Modelling deposit growth on tilted rotating cylindrical substrate in centrifugal spray deposition

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Centrifugal spray deposition (CSD) using a tilted rotating cylindrical substrate may offer considerable technical benefits over the conventional CSD process using a reciprocating substrate in producing ring preforms. A model has been developed to calculate the deposit growth rate as a function of the liquid volume flowrate, the substrate radius, the tilt angle, the position of the atomising disc, and the longitudinal position at the substrate. The deposit band length is determined by the substrate radius and tilt angle. The distribution of the deposit growth rate is symmetrical provided the atomising disc is positioned on the substrate axis or displaced along the direction perpendicular to the tilt plane. For a tilt angle of $<50{\cdot}46^\circ$, the deposit thickness uniformity can be improved by increasing the displacement. A tapered deposit with a controlled gradient can be obtained if the atomising disc is positioned offcentre on the tilt plane.

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LIST OF SYMBOLS

- dl an infinitesimal portion of the deposition line
- dL a longitudinal segment at the inner surface of the substrate
- dQ liquid metal volume flowrate corresponding to dl
- $d\theta$ spread angle of the spray corresponding to dl
- $d\theta_O$ spread angle of the spray corresponding to dl for the atomising disc positioned at point O
- $d\theta_X$ spread angle of the spray corresponding to dl for the atomising disc positioned at point X
- $d\theta_Y$ spread angle of the spray corresponding to dl for the atomising disc positioned at point Y
- g gravitational acceleration
- h deposit growth rate
- $\bar{h}$ mean deposit growth rate
- $h(0)$ growth rate at $\lambda = 0$
- $h(\lambda)$ deposit growth rate at λ
- $h(-\lambda)$ deposit growth rate at $-\lambda$
- l deposition line
- L longitudinal axis of the cylindrical substrate, longitudinal position
- L_D deposit band length
- O position of the disc centre, origin of the corresponding coordinate system
- Q total liquid metal volume flowrate
- r radial coordinate
- r_0 radius of the atomising disc
- R substrate radius
- t time
- u radial velocity of the spray droplets at the edge of the atomising disc
- v tangential velocity of the spray droplets at the edge of the atomising disc
- X position of the disc centre, origin of the corresponding coordinate system
- Y position of the disc centre, origin of the corresponding coordinate system
- x coordinate relative to the atomising disc
- y coordinate relative to the atomising disc
- z coordinate relative to the atomising disc, axis of the atomising disc, fall distance of the spray droplets

- α tilt angle of the substrate relative to the atomising disc
- Δ intermediate parameter, $\Delta = \lambda\, ctg\, \alpha + \phi_x$
- η deposit thickness variation factor
- λ relative longitudinal position, $\lambda = L/R$
- Λ intermediate parameter, $\Lambda = (1 - \lambda^2\, ctg^2\, \alpha)^{1/2}$
- ϕ_x dimensionless parameter describing the extent of the x direction displacement of the atomising disc relative to the substrate radius
- ϕ_y dimensionless parameter describing the extent of the y direction displacement of the atomising disc relative to the substrate radius
- θ angular coordinate
- ω rotation speed of the atomising disc

INTRODUCTION

The concept of centrifugal spray deposition (CSD) of metals was originally proposed by Singer and Kisakurek[1] and subsequently developed into a commercial process by Osborne Metals (subsequently Aurora Steels).[2] The process utilises a rapidly rotating disc or cup to break up a liquid metal stream and direct the atomised droplets onto the inner surface of a cylindrical substrate. With the substrate reciprocating vertically, the droplets deposit and solidify to form a near net shape ring preform. Like other spray forming technologies, CSD is a rapid solidification process and as a consequence offers important metallurgical benefits, such as low segregation, small grain sizes and uniform microstructures.[3–10] Direct conversion of liquid metals into near net shape preforms can also reduce the production cost. The CSD process is not as versatile as the Osprey type spray forming technology in producing different preform geometries and is currently limited to producing ring shaped components. However, CSD has an exclusive capability of operating under a reduced pressure or in a vacuum environment, eliminating the problems associated with gas entrapment and reducing the consumption of expensive process gases.[8,9] Because of these technical and economic advantages, the process is particularly suitable for the processing of some advanced materials of current interest to the aerospace industry. Considerable efforts are being made in the development of the CSD process as a means of producing low cost preforms for the manufacture of ring and casing components.[10]

