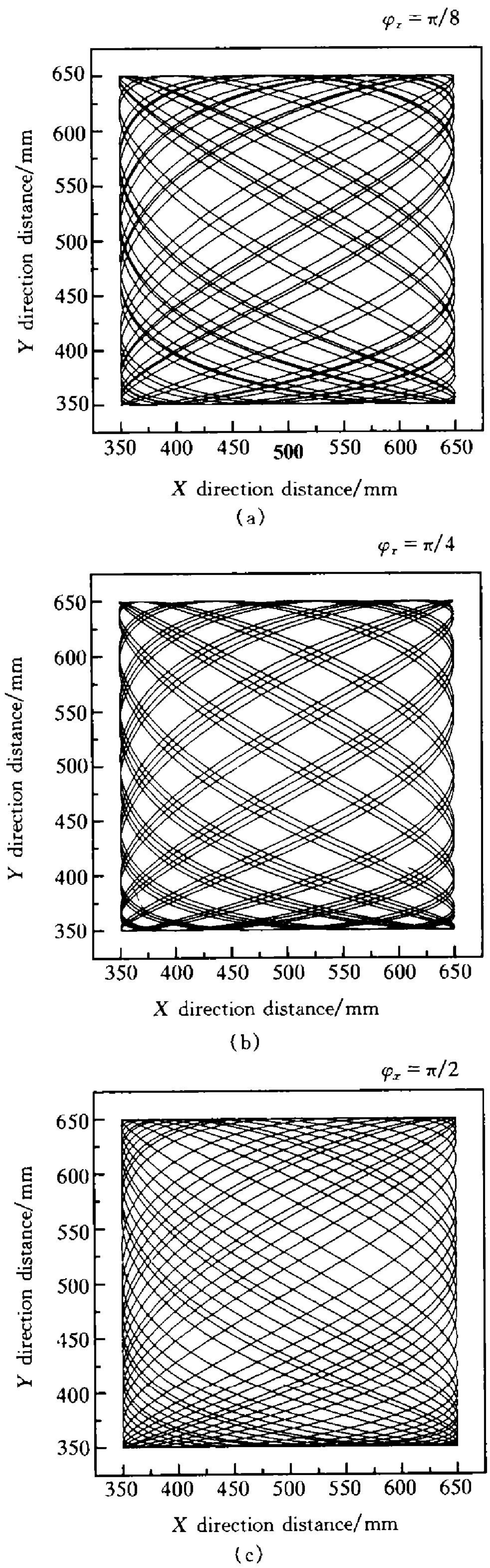


Fig.10 Influence of initial location on trace

between two initial angles is $\pi/2$, the footprint isideal. When the difference is small, the footprint repeats quickly. Obviously the length of brace has influence on motion, but it is ignored in consideration of actual experimental factility. The plate shape is optimized according to the above results.

5 CONCLUSIONS

(1) In case of constant annular velocity, the footprint will not repeat when the annular velocity ratio is irrational, which does good to thickness equality; To increase annular velocity near edges can decrease thickness difference throughout the substrate; Given constant line velocity and their proper ratio with long motion crycle, uniform plate can be produced.

(2) Initial location phase plays a great role on footprint. Both velocity ratio and initial location phase should be incorporated to improve plate shape.

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