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Plasma Spraying of WC-Co Part I: Theoretical Investigation of Particle Heating and Acceleration During Spraying

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Plasma-sprayed WC-Co coatings are used extensively in a variety of wear-resistant applications. The quality of these sprayed coatings depends greatly on the temperature and velocity of the powder particles impacting the substrate. Because it is both expensive and difficult to experimentally determine these particle parameters, the present study deals with a theoretical investigation of particle heatup and acceleration during plasma spraying of WC-Co based on a recently developed model. The effect of WC-Co particle size on the evolution of particle temperature and velocity is examined through calculations performed under typical spraying conditions. The implications of the powder particles, assuming an off-axis trajectory during their traverse through the plasma flame, are also discussed.

1. Introduction

WEAR-RESISTANT coatings based on WC-Co are widely used to enhance the performance and longevity of components that are subjected to extreme erosion and friction conditions during normal operation. These coatings may be produced using many of the available thermal spraying techniques, including atmospheric plasma spraying, low-pressure plasma spraying, and high-velocity oxyfuel flame spraying.[1-3] Although the relatively recent high-velocity oxyfuel spraying methods are particularly well suited for depositing such coatings due to the high gas velocities available and the relatively low combustion flame temperatures, which prevent decarburization of WC, plasma-sprayed WC-Co coatings are still used extensively in wear-resistant applications.

The quality of plasma-sprayed coatings depends greatly on the powder characteristics and the spray parameters used. To obtain dense and well-bonded coatings, the powder particles must generally be completely molten and traveling at a sufficiently high velocity when they impact the substrate. However, in some instances, such as during spraying of WC-Co powder, it is desirable not to melt the WC particles completely to thus minimize decarburization. In any event, for a given plasma spray gun operated at a specified power level with a fixed plasma gas composition, the extent of particle heating and its acceleration prior to impact are primarily determined by the particle size distribution of the powder. The gun-to-substrate stand-off distance, as well as the trajectory assumed by the powder particles during spraying, are also important, although the latter is not strictly a controllable parameter, being dependent, among other things, on the particle injection velocity and the particle size.[4]

The above-mentioned factors, which govern particle behavior during spraying, are therefore also likely to influence the microstructure and, consequently, the wear properties of the deposited coating. As such, an important objective of the present study (Part I) was to gain some insight into the evolution of particle temperature and velocity as a WC-Co particle traverses through a plasma flame. This article discusses a theoretical study designed to predict the heating and acceleration of WC-Co particles under a variety of conditions typically encountered in plasma spraying operations. The experimental study on particle behavior and coating microstructure observed during plasma spraying of WC-Co is the subject of a subsequent article (Part II).

Keywords: modeling, particle temperature, particle velocity, plasma spraying, tungsten carbide/cobalt

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2. Outline of the Prediction Model

The present study was accomplished using a reliable prediction model that was recently developed to assist both plasma and high-velocity oxyfuel spraying.[5] The model accounts for the various phenomena that influence gas-particle heat and momentum transfer under plasma conditions. It simultaneously considers (1) the effect of steep temperature gradients that prevail due to the large difference between the plasma gas and particle temperatures, (2) the influence of Knudsen discontinuum effects, which can be considerable because the typical particle size of spray-grade powders is comparable to the gas mean free path under plasma conditions, and (3) the contribution of internal heat conduction in particles, which although minor in case of particles of high thermal conductivity materials such as WC-Co, can be important during plasma spraying of low thermal conductivity ceramic powders. Furthermore, the model visualizes a realistic case in which the injected particle is exposed to a varying plasma temperature as it traverses through the flame and accounts for corresponding changes in all of the thermophysical gas properties.

The above model provides a valuable tool to assess particle behavior for any given powder-spray system combination. Preliminary results[6] have already demonstrated the capability of the model to realistically predict the temperature, velocity, and size of a ceramic particle during plasma spraying. Furthermore, comparison with experimental data has revealed[6] that the model enables significantly more accurate predictions compared to other existing models.[7,8] The improvement in accuracy is attributed to the consideration of all the above-cited factors in performing the plasma-particle heat and momentum transfer calculations. The importance of accounting for these factors is also highlighted by results published elsewhere.[6]

The mathematical formulation of the problem and the solution procedure adopted to determine the model predictions have already been discussed in considerable detail.[6] However, the constitutive equations used to generate the results subsequently discussed in this article are provided below for completeness.