The cylindrical substrates used in CSD are generally supported on hydraulic rams and reciprocate vertically to allow the controlled buildup of the deposits. The reciprocal motion of the substrate is usually relatively slow owing to the practical difficulties in maintaining a high speed motion. As a result, the as produced deposits often exhibit distinctly layered microstructures and discrete bands of porosity between the successive spray passes because of the incomplete consolidation of the atomised droplets following impact.[9] To reduce the porosity and to improve the microstructure of the deposit, a potentially superior alternative to the reciprocating substrate is a tilted rotating substrate. In the former case, the plane of the spray droplets is perpendicular to the longitudinal axis of the cylindrical substrate. The band length of the deposit, i.e. the longitudinal length of the resulting ring component, is controlled by the reciprocating distance. Instead of being vertically positioned, the substrate in the latter case is tilted so that an angle smaller than 90° is formed between the spray plane and the longitudinal axis of the substrate. The spray can therefore cover a certain length of the substrate dependent on the tilt angle. As the cylindrical substrate rotates during the deposition, a ring shaped deposit gradually builds up. The deposit is inherently uniform in wall thickness along the ring periphery. A moderate rotation speed of the substrate is probably sufficient to eliminate the layered structure and the associated porosity bands between the spray passes.

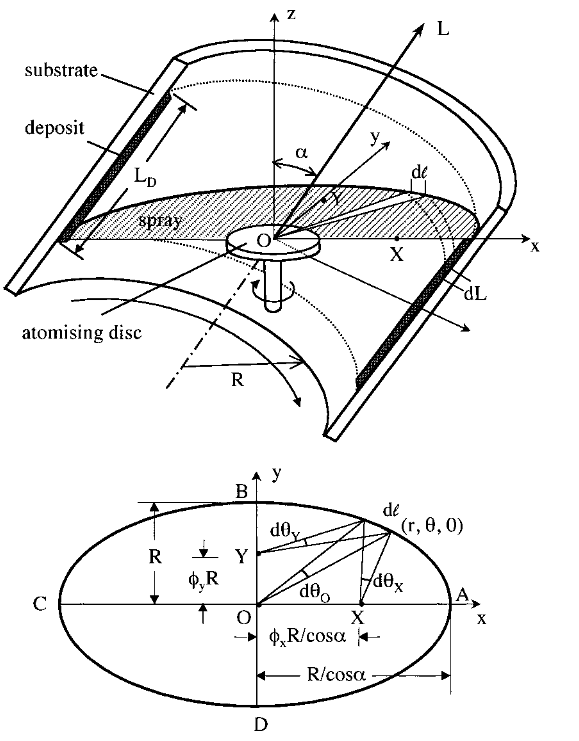
Further benefits may be derived from its capability of moderating the impact velocity of the spray droplets relative to the substrate. For instance, the substrate can be programmed to rotate in the same direction as that of the atomising disc, effectively reducing the impact intensity of the droplets. The material losses owing to both bounce off and splashing may be reduced and the deposition yields are consequently increased. From a practical point of view, the rotation motion of the substrate is simpler and cheaper to implement than the reciprocating motion. For some applications, these advantages, derived from using a rotating substrate, may outweigh the disadvantages of a limit to the practically achievable deposit band length and a difficulty in controling the profiles of the deposit thickness along the band length.

This paper develops a model to calculate the deposit growth rate as a function of the longitudinal position at the inner surface of a tilted rotating cylindrical substrate in centrifugal spray deposition, to evaluate the effects of the tilt angle of the substrate and the position of the atomising disc relative to the substrate on the distribution of the deposit growth rate over the deposit band length, and to discuss the implications of these effects for improving the uniformity in thickness of the resulting deposit.

MATHEMATICAL MODEL

Problem formulation

The CSD process using a rotating cylindrical substrate is shown schematically in Fig. 1. A liquid metal stream flows under gravity on to the centre of a rapidly rotating disc where it is accelerated both radially and tangentially towards the edge of the disc and broken up into a flat spray of droplets. The ejected droplets travel horizontally at high velocities and impinge on the inner surface of the cylindrical substrate, which is tilted on the x–z plane to an angle α between its longitudinal axis L and the disc axis z. During the deposition of the spray droplets, the substrate rotates around its axis L. As a result, a ring shaped deposit with an outer radius equal to the inner radius of the



1 Schematic diagram of deposit growth on tilted rotating cylindrical substrate in centrifugal spray deposition

substrate R and a band length $L_D = 2R \cdot tg\,\alpha$ builds up continuously.

