A SIMULATION TECHNIQUE FOR PREDICTING THICKNESS OF THERMAL SPRAYED COATINGS

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ABSTRACT

The complexity of many of the components being coated today using the thermal spray process makes the trial and error approach traditionally followed in depositing a uniform coating inadequate, thereby necessitating a more analytical approach to developing robotic trajectories. A two dimensional finite difference simulation model has been developed to predict the thickness of coatings deposited using the thermal spray process. The model couples robotic and component trajectories and thermal spraying parameters to predict coating thickness. Simulations and experimental verification were performed on a rotating disk to evaluate the predictive capabilities of the approach.

INTRODUCTION

Development of robotic trajectories to deposit uniform thickness coatings using the thermal spray process has traditionally followed a trial and error approach. The complexity of many components being coated today makes such an approach costly and time consuming. Rapid development of appropriate robotic trajectories for complex shapes or spray-forming to near net shape requires a more informed, systematic analysis. The use of computer simulation can be an effective tool in achieving increased efficiencies, process optimization, reduction of component cost and production of near net shape components. Computer simulation can also provide a greater understanding of how changes and errors in robot and component trajectory affect coating thickness without the costs incurred in spraying actual components. When combined with the experience and knowledge of the design engineer and spray technician, computer simulation can be an effective means of producing consistent, uniform coatings on complex components.

Several models, following several different approaches, have been presented in the literature for predicting coating thickness. Cirolini[1] developed a morphological analysis of splat build-up during the spraying process to model coating formation. The coating thickness, roughness, porosity and temperature are predicted from the analysis. The model, while useful in predicting coating properties, is limited as a means of developing robot trajectories.

A second approach is to divide the surface to be coated into a grid of small square regions, or voxels.[2,3] The thickness of the coating over a voxel is determined by accumulating powder particles in the voxel. The number of particles in the voxel, and hence the coating thickness, is determined by the robot trajectory and a Monte Carlo description of the particle distribution. The resolution of the technique is determined by the size of the voxel; increased resolution requires a greater number of smaller voxels with a corresponding increase in computation time.

An empirical approach has been used by Figueroa[4] and Fasching.[5] A coating, deposited along a straight line using a constant velocity robot trajectory, is modeled using a Gaussian equation. The coating lines are then summed, according to the robot trajectories, to build a layered structure. The technique is useful when

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simple straight-line, constant velocity trajectories are required, but is less useful when complex robot and component motions are employed.

The finite difference approach followed here expands the empirical description of the deposit rate to 2-dimensions, providing a more complete description of the deposit rate and enabling simulation of more complex and useful robot motions. The coating thickness is determined by numerical integration involving the robot and component trajectories, time and a deposit rate function. This approach allows the coating thickness to be accurately determined at any given point on the component.

MODEL

The coating thickness at any point on a component is determined by the simple equation:

$$dT = R \bullet dt \tag{1}$$

where dT(cm) is the deposit thickness, R(cm/s) is the deposit rate of the thermal-sprayed powder and dt(s) is the time. The deposit rate of the powder, R(cm/sec), can be approximated using an idealized Gaussian function:

$$R = A \bullet \exp\left(-\frac{\rho(x,y)^2}{\sigma^2}\right) \tag{2}$$

where A(cm/sec) and σ(cm) are the amplitude and standard deviation of the Gauss distribution function, respectively; and ρ(cm) is the distance in the plane of the substrate from the point at which the gun is aimed to the point at which the thickness is being calculated, figure 1. The deposit rate parameters, A and σ, are functions of standoff distance. The standoff distance is defined as the normal distance between the gun and component. For this 2-dimensional model the standoff distance is fixed and these values are constant.

The coating thickness at a point is determined from the integration of equation (1). Consider the simple case of a point on a stationary component and a gun traveling along the x-axis at constant velocity across the component, figure 1. The coating thickness at a point, y, is given by the integral of the rate along the gun path with respect to time:

$$T = 2 \bullet \int_0^{\infty} A \exp\left(-\frac{\rho(y,t)^2}{\sigma^2}\right) dt \tag{3a}$$

The gun-to-point distance, ρ can be written in terms of the gun velocity, V_x, and the perpendicular distance from the point to the gun path, y:

$$\rho^2 = V_x^2 t^2 + y^2 \tag{3b}$$

Substituting equation (3b) into equation (3a) and integrating with respect to t yields:

$$T = \frac{A\sigma\sqrt{\pi}}{V_x} \exp\left(-\frac{y^2}{\sigma^2}\right) \tag{4}$$

Equation (4) describes the thickness of the deposit at a point, y, for a constant velocity traverse along the x-axis. A detailed derivation of these equations is provided in the appendix.

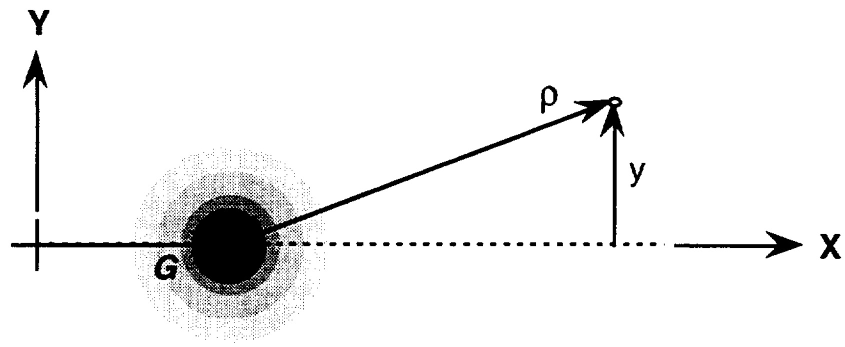

Figure 1.—The coating thickness at a point y is determined by integrating the rate equation over time. The gun moves along the x-axis; its position is given by G. The gun to point distance, ρ, needed to perform the integration can be described as a simple function of the gun and point positions as a function of time.