3. Governing Equations for Plasma-Particle Heat and Momentum Transfer

The formulation of the overall problem on which the model is based assumes that the flow pattern is one-dimensional and that the particle loading is sufficiently low for the temperature and flow fields in the plasma to be unaffected by the injected powder. The validity and advantages of making the latter assumption, as well as a possible analytical approach to account for the particle loading effects, are discussed in the literature.[9-11]

With the above assumptions, the governing equation for heat transfer between a single spherical particle of diameter d_p and the plasma gas is:

$$\rho_p C_p \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r}\left(r^2 k_p \frac{\partial T}{\partial r} \right) \qquad [1]$$

where ρ_p, C_p, and k_p, respectively, denote the density, specific heat, and thermal conductivity of the particle material. Also, in Eq 1, t is the time coordinate; r is the radial coordinate; and T the corresponding temperature. This transient heat conduction equation may be solved using the initial condition:

$$t = 0, \text{all } r < d_p/2, T(r,t) = T_{po} \qquad [2]$$

and the boundary conditions

$$t > 0, (\partial T/\partial r)_{r=o} = 0 \qquad [3]$$

$$t > 0, [k_p(\partial T/\partial r)]_{r=d_p/2} = h\varphi\,(T_f - T_{ps}) \qquad [4]$$

where T_{po} is the initial uniform particle temperature at the time of injection; T_f is the bulk plasma gas temperature; and T_{ps} is the particle surface temperature.

The heat transfer coefficient h in Eq 4 can be calculated using the relationship:

$$h = \frac{\bar{k}_f}{d_p}(2.0 + 0.514\ \mathrm{Re}^{0.5}) \qquad [5]$$

where $\bar{k}_f$ is the integral mean thermal conductivity of the plasma gas used exclusively to account for the steep temperature gradients in the thermal boundary layer.[12] Re is the particle Reynolds number defined by the expression $\mathrm{Re} = d_p\,|U_p - U_f|\,\rho_f / \mu_f$ where U, ρ, and μ are the velocity, density, and viscosity, respectively, with the subscript p denoting the particle and the subscript f denoting the plasma gas.

The quantity φ in Eq 4 is effectively a correction factor that accounts for the Knudsen discontinuum effects that can significantly influence the gas particle transport process under plasma conditions. As indicated by Chen and Pfender,[13] it can be estimated from the expression:

$$\varphi = \frac{1}{\left[1 + 4\left(\frac{2-\theta}{\theta}\right)\left(\frac{\Gamma_{ps}}{1+\Gamma_{ps}}\right)\frac{\mathrm{Kn}^*}{\mathrm{Pr}_{ps}}\right]} \qquad [6]$$

In the above equation, θ is the thermal accommodation coefficient, whereas Γ_{ps} and Pr_{ps} are the specific heat ratio and the Prandtl number, respectively, evaluated at the particle surface temperature. Kn^* is a particle-size-dependent dimensionless parameter, called the modified Knudsen number, which provides a measure of the significance of the Knudsen noncontinuum effects and may be calculated based on the thermophysical plasma gas properties and the value of d_p.

As the injected particle gradually becomes heated during its traverse through the plasma flame, the particle surface eventually reaches the melting temperature. A heat balance at the moving solid-liquid interface must then account for the latent heat associated with melting. Therefore:

$$\Delta H_m\, \rho_{p,s} \frac{dr_m}{dt} = k_{p,l} \left.\frac{\partial T}{\partial r}\right|_{r=r_{m,l}} \qquad [7]$$

where r_m is the radial position of the melting front, and ΔH_m is the latent heat of fusion, with subscripts s and l designating the solid and molten regions in the particle.

The governing equation for heat transfer and other auxiliary equations provided above have to be solved in conjunction with a corresponding set of equations describing the plasma-particle momentum transfer process. The acceleration of a spherical particle injected into a plasma gas stream is given by:

$$\frac{dU_p}{dt} = \frac{3}{4}\frac{C_D}{d_p}\frac{\rho_f}{\rho_p}(U_f - U_p)\left|U_f - U_p\right| \cdot \varphi^{0.45} \qquad [8]$$

C_D in the above equation is the drag coefficient, which is a function of the particle Reynolds number and can be estimated using the most appropriate of the various empirical correlations available in the literature.[6,8] φ is the factor calculated from Eq 6 and appears in the above equation as a correction for the drag coefficient to account for the discontinuum effect on momentum transfer.[14]

The initial condition for solving Eq 8 is

$$t = 0, U_p = U_{po} \qquad [9]$$

where U_{po} is the particle injection velocity. Knowing the axial location of the powder injection port, the axial position of an injected particle can be readily calculated at any given time t, because $dz/dt = U_p$.