Assuming that the effect of the gravitational force on the droplet trajectories is negligible, the droplets ejected from the atomising disc form a horizontal flat sheet of spray. The intercept between the spray sheet and the inner surface of the substrate forms an oval deposition line ABCDA, as shown in Fig. 1. Because the spray spreads out uniformly from the disc edge at all radial directions, the volume flowrate dQ of the incoming spray at an infinitesimal portion of the deposition line dl is proportional to the spread angle $d\theta$ of the corresponding part of the spray

$$dQ = \frac{|d\theta|}{2\pi} Q \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where Q is the total liquid metal volume flowrate. In using equation (1), the origin of the spread angle $d\theta$ must be the centre of the atomising disc. For example, the spread angle of the spray corresponding to dl is $d\theta_O$, $d\theta_X$, or $d\theta_Y$ for the atomising disc positioned at point O, X, or Y respectively, as shown in Fig. 1. Hence, the centre of the atomising disc is always taken as the origin of the coordinate system in this paper.

For a fixed substrate tilt angle α, a portion of the deposition line dl corresponds to a segment dL at the inner surface of the substrate along the longitudinal direction (Fig. 1). As the substrate rotates at a sufficiently high speed, the volume flowrate of the spray droplets received by the segment dL is therefore equivalent to that impinging on the deposition line dl. If all the spray droplets impinging on the substrate surface are assumed to consolidate to form the deposit without any bounce off and splashing, the volume increment of the deposit in unit time is equal to the volume flowrate of the incoming droplets. The deposit growth rate at dL, i.e. the increase in the deposit thickness in unit time, can thus be expressed by

$$h = \frac{dQ}{2\pi R|dL|} = \frac{Q}{4\pi^2 R}\left|\frac{d\theta}{dL}\right| \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The problem thus becomes determining the mathematical relationship between the angular coordinate θ and the longitudinal position L at the oval deposition line on the inner surface of the substrate. Because the origin of the coordinate system changes with the position of the atomising disc, the situations where the atomising disc is positioned at typical locations relative to the substrate are considered separately.

Atomising disc positioned on substrate axis

Considering the situation where the atomising disc is positioned at point O on the substrate axis (Fig. 1), the volume flowrate of the spray at the oval deposition line ABCDA is symmetrical about both the x and y axes. If the longitudinal position of the cross-sectional plane perpendicular to the substrate axis and passing through point O is taken as $L=0$, the deposit growth on the substrate is symmetrical about the plane $L=0$ and the deposit growth rate at L is equal to that at $-L$. Consequently, only the deposit growth resulting from the spray in the first quadrant (OABO) needs to be considered.

Taking point O as the origin of the coordinate system, the equation describing the oval deposition line in cylindrical polar coordinates is

$$r^2\cos^2\theta\cos^2\alpha + r^2\sin^2\theta = R^2 \qquad (3)$$

where r and θ are the radial and angular coordinates of a point on the deposition line. The longitudinal position of any point $(r, \theta, 0)$ on the deposition line on the substrate is given by

$$L = r\cos\theta\sin\alpha \qquad (4)$$

Combining equations (3) and (4), the variation of θ as a function of L on arc AB can be obtained as

$$\theta = \text{arc}\ tg\left[\frac{(R^2\sin^2\alpha - L^2\cos^2\alpha)^{1/2}}{L}\right] \qquad (5)$$

Differentiating equation (5) with respect to L gives

$$\frac{d\theta}{dL} = -\frac{R^2}{(R^2+L^2)(R^2\sin^2\alpha - L^2\cos^2\alpha)^{1/2}} \qquad (6)$$

The spray in the first quadrant (OABO) and that in the fourth quadrant (ODAO) contribute equally to the deposit growth at $L \geqslant 0$, as shown in Fig. 1. The overall deposit growth rate at any point ($L \geqslant 0$) is twice of that resulting from the spray in the first quadrant and can be obtained by substituting equation (6) into equation (2) and multiplied by 2

$$h = \frac{Q}{2\pi^2R^2}\frac{1}{\sin\alpha(1+\lambda^2)\Lambda} \qquad (7)$$

where $\lambda = L/R$ is a parameter describing the relative longitudinal position, and $\Lambda = (1-\lambda^2\,ctg^2\,\alpha)^{1/2}$. There exist solutions for equation (7) under the condition $-tg\,\alpha \leqslant \lambda \leqslant tg\,\alpha$. This is consistent with the fact that the deposit band length is $L_D = 2R\cdot tg\,\alpha$, as shown in Fig. 1.