The Gaussian rate equation can be integrated in closed form for a very limited number of cases. Considering the innumerable gun and component trajectories the problem is well suited to a finite difference solution. A generalized finite difference approach can be developed using simple vector analysis and finite difference techniques. The thickness at any point on the component is determined by stepping through time and accumulating material at the point during the spraying cycle.

The coating thickness at a point on the component is determined by continually assessing equations (1) and (2) over the duration of the spraying process. The only information required to solve the equations are the Gauss rate parameters, A and σ, and the gun to point distance, ρ. The rate equation amplitude, A, and standard deviation, σ, are determined experimentally. The gun to point distance, ρ, is determined by tracking the trajectories of the gun and the point on the component using simple vector addition.

The non-trivial case of spraying a rotating disk was selected to evaluate the model. The position of the disk is specified relative to the axis of rotation by the vector ***C(x,y,t)***, figure 2. The position of the gun is specified by the vector **G(*x,y,t*)**. The thickness is calculated at a point ***P(x,y,t)***, specified relative to the axis of rotation of the disk. The distance between the gun and the point is determined by vector addition:

$$\boldsymbol{\rho} = \boldsymbol{P} + \boldsymbol{C} - \boldsymbol{G} \tag{5}$$

For this study the robot motions were simulated by establishing a time, distance and velocity data file which describes the location of the robot guided spray gun during the cycle. The disk was fixed in the XY plane and rotated about the Z-axis. The thickness was calculated at a number of points on the rotating disk. The initial rotation angle of the disk was randomized at the beginning of each cycle to simulate the random starting position associated with the normal spraying operation.

Equations (1) and (2) are easily solved using the finite difference method. The simple approach is to step through the process in fixed increments of time; however, this is an inefficient and often inaccurate means of solving the finite difference equations. The calculation accuracy and execution time can be improved by employing an adaptive step method.[6] In general, any point on the component will spend a large fraction of the spraying cycle far from the gun where the accumulation rate is insignificant. The calculation time can be reduced by increasing the time step when the deposit rate is insignificant, and decreasing the time step as the point approaches the gun and the deposit rate is increasing. To account for different gun and component velocities, the time step is controlled by limiting the distance traced by the gun to point distance vector, ρ. In effect, the finite difference method proceeds by stepping through space rather than time.

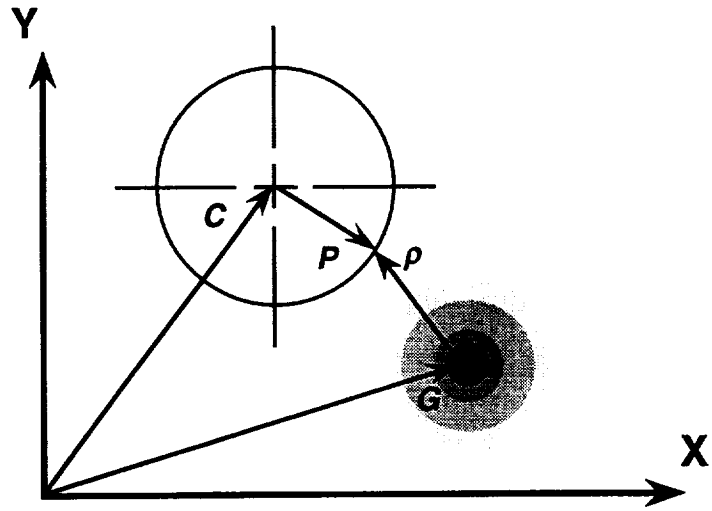

Figure 2.—The two dimensional vector description of the system. The center of the component, which rotates about the z-axis, is described by ***C***. The gun is directed along the z-axis, the gun position is described by ***G***. The coating thickness is calculated at the point ***P***. The resultant gun to point distance vector is given by ***ρ***

An empirical equation, paralleling the Gaussian deposit rate function, was developed to establish the step size, dL:

$$dL = A\sigma\left[1 - \exp\left(-\left(\frac{\rho^2}{v^2}\right)\Big/\sigma^2\right)\right] \tag{6}$$

where υ is a scaling parameter, typically (0.5-4.0), which is selected to optimize the solution convergence. As ρ approaches 0, that is, as the gun to point distance approaches 0, the step distance goes to 0 and the calculation stalls. To avoid this, a minimum value is also placed on the step size. This is an empirical equation designed to contol the step size and optimize calculation time and accuracy, alternate equations may function with equal effectiveness.

EXPERIMENTAL

Stainless steel disks were air plasma sprayed with an 8 percent yttria stabilized zirconia powder. The disks were 0.635 cm (0.25 in.) thick, and 14 cm (5.5 in.) in diameter. They were rotated at 360 RPM at a 10 cm standoff. An EPI O3-CP plasma generator with a O3CA-27 cathode and a O3CA-167 anode was used. The arc gas was Ar-40%He flowing at 24 SLPM with an arc power of 40 kW at 1000 A. The powder was delivered to an external port through a closed loop hopper at a powder feed rate of 20 gm/min and a feed gas flow rate of 2L/min. Gun motion was controlled with a Mitsubishi AR1000 robot.

The deposit rate function parameters, A and σ, were determined experimentally using equation (4) and a constant velocity robot traverse. Two plates were sprayed, one using a horizontal robot traverse, the second using a vertical robot traverse. The plates were sectioned and thickness profiles were determined from digitized measurements of micrographs. The parameters, A and σ, were determined by fitting the profiles to equation (4), as illustrated in figure 3. While the profiles for the vertical and horizontal robot traverse had the same general Gaussian shape, the vertical traverse profiles yielded somewhat larger values of σ and smaller values of A than those of the horizontal traverse profile. The values used in the model, A = 0.0123 cm/sec and σ = 0.3909 cm, were determined from an average of the vertical and horizontal profiles.