The above set of equations can be separated using a finite difference scheme and can be solved using a variable grid method, which has been detailed by Yoshida and Akashi.[15] In the present study, this approach was used to investigate the variations

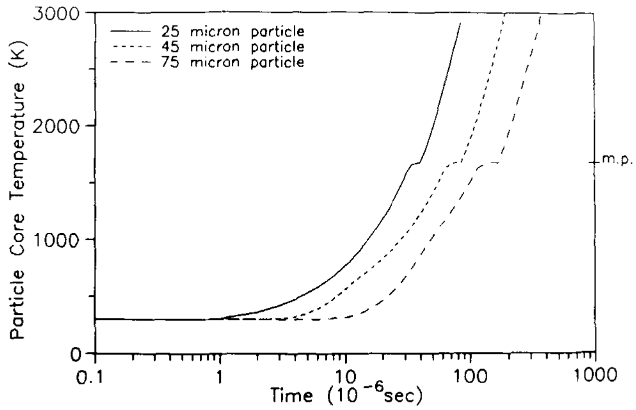

Fig. 3 Temperature evolution of WC-Co particles of different sizes during their traverse along the centerline of a plasma flame. The melting temperature of the material is indicated.

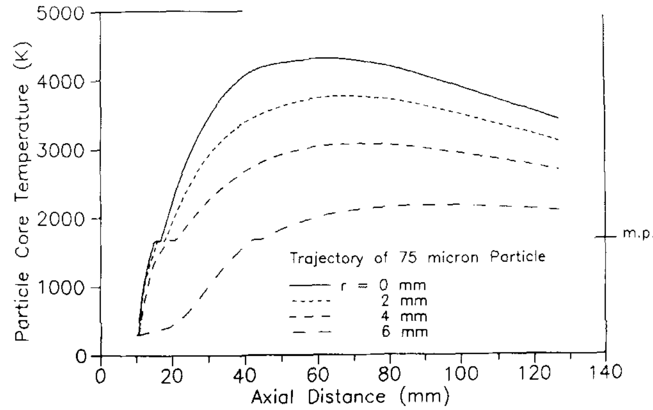

Fig. 5 Influence of an off-centerline trajectory on evolution of WC-Co particle temperature during plasma spraying.

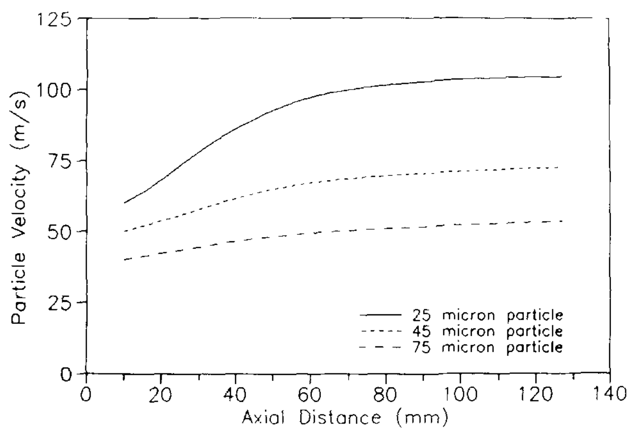

Fig. 4 Velocity evolution of WC-Co particles of different sizes during their traverse along the centerline of a plasma flame.

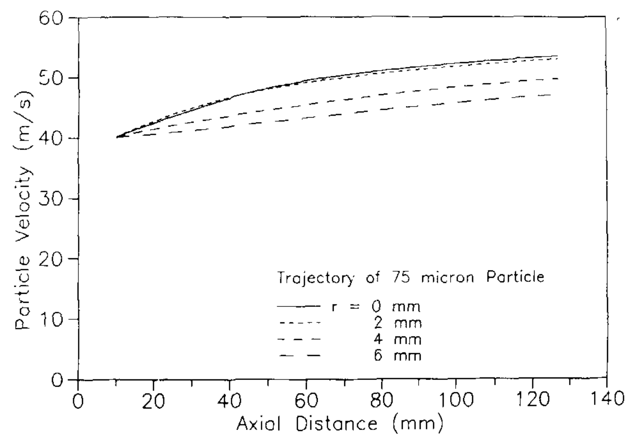

Fig. 6 Influence of an off-centerline trajectory on evolution of WC-Co particle velocity during plasma spraying.