Atomising disc displaced on *x* axis

Considering the situation where the atomising disc is positioned at point X on the x axis with a displacement of $\phi_x R/\cos\alpha$ from the longitudinal axis of the cylindrical substrate (Fig. 1), where ϕ_x $(0 \leqslant \phi_x \leqslant 1)$ is a dimensionless parameter describing the extent of the x direction displacement relative to the substrate radius, the volume flowrate of the spray at the oval deposition line ABCDA is symmetrical about the x axis but not about the y axis. As a consequence, the deposit growth resulting from the spray in both the first quadrant (XABX) and the second quadrant (XBCX) needs to be considered.

Taking point X as the origin of the coordinate system, the equation describing the oval deposition line in cylindrical polar coordinates is

$$(r\cos\theta\cos\alpha + \phi_x R)^2 + r^2\sin^2\theta = R^2 \qquad (8)$$

If the longitudinal position of the cross-sectional plane perpendicular to the substrate axis and passing through point X is taken as $L=0$, the relationship between the longitudinal position L on the substrate and the coordinates r and θ $(z=0)$ for any point on the deposition line ABCDA still follows equation (4). Combining equations (8) and (4), the variation of θ as a function of L on arc ABC can be obtained as

$$\theta = \text{arc}\ tg\left\{\frac{\sin\alpha}{L}[R^2-(L\,ctg\,\alpha+\phi_x R)^2]^{1/2}\right\} \qquad (9)$$

The spray in the first (XABX) and second (XBCX) quadrants and that in the third (XCDX) and fourth (XDAX) quadrants contribute equally to the deposit growth, because the spray is symmetrical about the x axis. The overall deposit growth rate at any point is therefore twice of that resulting from the spray in the first and second quadrants. Differentiating equation (9), substituting the derivative into equation (2), and then multiplied by 2 gives

$$h = \frac{Q}{2\pi^2R^2}\frac{\sin\alpha(1+\phi_t\Delta)}{(1-\Delta^2)^{1/2}[\lambda^2+\sin^2\alpha(1-\Delta^2)]} \qquad (10)$$

where $\Delta = \lambda\,ctg\,\alpha + \phi_x$. There exist solutions for equation (10) under the condition $-(1+\phi_x)tg\alpha \leqslant \lambda \leqslant (1-\phi_x)\,\text{tg}\,\alpha$.

Atomising disc displaced on *y* axis

When the atomising disc is positioned at point Y on the y axis with a displacement of $\phi_y R$ from the longitudinal axis of the cylindrical substrate (Fig. 1), where ϕ_y $(0 \leqslant \phi_y \leqslant 1)$ is a dimensionless parameter describing the extent of the y direction displacement relative to the substrate radius, the volume flowrate of the spray at the oval deposition line ABCDA is symmetrical about the y axis but not about the x axis. If the longitudinal position of the cross-sectional plane perpendicular to the substrate axis and passing through point Y (or point O) is taken as $L=0$, the deposit growth at the substrate is symmetrical about the plane $L=0$, i.e. the deposit growth rate at L is equal to that at $-L$. For any point where $L \geqslant 0$, however, the contributions to the deposit growth from the spray in the first quadrant (YABY) and that in the fourth quadrant (YDAY) are different and need to be considered separately.

Taking point Y as the origin of the coordinate system, the equation describing the oval deposition line in cylindrical polar coordiates is

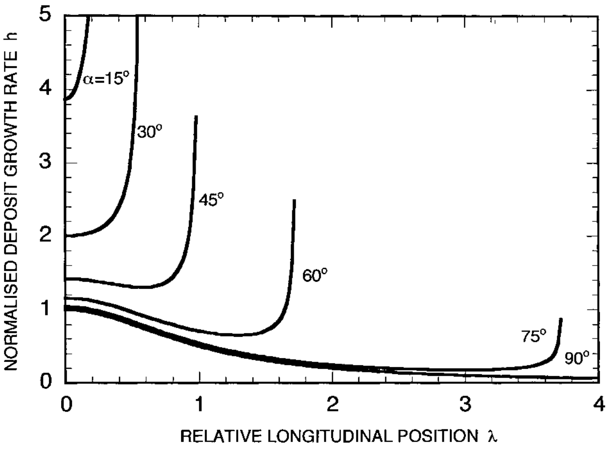
$$r^2\cos^2\theta\cos^2\alpha + (r\sin\theta + \phi_y R)^2 = R^2 \qquad (11)$$

Because the relationship between the longitudinal position L on the substrate and the coordinates r and θ $(z=0)$ for any point on the deposition line follows equation (4), combining equations (11) and (4) gives the variation of θ as a function of L on arc DAB as