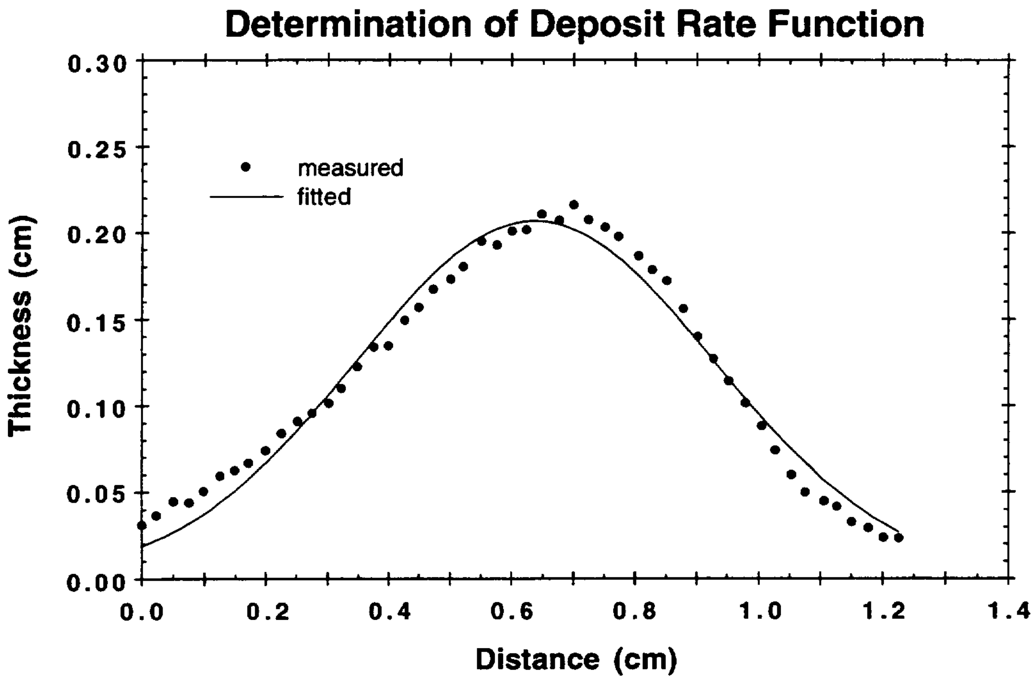

Figure 3.—The cross-sectional profile and fitted equation of the deposit from a horizontal trace used to determine the Gauss deposit rate function parameters. The data is fitted to the equation $T = n \bullet (A\sigma\sqrt{\pi}/V) \bullet \exp(-(x - x_o)^2/\sigma^2)$, n is the number of passes; $n = 120$, $V = 5$ cm/s; $A = 1.7235 \bullet 10^{-3}$ cm/sec, $x_o = 0.6369$ cm, $\sigma = 0.4127$ cm (see appendix for derivation).

The calculations were performed on a Sun™ workstation using the Sparc™ FORTRAN 77 compiler. All calculations were run using a minimum step size of 0.05σ and a maximum step size of 0.5σ. The adaptive step scaling factor, υ, as required by equation (6), was set to 4 for all calculations.

The coating thickness was measured using an automated XYZ positioner and a digital dial gauge with a resolution of ±12.7 μm (±0.5 mils) and a reproducibility of ±25.4 μm (±1 mil)

RESULTS AND DISCUSSION

Several tests were run using different robot trajectories to compare predicted thickness profiles to those of actual sprayed disks. The robot trajectories were designed to develop a basic understanding of how changes in robot trajectory affect coating thickness and what trajectories are required to establish a uniform coating over the entire disk.

The first test was a simple constant velocity (5 cm/sec) robot traverse across the center of the rotating disk, figure 4. The resulting measured and predicted thickness profiles are presented in figure 5.

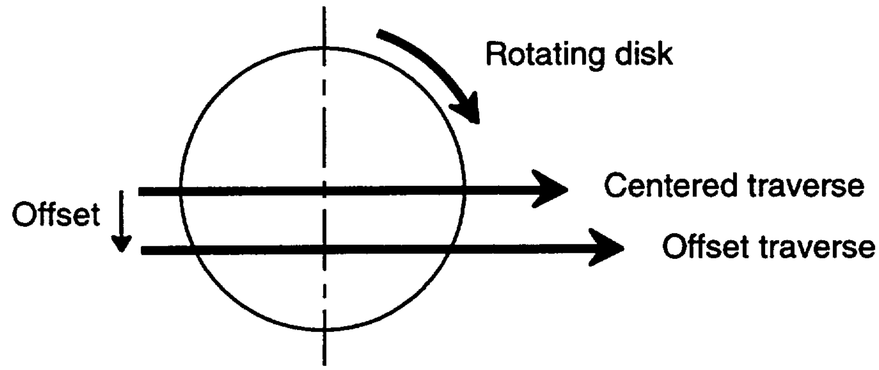

Figure 4.—Schematic illustrating the robot trajectory across the center of the disk and offset from the center of the disk.

The extreme in coating thickness at the center of the disk is a predictable result of the constant traverse velocity. As the gun moves toward the center of the disk the effective area being coated decreases; this results in an increase in coating thickness.

The second test was designed to predict changes in coating thickness when the gun path is offset from the center of the disk, rather than traveling directly across the center, figure 4. The results for a constant velocity (5 cm/sec) robot traverse with the gun offset 1 cm from the center of the disk are presented in figure 6. The previous test, with the gun traveling across the center of the disk, resulted in a buildup of coating at the center. Offsetting the gun causes a buildup of coating about a circle with a radius approximately equal to the offset of 1 cm plus 0.5σ. In the cross–section profile, the buildup appears as two separate peaks. As the offset is increased, the separation between the two peaks increases with little or no material deposited between the peaks.