4.1.2 *Particle Acceleration*

Figure 4 illustrates the velocity evolution of three differently sized WC-Co particles as they travel along the central axis of the plasma flame. As expected, the particle velocities increase with decreasing particle size. The finer 25-μm particle accelerates rapidly, and comparison with Fig. 2 reveals that it eventually attains a velocity that is nearly equal to the plasma gas velocity. The coarser particles, on the other hand, are heavier and attain much lower velocities by the time they impact the substrate. The velocity evolution of a particle is also strongly dependent on the density of the powder material and WC-Co particles, due to their high density (about 14,000 kg/m^3 compared to 3900 kg/m^3 for alumina). They are accelerated much less rapidly than similarly sized particles of most other materials.[5]

4.2 *Effect of Off-Centerline Particle Trajectory*

As shown in Fig. 1 and 2, both the gas temperature and gas velocity vary considerably with increasing distance from the centerline of the plasma jet axis. Therefore, particle heatup and acceleration can be significantly influenced by the trajectory assumed by a particle during its traverse through the plasma flame. An illustrative theoretical analysis of the extent to which the in-flight parameters of a WC-Co particle are dependent on the trajectory of the particle is presented in this section. However, it is important to realize that it is extremely difficult to actually control the trajectory of powder particles during spraying, although recent work does suggest that sophisticated schemes involving real time, nano-pulsed laser diagnostics can provide measurements to enable such control.

Figure 5 shows the evolution of the particle core temperature of a 75-μm WC-Co particle for hypothetical particle trajectories, each parallel to the plasma jet axis but at varying distances from the centerline of the plasma flame. Note that the particle core temperature varies with respect to its trajectory. The particle traveling along the periphery of the flame is not exposed to the hot core of the plasma jet, and the reduced driving force for heat transfer leads to a progressively lower particle temperature with increasing radial distance away from the centerline. Incidentally, the noted cooling of the particles in the tail-end of the plasma flame as well as their deceleration[8] imposes a practical limitation on the gun-to-job standoff distance. The optimum distance required varies with the type of powder and is usually governed by the need to prevent resolidification of the powder particles in flight.

Figure 5 depicts temperature profiles for a particle only up to 6 mm away from the centerline due to lack of more exhaustive input data concerning the plasma flame profiles. However, it is possible that some particles may stray further from the centerline during actual spraying.[4] In such cases, the results depicted in Fig. 5 suggest that, while spraying powders with a size distribution containing a tail of coarse particles, it is possible for particles traveling in the fringe of the flame to have an unmolten core when they impact the substrate. In addition, the inability of fine particles to enter the hot core of the plasma jet due to glancing off the viscous plasma[17] may also give rise to unmolten particulates in coatings.

The plasma gas velocity at any given axial location also varies substantially with distance from the centerline of the plasma jet axis. However, its effect on the velocity evolution of a 75-μm WC-Co particle is far less significant, as evident from Fig. 6. This may be attributed to the fact that acceleration of a coarse particle of a high-density material such as WC-Co is, in any case, lethargic. The difference in velocities of particles following different off-centerline trajectories is somewhat more pronounced in the case of similarly sized powders of lighter materials such as alumina.[18] It is also apt to point out that the cross-over of the top two curves in Fig. 6 is the result of the fact that the in-flight particle parameters are governed by the plasma-particle transport phenomena, which depend on a variety of factors, such as the temperature and flow fields in the plasma flame and the thermophysical properties of the plasma gas. Because the spatial variations in the plasma gas temperature and velocity are steep,[8] and as the transport parameters (e.g., thermal conductivity and viscosity) exhibit unusual temperature dependencies under plasma conditions due to dissociation and ionization,[12] such cross-overs are often noted during plasma-particle heat, momentum, and mass transfer calculations.[8,19]

5. Conclusions

This article discusses a theoretical investigation of particle behavior during plasma spraying of a WC-Co powder. The analysis is based on a comprehensive, one-dimensional prediction model recently developed by the author to assist plasma and HVOF spraying processes. The results presented in this article reveal the melting response of typical spray grade WC-Co powders. The particle size significantly influences the particle temperature and the particle velocity at impact, both these parameters being crucial in determining the spreading characteristics of each impacting particle and, thereby, the mechanical properties of the coating. Furthermore, an off-axis trajectory of the powder particles is found to reduce the gas-solid heat and momentum transfer rates. Consequently, the results indicate the possibility of certain particles having an unmolten core when they impact the substrate, if they have traveled in the fringe of the flame during flight. Although these trends hold true for plasma spraying of all materials, actual particle heatup and acceleration data for any given spray grade powder can be generated by solving the set of equations provided in this article using appropriate thermophysical properties of the material and plasma gas.

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