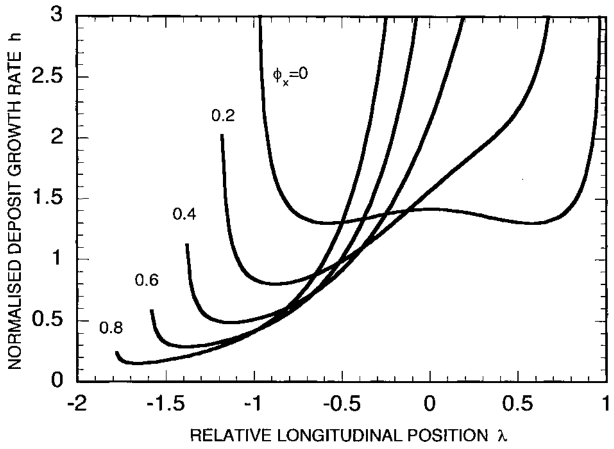
$$\theta = \text{arc}\ tg\left[\frac{\sin\alpha}{\lambda}(\pm\Lambda - \phi_y)\right] \qquad (12)$$

where the positive sign before Λ corresponds to the first quadrant (YABY) and the negative to the fourth quadrant (YABY). By differentiating equation (12) and substituting the derivatives into equation (2) separately for both the first and fourth quadrants, the overall deposit growth rate can be obtained as

$$h = \frac{Q}{4\pi^2R}\left(\left|\frac{d\theta}{dL}\right|_{\text{first}} + \left|\frac{d\theta}{dL}\right|_{\text{fourth}}\right) = \frac{Q}{2\pi^2R^2}\frac{1+\lambda^2+\phi_y^2-2\lambda^2\Lambda^2}{\sin\alpha\Lambda[(1+\lambda^2+\phi_y^2)^2-4\lambda^2\Lambda^2]} \qquad (13)$$



2 Relationship between normalised deposit growth rate h and relative longitudinal position λ for different substrate tilt angles α



3 Relationship between normalised deposit growth rate h and relative longitudinal position λ at tilt angle $\alpha = 45°$ for different x direction displacements ϕ_x

DISCUSSION

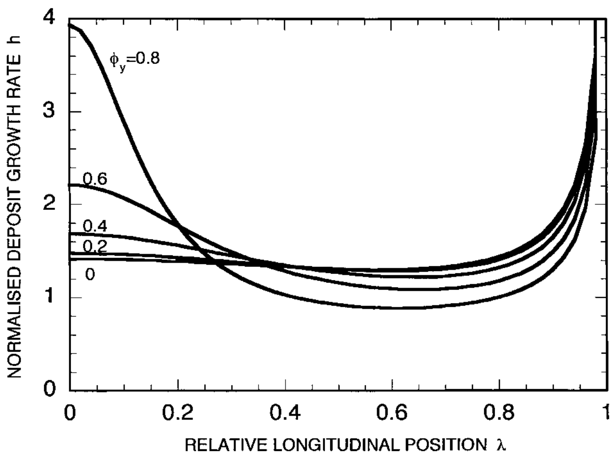
Deposit growth rate

The deposit growth rate can be calculated directly by equations (7), (10), or (13) if the bounce off and splashing of the impinging spray droplets are negligible and the deposition efficiency is 100%. In practice, there are always some material losses owing to the bounce off and splashing. The deposit growth rate should be calculated by including an efficiency coefficient in these equations, which can be determined by experimental means. For convenience, the deposition efficiency is taken as 100% in the following discussions.

The deposit growth rate as a function of the substrate longitudinal position is related to the total liquid metal volume flowrate, the substrate radius, the substrate tilt angle, and the disc position relative to the substrate as seen from equations (7), (10), and (13). Whereas the deposit growth rate at any point is proportional to the liquid volume flowrate Q and inversely proportional to the square of the substrate radius R, its distribution along the relative substrate longitudinal position λ is determined by the substrate tilt angle α and the x direction displacement ϕ_x or the y direction displacement ϕ_y of the disc centre from the substrate axis. To illustrate the variation of the deposit growth rate along the relative substrate longitudinal position under different conditions, the deposit growth rate is normalised by assuming