The coated surface has a visible spiral pattern appearance which is derived from small variations in coating thickness. These small variations might be misconstrued as uncertainty in the thickness measurements; however, they are predicted by the simulation. A similar spiral pattern was also observed and predicted on the preceding test, figure 5; however, the small variations in thickness are more difficult to see relative to the greater total thickness. These tests indicate that the model approach is capable of predicting coating thickness. The use of the idealized Gaussian deposit rate function provides an accurate model for predicting coating thickness, despite the true, asymmetric shape of the function. Refinement of the deposit rate function to reflect the actual asymmetric form could further improve the predictive capability of the model.

Differences between measured and predicted coating thickness are most pronounced in regions where the coating thickness increases rapidly, such as near the center of the disk, figure 5. In practice, such localized coating buildup is undesirable; the simulation can aid in avoiding such conditions. Incorporation of a deposit efficiency correction, to account for decreased deposit efficiency at incident high angles, would also further increase the predictive capability of the model under these conditions.

To reduce the extreme in coating thickness at the center of the disk the gun traverse velocity was increased from 5 cm/sec at the outside edge of the disk to 25 cm/sec at 3 cm from the center. The measured and predicted thickness profiles for this 2-step velocity trajectory are presented in figure 7.

The simulation predicts the general form of the coating profile; the results however, are less accurate than those made when a constant velocity traverse was employed. The errors are a direct result of differences between the actual and simulated robot trajectory during periods of robot acceleration and deceleration. Since the coating thickness is inversely proportional to the gun velocity, any errors in simulated velocity or acceleration generate errors in predicted coating thickness. It should also be noted that different paths are followed during robot acceleration and deceleration which leads to asymmetry in the thickness profile about the center of the disk. Given the simple robot simulation employed here, it is difficult to predict the exact position and velocity of the robot during these periods.

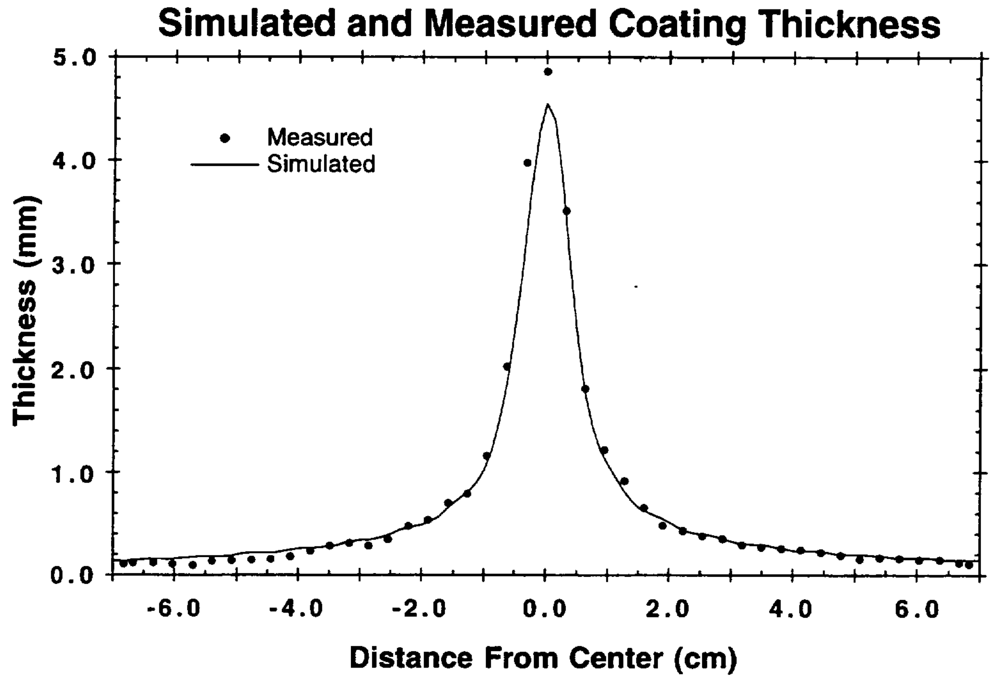

Figure 5.—Measured and predicted coating thickness on a rotating disk using a constant velocity robot traverse of 5 cm/sec across the center of the disk (268 passes).

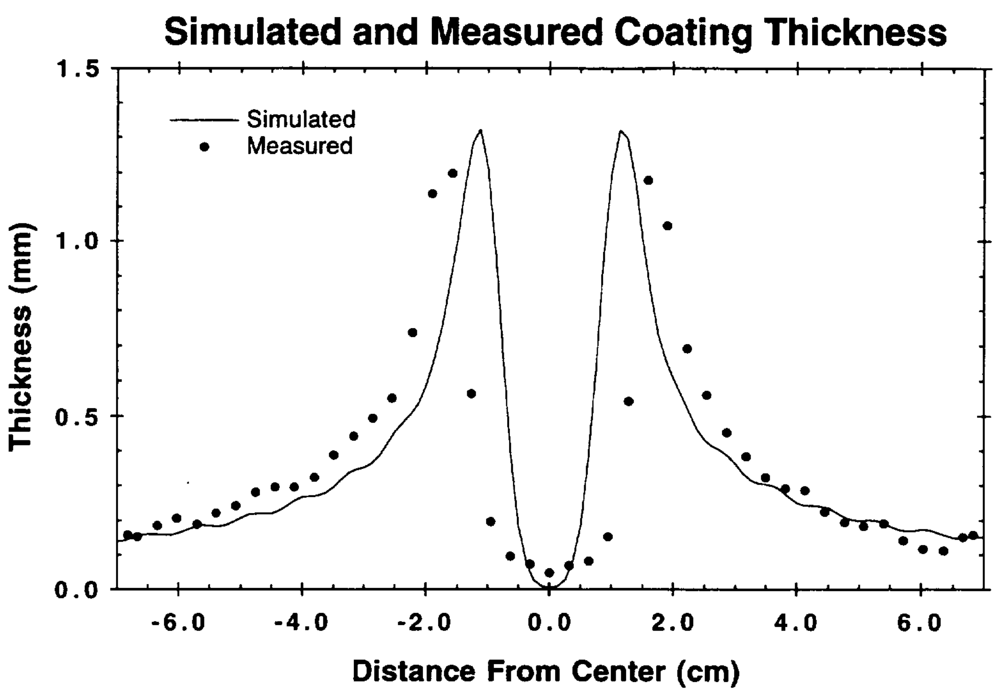

Figure 6.—Measured and predicted coating thickness profiles for a constant velocity gun traverse (5 cm/sec) with the gun offset from the center of the disk by 1 cm (268 passes).