$$\frac{Q}{2\pi^2 R^2} = 1.$$

Figure 2 shows the relationship between the normalised deposit growth rate h and the relative substrate longitudinal position λ with different substrate tilt angles α when the atomising disc is positioned on the substrate longitudinal axis. Because the deposit growth rate is symmetrical about the plane $\lambda = 0$ [$h(\lambda) = h(-\lambda)$], only the variations at $\lambda \geqslant 0$ are shown. Given a fixed substrate radius, increasing the tilt angle increases the deposit band length L_D but decreases the deposit growth rate at $\lambda = 0$. Varying the tilt angle also changes the pattern of the distribution. If the tilt angle $\alpha \leqslant 35{\cdot}23°$, the distribution has one minimum at $\lambda = 0$. The deposit growth rate increases with increasing λ ($\lambda > 0$) or decreasing λ ($\lambda < 0$). If the tilt angle $\alpha > 35{\cdot}23°$, then the distribution has one maximum at $\lambda = 0$ and two minima at a certain λ and $-\lambda$ determined by the tilt angle. With increasing λ ($\lambda > 0$) or decreasing λ ($\lambda < 0$), the deposit growth rate initially decreases but then increases. When λ approaches $\pm tg\, \alpha$, the deposit growth rate increases rapidly towards infinity.

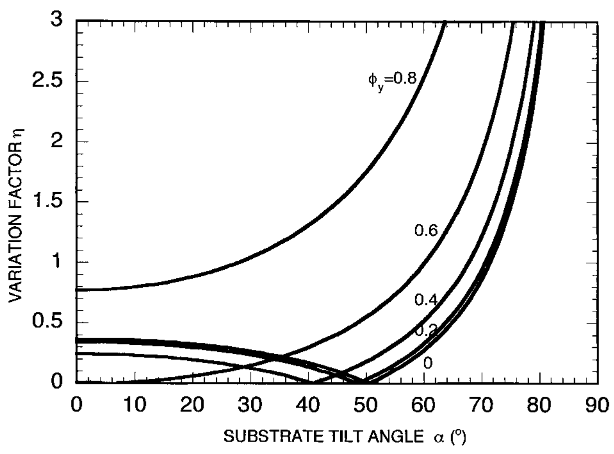


4 Relationship between normalised deposit growth rate h and relative longitudinal position λ at tilt angle $\alpha = 45°$ for different y direction displacements ϕ_y

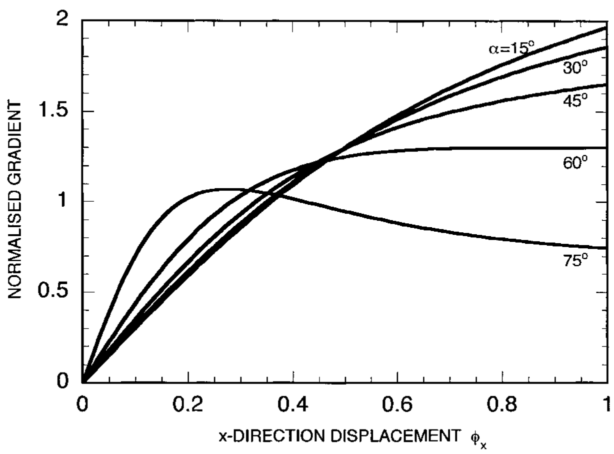
Figure 3 shows the relationship between the normalised deposit growth rate h and the relative substrate longitudinal position λ with a substrate tilt angle $\alpha = 45°$ when the atomising disc is positioned at a series of x direction displacements from the substrate axis. Without a displacement, the deposit growth is symmetrical about the plane $\lambda = 0$ and relatively uniform across the deposit band length. With a displacement, the deposit growth rate curve is inclined along the substrate longitudinal direction. As a result, the slope of the resulting deposit will increase with increasing the x direction displacement of the atomising disc.

Figure 4 shows the relationship between the normalised deposit growth rate h and the relative substrate longitudinal position λ with a substrate tilt angle of $\alpha = 45°$ when the atomising disc is positioned at a series of y direction displacements from the substrate axis. The deposit growth is still symmetrical about the plane $\lambda = 0$ but its distribution changes with varying the y direction displacement. At a tilt angle of 45°, the difference in the deposit growth rates between the maximum at $\lambda = 0$ and the minima increases with increasing the displacement.