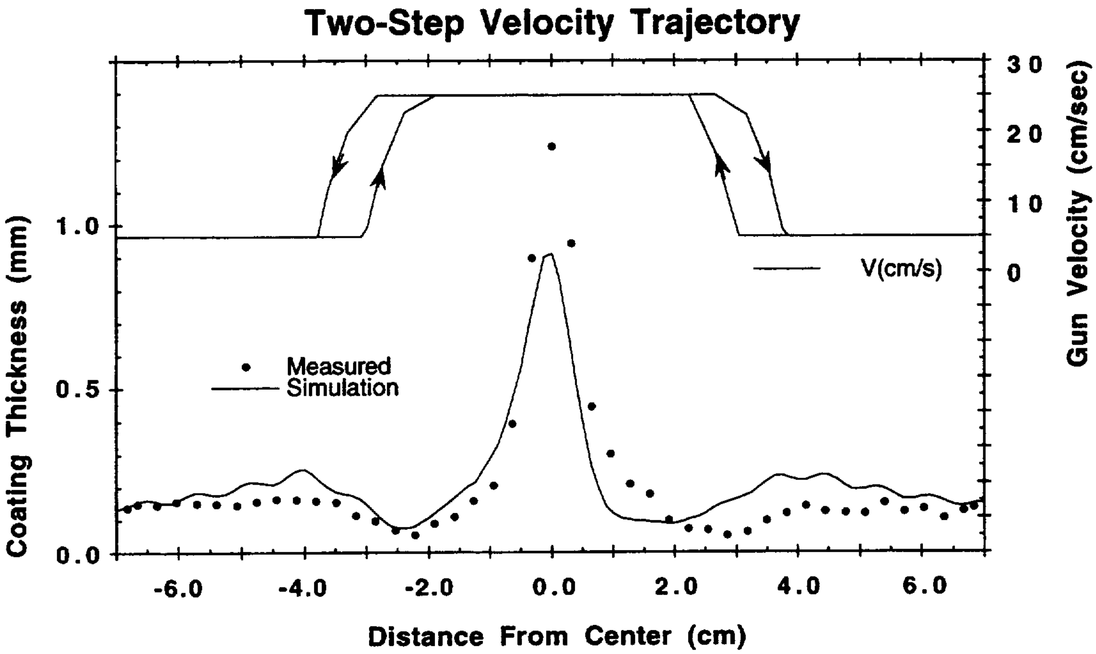

Figure 7.—Measured and predicted coating thickness for the 2-step velocity profile. The velocity profile is illustrated relative to the right-hand axis. The robot acceleration (400 cm/s^2) and deceleration paths are indicated by the arrows.

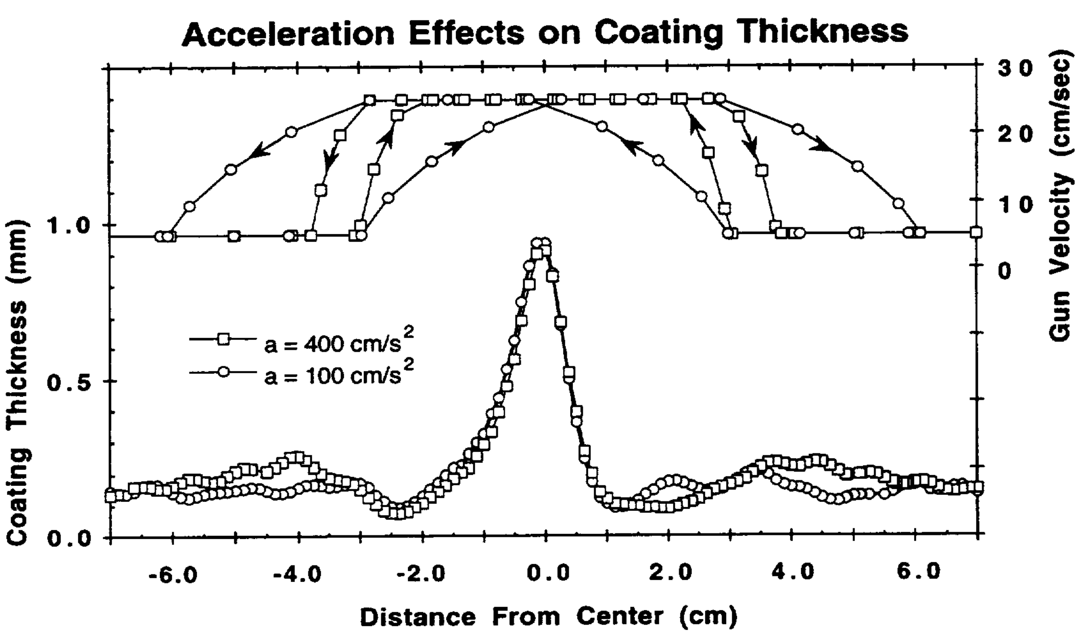

Figure 8.—The effect of acceleration on coating thickness is illustrated by a comparison of robot trajectories run at robot accelerations of 100 cm/s^2 and 400 cm/s^2. The velocity profiles are illustrated relative to the right-hand axis. The acceleration and deceleration paths are indicated by the arrows. Changing the acceleration, via the simulation, alters the robot trajectory and consequently the coating thickness.

Problems associated with the inability to predict robot velocity and acceleration are not restricted to this simulation, but extend to actual spraying operations. Robot trajectories are often programmed under the assumption that changes in velocity are made 'instantly', neglecting the finite robot acceleration. The effect of robot acceleration and trajectory on coating thickness is illustrated, via simulation, by running the two-step velocity program, figure 7, at a reduced robot acceleration of 100 cm/s^2, figure 8. The change in acceleration alters the trajectory and consequently the coating thickness. Neglecting the effect of robot acceleration and trajectory can result in unexpected departures from the desired coating thickness. Coating simulation programs can be used to identify and correct such problems early in the process, before a component is sprayed.

To produce a uniform coating over the entire disk the velocity must continuously increase as the gun approaches the center of the disk. The required velocity profile is dictated by equations (4) and (8), (detailed derivation provided in the appendix).

$$T_\rho = 2 \bullet \frac{A\sigma^2}{V_\rho} \bullet \frac{1}{2\pi\rho} \tag{8}$$

Equation (8) describes the velocity as a function of ρ, the radial distance from the center of the disk; T_ρ is the desired deposit thickness and V_ρ is the gun velocity. Equation (8) strictly applies for $\rho >> \sigma$. As ρ approaches the center of the disk ($\rho \rightarrow 0$) the velocity specified by equation (8) goes to infinity. The velocity required to deposit a coating of thickness T_ρ at the center of the disk is finite and can be calculated from equation (4).

In practice, the required velocity profile was beyond the capabilities of the robotic system. A simplified mult-istep velocity trajectory in which a limited number of velocity changes were made was used as an experimentally achievable model case. The measured and predicted coating thickness profiles and the velocity profile are presented in figure 9.

The multi-step velocity profile simulation accurately predicts the general form of the coating; however the total measured coating thickness is somewhat greater than predicted by the simulation. The more accurate prediction for the multi-step profile, as compared to the two-step profile, is a result of the lower velocities and consequently the reduced effect of acceleration/deceleration on the coating thickness. In this case, the required velocities, as determined from equation (8), are much less than those used in the 2-step velocity profile; hence, the effect of acceleration and deceleration is much less resulting in a better prediction of the coating thickness.

The use of a limited number of discrete velocity steps causes a predictable departure from the desired constant thickness coating. Consider the observed increase in coating thickness from the edge of the disk (7 cm) to a radius of 5 cm. The velocity at the edge of the disk was calculated using equation (8) for a deposit of 0.5 mils (12.7 μm) of coating per pass. As the robot moves toward the center of the disk the velocity remains constant but less than that required by equation (8); thus, the coating thickness increases. A similar variation in coating thickness is associated with each velocity step.

While the general form of the profile is accurately predicted by the simulation, the total measured thickness is more than predicted. The coating thickness is related to A, the amplitude of the deposit rate function while the shape of the profile is related to σ, the distribution parameter of the Gaussian rate function. These parameters were determined using a constant velocity traverse of 5 cm/s. The velocities used for the multistep trajectory, are on average, much less than this. This suggests that the amplitude parameter, A, increases with decreasing gun velocity, possibly due to an increase in local surface temperature and deposit efficiency with decreasing velocity.

If the current limitations of the robot system are ignored, a velocity profile can be designed via simulation which provides a uniform coating over the majority of the disk. A trajectory was designed using equations (8) and (4) to deposit a uniform coating over the entire disk using constant velocity steps of 0.1 cm. The maximum velocity at the center of the disk is dictated by equation (4). The predicted coating profile is presented in figure 10. The equations successfully described the required velocity profile except at the very center of the disk. Equation (8) strictly applies when $\rho >> \sigma$. Efforts to decrease coating thickness at the center by increasing velocity proved unsuccessful. The same velocity profile, but offset from the center by a distance 1.0σ, reduces the coating deposited at the center of the disk. An offset between these two values of 0.22σ, moderates these extremes in coating thickness and may, in practice, provide a coating within allowed tolerance limits, particularly when post-spray machining processes are to be performed. Some combination of trajectories across the center and offset from the center may provide an additional means of depositing a uniform coating over the entire disk.

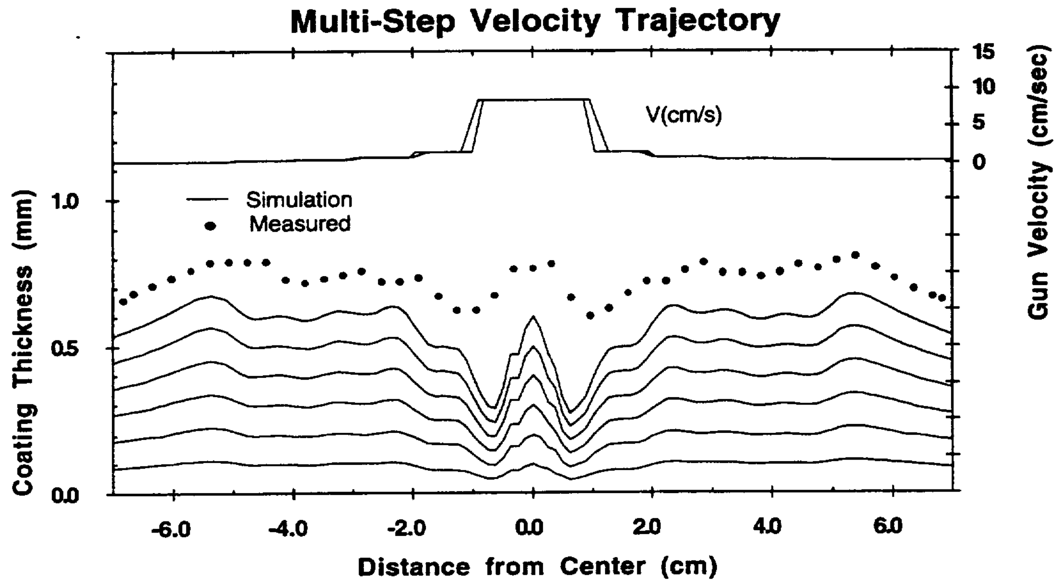

Figure 9.—Measured and predicted coating thickness profile for a multi-step velocity traverse across the center of the disk. The velocity profile is illustrated relative to the right-hand axis. The velocity profile during acceleration differs from that followed during deceleration. The coating thickness for the first 10 cycles and every 5 subsequent cycles are illustrated. A total of 30 cycles, or 60 passes, was made.