During centrifugal spray deposition, the effective substrate radius, i.e. the substrate radius minus the instant deposit thickness, decreases with time. The deposit growth rate varies continuously throughout the deposition period because it is actually a function of the effective substrate



5 Relationship between deposit thickness variation factor η and substrate tilt angle α for different y direction displacements ϕ_y



6 Relationship between normalised gradient of deposit growth rate curve and x direction displacement ϕ_x for different substrate tilt angles α

radius. However, the deposit thickness is generally much smaller than the substrate radius. The effective substrate radius can be treated as constant and equal to the substrate radius during deposition, except near the deposit band boundaries. The deposit growth rate in the central region of the deposit band is approximately constant during deposition. The deposit thickness can therefore be calculated readily from equations (7), (10), and (13). In the regions close to the deposit band boundaries ($\lambda \to \pm tg\,\alpha$), the deposit growth rate is extremely high as shown in Figs. 2–4. As a result, the effective substrate radius and thus the deposit band length would decrease rapidly. Therefore, equations (7), (10), and (13) cannot be used in the calculations of the deposit thickness near the band boundaries. In fact, the deposit growth is restricted by the spray sheet and the maximum deposit thickness achievable at any longitudinal position L is $(L_D - L) \cdot ctg\,\alpha$, as illustrated in Fig. 1. As a consequence, the deposit thickness near the boundaries can be approximated by $(L_D - L) \cdot ctg\,\alpha$. The deposit thickness is zero at the boundaries ($L = L_D$), but increases nearly linearly with decreasing L.

Deposit thickness uniformity

In the manufacture of near net shape rings by CSD, the ability to control the ring radius, length, and thickness is essential. In the CSD process using a tilted cylindrical substrate, it is easy to control the outer radius of the ring deposit, as it is exactly the same as the inner radius of the substrate. The length of the ring, i.e. the deposit band length, follows $L_D = 2R \cdot tg\,\alpha$. In theory, a ring deposit of any band length can be produced by varying the substrate tilt angle for any given substrate radius. A substrate tilt angle greater than 45°, however, may not be practical, especially for small rings.

The extent of the substrate tilt is restricted by the physical size of the mechanism driving the atomising disc. If the tilt angle is too great, the substrate can also obstruct the passage of the liquid metal stream to the atomising disc. Therefore, the maximum deposit band length achievable may not be greater than $2R$. Whereas the mean deposit thickness can be controlled by the volume flowrate of the liquid metal stream and the deposition time, the degree of uniformity in the deposit thickness over the whole band length is a major concern. A deposit with little variation in thickness is often desirable in order to minimise the subsequent machining and therefore material losses.

The deposit is symmetrical about the plane $\lambda = 0$ when the atomising disc is either positioned on the substrate axis or displaced on the y axis. Figures 2 and 4 show that the variation in deposit thickness over the band length depends markedly on the substrate tilt angle and the y direction disc displacement. The deposit growth rate has a minimum or a maximum at $\lambda = 0$, dependent on the substrate tilt angle. The critical tilt angle for $\phi_y = 0$ is 35·23°. The difference between the deposit growth rate at $\lambda = 0$, $h(0)$, and the mean deposit growth rate over the deposit band length, $\bar{h}$, i.e. $|h(0) - \bar{h}|$, is a good indicator of the degree of variation in the deposit thickness. The degree of uniformity in the deposit thickness can therefore be assessed quantitatively by a variation factor η, which is the ratio of the difference between $h(0)$ and $\bar{h}$ to $\bar{h}$, i.e. $|h(0) - \bar{h}|/\bar{h}$. The smaller the variation factor η, the higher the degree of uniformity. The deposit growth rate at $\lambda = 0$, $h(0)$, can be readily calculated from equations (7) or (13).

The mean deposit growth rate $\bar{h}$ is simply the liquid volume flowrate Q divided first by the substrate periphery $2\pi R$ and then by the deposit band length L_D. The expression for the variation factor is therefore

$$\eta = \left| 1 - \frac{h(0)}{\bar{h}} \right| = \left| 1 - \frac{2}{\pi(1 - \phi_y^2)\cos\alpha} \right| \quad . \quad . \quad . \quad (14)$$

Figure 5 shows the relationship between the variation factor η and the substrate tilt angle α for a series of y direction disc displacements ϕ_y. When the atomising disc is positioned on the substrate axis ($\phi_y = 0$), the minimum variation factor ($\eta = 0$) is at a tilt angle $\alpha = 50·46°$. To achieve a certain deposit band length, the substrate tilt angle is usually fixed. If the tilt angle is $\alpha < 50·46°$, increasing disc displacement ϕ_y in a certain range can reduce the variation factor and therefore improving the deposit uniformity. If the tilt angle is $\alpha > 50·46°$, however, increasing ϕ_y always increases the variation factor and accordingly reduces the deposit uniformity. A tilt angle greater than 60° should be avoided because the high variation factor may result in an unacceptable deposit thickness profile.