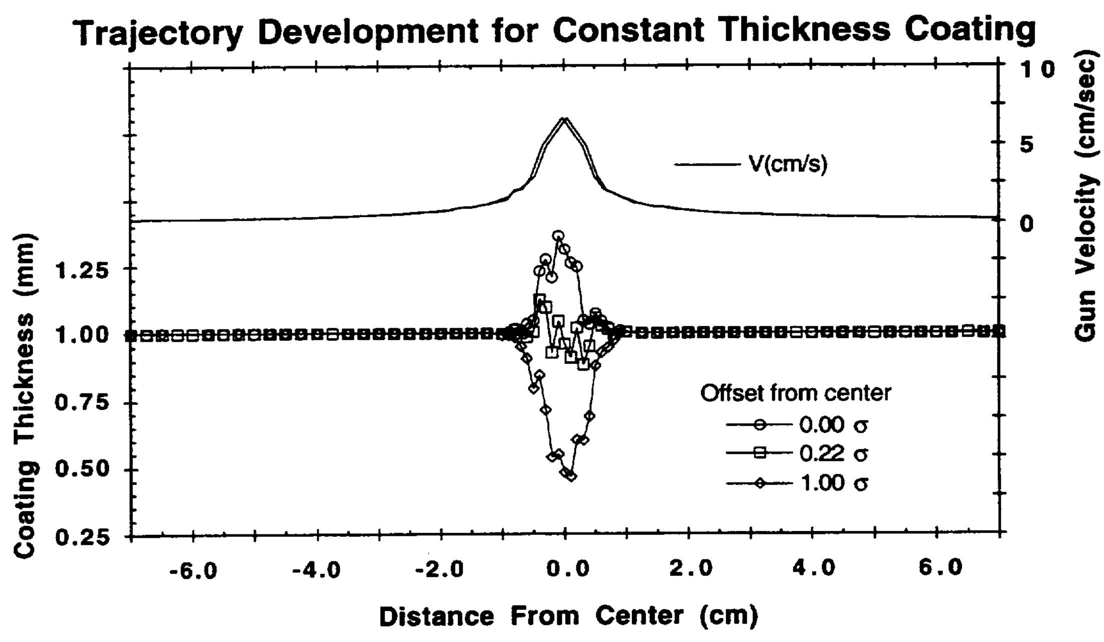

Figure 10.—A simulation designed to produce a uniform coating over the entire disk through application of equations (4) and (8). The traverse directly across the center of the disk results in excessive coating buildup at the center of the disk. A traverse offset from the center of the disk by 1.0σ results in a depression at the center. These two extremes are moderated by using an offset of 0.22σ, the coating however, is not completely uniform.

It is clear that the two dimensional finite difference model presented here provides a powerful means of predicting coating thickness on complex components. The errors in predicting the actual coating profiles can be explained and corrected within the context of the model assumptions. In general, the differences between the measured and predicted thickness profiles can be attributed to differences between the actual deposit rate and the idealized Gauss model and to differences between the actual and simulated robot trajectory.

The finite difference method involves certain inherent calculation errors due to the use of finite steps rather than closed form integration solutions. There are also inherent round-off errors associated with digital computer calculations. These errors have been estimated by comparison of computer calculations with the closed form solution for the specific cases addressed by equations (4) and (8). The inherent calculation error is less than 0.1 percent and is insignificant relative to those errors resulting from model assumptions and approximations.

The assumed Gauss deposit rate function, equation (2), is symmetric about the x and y axis; however, the actual deposit rate is not Gaussian but highly asymmetric. Departures from this idealized behavior result in differences between the measured and predicted shape and thickness of the coating profile. While the Gaussian equation provides a simple means of calculating the deposition rate, other more complex functions which provide a more accurate description of the rate would improve the simulation results. The rate could also be determined empirically using an accurately measured point-by-point topological description of the deposit and interpolation methods.

The robot trajectory can be a significant source of error. The exact trajectory followed is unique to the robot system. Errors in predicting trajectory are most pronounced during acceleration and deceleration periods involving large changes in velocity. Because coating thickness is inversely proportional to traverse velocity, errors in assumed velocity generate errors in predicted coating thickness. Integrating the coating model into a more sophisticated robot simulation program to reduce the differences between simulated and actual robot trajectory would also improve the simulation results.

Factors such as deposit efficiency could also be incorporated into the model to further improve the simulation. Measured data for deposition efficiency as a function of incident angle for a number of different powder chemistries is available[7] and could be integrated into the calculation.

CONCLUSIONS

The finite difference approach to predicting coating thickness offers a promising means of guiding development of new robot trajectories, or optimizing current processes, to produce uniform coatings over complex components. The two dimensional model demonstrates the feasibility of the finite difference path integral approach to predicting coating thickness on thermal sprayed components. While the two dimensional simulation is limited in application it offers insights into the factors which must be considered when modeling and spraying components. Expansion of the approach to three dimensional form and incorporation of a more accurate robot simulation would provide the level of sophistication required by a thermal spray engineer and technician. More sophisticated approaches for estimating the deposit rate function and incorporation of second order corrections such as deposit efficiency will further increase the utility of thermal spray simulations. Use of such models will enable the optimization of thermal spray process, reducing the time to develop trajectories and spray components, the materials required and post finishing processing.

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APPENDIX

The deposit rate, R (cm/sec), can be described using the Gauss equation:

$$R(x,y,t) = A \bullet \exp\left(-\frac{\rho(x,y,t)^2}{\sigma^2}\right) \tag{A1}$$

where A(cm/sec) and σ(cm) are amplitude and standard deviation of the Gauss function and ρ(cm) is the distance, in the plane of the substrate, between the gun and the point at which the coating thickness is to be calculated.

The coating thickness at a point of interest is determined by integrating the rate equation over the time

$$T = \int_0^\infty A \bullet \exp\left(-\frac{\rho(x,y,t)^2}{\sigma^2}\right) \bullet dt \tag{A2}$$

or alternatively, over the path of $\rho(x,y)$:

$$T = \oiint A \bullet \exp\left(-\frac{\rho(x,y,t)^2}{\sigma^2}\right) \bullet \partial x \partial y \tag{A3}$$

ρ is, in general, a complex function of x, y and t. For a simple straight-line trajectory, ρ can be determined from the trigonometric relation:

$$\rho^2 = (x - x_o)^2 + (y - y_o)^2 \tag{A4}$$

x and y are the coordinates of the gun, x_o and y_o are the coordinates of the point at which the coating thickness is to be calculated. Introducing even simple equations for the gun motion such as

$$x = V_x t + x_i \; ; \; y(t) = V_y t + y_i \tag{A5}$$

complicates the integration. V_x and V_y are the vector components of the gun velocity, x_i and y_i are the initial coordinates of the gun. A similar set of equations are required to describe a moving component. Combining equations (A3), (A4) and (A5) yields:

$$T = \int_0^\infty A \bullet \exp\left(-\frac{\left(\left((V_x t + x_i) - x_o\right)^2 + \left((V_y t + y_i) - y_o\right)^2\right)}{\sigma^2}\right) \bullet \partial t \tag{A6}$$

Consider the case for a constant velocity traverse along the x-axis across a stationary point located at (x_o, y_o). The robot traverse is along the x-axis; $V_y = 0$, $y_i = y_o$ = constant. Moving constants outside the integral yields:

$$T = A \bullet \exp\left(-\frac{(y_i - y_o)^2}{\sigma^2}\right) \bullet \int_0^\infty \exp\left(-\frac{(V_x t + x_i - x_o)^2}{\sigma^2}\right) \bullet \partial t \tag{A7}$$

The integration can be performed with the aid of the definite integral:

$$\int_0^\infty \exp\left(-a^2u^2\right)\bullet\partial u = \frac{\sqrt{\pi}}{2a};\ a>0 \tag{A8}$$

The range for the definite integral is $0 \le u \le -\infty$. The additional assumption that $x_i = x_o$ must be made to solve equation (A7) using the definite integral. This limitation provides only half the required solution; by symmetry the entire solution is

$$T = 2\bullet A\bullet\exp\left(-\frac{(y_i-y_o)^2}{\sigma^2}\right)\bullet\int_0^\infty \exp\left(-\frac{(V_x t)^2}{\sigma^2}\right)\bullet\partial t \tag{A9}$$

Let $u = V_x t$; $du/dt = V_x$, substituting and integrating yields:

$$T = \frac{A}{V_x}\bullet\exp\left(-\frac{(y_i-y_o)^2}{\sigma^2}\right)\bullet\sigma\sqrt{\pi} \tag{A10}$$

If $y_i = y_o = 0$, equation (A10) reduces too:

$$T = \frac{A\sigma\sqrt{\pi}}{V_x} \tag{A11}$$

Equation (A11) describes the thickness of the coating at a point along the line at which the gun travels. For these simple cases the thickness is equal to the area under the Gauss rate function appropriately scaled by $1/V_x$.

The thickness along the circumference of a rotating disk can be evaluated following a similar integration. The thickness at some radial distance x from the center of a rotating disk can be calculated by integrating over x and y, then distributing this material over the circumference of the disk.

$$G = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A\bullet\exp\left(-\frac{\left((x-x_o)^2+(y-y_o)^2\right)}{\sigma^2}\right)\bullet\partial x\partial y \tag{A12}$$

Assuming $x_i = x_o = 0$, $V_y = 0$, $y_i = y_o = 0$; integrating over y:

$$G = A\sigma\sqrt{\pi}\bullet\int_{-\infty}^{\infty}\exp\left(-\frac{x^2}{\sigma^2}\right)\bullet\partial x \tag{A13}$$

and x

$$G = \frac{A\sigma^2\pi}{V_x} \tag{A14}$$

This equation describes the cross-sectional area of a deposit for a constant velocity robot traverse along the x-axis.

An estimate of the coating thickness at some radius x can be made by distributing this integrated area over the circumferential distance of the disk, $2\pi x$. The gun intersects this radial point twice as it traverses across the rotating disk, requiring the coefficient of 2.

$$T_x = 2 \bullet \frac{A\sigma^2}{V_x} \bullet \frac{1}{2\pi x} \tag{A15}$$

This derivation is only valid at high rotation rates such that the material is evenly distributed along the circumference; and at $x >> \sigma$. At $x = 0$ the thickness is determined by equation (A11).

The deposit rate functions A and σ as defined in equation (A1) can be determined experimentally using equation (A10) where y_0 is equal to the center of the distribution, μ, equation (A16). A and σ are determined using nonlinear regression techniques applied to the measured profile.

$$T = \frac{A}{V_x} \bullet \exp\left(-\frac{(y-\mu)^2}{\sigma^2} \right) \bullet \sigma\sqrt{\pi} \tag{A16}$$

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The complexity of many of the components being coated today using the thermal spray process makes the trial and error approach traditionally followed in depositing a uniform coating inadequate, thereby necessitating a more analytical approach to developing robotic trajectories. A two dimensional finite difference simulation model has been developed to predict the thickness of coatings deposited using the thermal spray process. The model couples robotic and component trajectories and thermal spraying parameters to predict coating thickness. Simulations and experimental verification were performed on a rotating disk to evaluate the predictive capabilities of the approach.

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