Deposit gradient

For some applications, it is desirable for the CSD ring preforms to have a tapered longitudinal cross-section. This can be achieved by positioning the atomising disc on the x axis with a displacement from the substrate axis. Figure 3 shows that the gradient of the deposit growth rate curve with respect to the substrate longitudinal direction increases with increasing the x direction displacement. The slope of the resulting deposit thickness is proportional to the gradient of the deposit growth rate curve as well as to the deposition time. The gradient of the deposit growth rate curve can be characterised by the derivative of the normalised deposit growth rate with respect to the relative longitudinal position at the midpoint of the deposit band ($\lambda = -\phi_x tg\,\alpha$) and can be obtained by differentiating equation (10) with respect to λ

$$\left.\frac{dh}{d\lambda}\right|_{\lambda=-\phi_x tg\alpha} = \frac{Q}{2\pi^2 R^2}\phi_x \cos\alpha\left(1+\frac{2}{\phi_x^2+\cos^2\alpha}\right) \quad (15)$$

Figure 6 shows the relationship between the normalised gradient of the deposit growth rate curve and the relative x direction displacement ϕ_x for a series of substrate tilt angles α. The gradient is mainly controlled by the x direction displacement ϕ_x, but is also affected by the tilt angle α. When the tilt angle $\alpha < 60°$, the gradient of the deposit growth rate curve increases with increasing ϕ_x. When $\alpha > 60°$, the gradient first increases and then decreases with increasing ϕ_x.

Effect of gravitation on spray

The present model is developed under the assumption that the effect of the gravitational force on the droplet trajectories is negligible and as a result the droplet spray is a flat sheet. The model is not applicable if the spray droplets fall considerable vertical distances before they impact at the substrate surface. In fact, the free fall distance of the spray at any radial distance can be calculated if the initial velocities of the droplets are known. Considering a droplet ejected from the atomising disc edge at a radial velocity u and a tangential velocity v, the radial distance of the droplet from the disc centre at any time t after being ejected from the disc is $r = [(ut + r_0)^2 + (vt)^2]^{1/2}$, where r_0 is the radius of the atomising disc. The fall distance of the droplet at time t is $z = \frac{1}{2}gt^2$, where $g = 9{\cdot}8$ m s^{-2} is the gravitational acceleration. Given the liquid volume flowrate, atomising disc radius, and rotation speed, the liquid velocities at the disc edge u and v can be calculated by the models developed by Zhao and co-workers.[11–13] The fall distance of the spray z as a function of the radial distance r can then be calculated. Under typical CSD conditions, however, the tangential velocity of the liquid v is only slightly smaller than that of the disc and can be approximately treated as $v \approx \omega r_0$, where ω is the disc rotation speed. The radial velocity of the liquid u is usually small compared with v. As an estimation, the free fall distance of the spray as a function of the radial distance r ($r > r_0$) is approximately

$$z \approx \frac{gr^2}{2\omega^2 r_0^2} \quad (16)$$

Considering a typical CSD condition: $r_0 = 0{\cdot}05$ m and $\omega = 314$ radian s^{-1} (3000 rev min^{-1}, which is the rotation speed of an industrial motor for a 50 Hz power supply), the free fall distance at a radial position $r = 0{\cdot}5$ m is $z \approx 0{\cdot}01$ m. The disc rotation speed used in CSD is often higher than 3000 rev min^{-1}, in order to obtain a fine microstructure in the deposit. The free fall distance is even smaller. Therefore, the present model is sufficient for predicting the deposit growth rate for most practical conditions.

CONCLUSIONS

A model has been developed to calculate the deposit growth rate as a function of the longitudinal position on a tilted rotating cylindrical substrate in CSD using a centred or offcentre atomising disc. The deposit growth rate at any position is proportional to the total volume flowrate of the spray and inversely proportional to the square of the substrate radius. The band length of the ring deposit is determined by the substrate radius and the tilt angle. The distribution of the deposit growth rate over the deposit band length depends on the substrate tilt angle and the x or y direction displacement of the atomising disc. The degree of uniformity in the deposit thickness depends not only on the substrate tilt angle but also on the position of the atomising disc relative to the substrate axis. For a tilt angle smaller than 50·46°, the deposit thickness uniformity can be improved by positioning the atomising disc offcentre with a y direction displacement. Too high a tilt angle results in very poor deposit thickness uniformity. An x direction displacement of the atomising disc leads to a tapered deposit, with the gradient mainly controlled by the displacement.

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