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# Energy transport during plasma enhanced surface coating mechanism: a mathematical approach

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## ABSTRACT

Heat transfer enhancement is still needed for the compactness and its smaller temperature difference of evaporator. This paper is introducing a mathematical model (Tailor-Chandra Model) for energy transport in plasma sprays process of a droplet. The model useful for calculate heat transfer through surfaces processed by thermal spraying. The model describes fluid flow of particle droplet during plasma spraying and its different energies: Thermal Energy ($E_{Th}$), Surface Energy ($E_S$), Kinetic Energy ($E_K$) and the energy lost by way of radiation ($E_R$) before deposition on substrate. A dynamic and thermal balance allows to calculate particle temperature and all energies of droplet during the spray process. As a result point of view, the model is able to show how molten droplets produced higher heat transfer as well as the effect of channel orientation in the low quality, low mass flux condition. Copyright © 2013 VBRI press.

**Keywords:** Plasma spraying; modeling; energy transport.

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## Introduction

The plasma spray techniques used to deposit coatings consist of atomization and deposition of molten or semi-molten droplets of the coating material on substrates. Now a day's plasma spray (atmospheric plasma and vacuum plasma) is the most common spray technique for depositing a wide range of nano-composite powder coatings **[1]**. Plasma sprayed coatings are used as erosion or abrasion, wear resistant coatings in a wide variety of industrial applications. Recent research shows the preprocessing like mechanical alloying **[2-3]** and plasma spray deposition parameters like current input in the plasma, powder properties and spray distances, affect the porosity, splat size, phase composition, hardness etc. of plasma sprayed coatings **[2, 4-5]**. Beside another spray forming set-up used to deposit coatings of $ZrSiO_4$ reinforced Al-Si-Sn alloy and Al-Si-Pb alloys and examined for their wear behaviour and thickness uniformity respectively **[6-7]**.

Shell of organic compounds, surfactants or polymers are formed around nanoparticles of various materials in order to add stability to them preventing their aggregations and minimizing surface energies **[8]**. In plasma spray process, a large number of very small atomized molten droplets forms and each droplet contain its kinetic energy, surface energy as well as thermal energy and further droplet deposited on substrate and transfers all the energies **[1]**.

In the last two decades a great deal of work has been done on the development of mathematical models to describe plasma spraying operations. However, to date, none of these models contain a full energy interaction between the plasma, the particles and the coating. Mathematical models of the atmospheric pressure plasma spray process have existed for almost thirty years and are in an advanced stage of development **[9-11]**. Techniques for predicting the velocities and temperatures in the plumes issuing from DC plasma torches have been tested extensively against experimental measurement **[12-13]**. While it is possible to make reasonably accurate predictions of the plasma plume using standard models of turbulence the turbulent nature of the plume is still not fully understood. While an accepted methodology for calculating the velocity and temperature histories of particles injected into the plume exists, it has still not been adequately validated against experimental measurement. In particular, little work has been done on the calculation of multiple particle trajectories **[14-16]**. In spite of a few problems which are not yet solved such as the engulfment process of the cold surrounding gas, the dispersion of the particles trajectories due to their size and velocity distributions as well as their collision between themselves and the injector wall, the particles parameters at impact are rather well modelled. It is now well recognized that these parameters: diameter, velocity and temperature control coating properties and reproducibility **[16]**. However the main drawbacks of the existing sophisticated codes is the computing time which is not compatible with industrial needs. That is why there is boom for simplified models able to give quickly (in few seconds) at least good trends. This is the goal of this paper.

The problem of the deposition and solidification of the plasma sprayed coating has received little attention to date and remains the least understood part of the process. Any analysis is complicated by the fact that the motion of two moving boundaries must be calculated; the motion of the top surface of the coating as the particles arrive, and the subsequent motion of the solid/liquid interface within the coating. A fundamental understanding of heat transfer in the coating is, however, critical for the prediction of the microstructural characteristics of the deposited coatings, the understanding of the mechanisms involved in the formation of defects, and the prediction of thermal stresses inside the coating. This, of course, requires addressing the deposition problem at both macroscopic and microscopic levels.

The objectives of present study are to describe a model of the plasma spray process that integrates a description of the plume, the plasma/particle interaction, and the buildup and solidification of the deposited coating. The purpose of the work is to gain an increased understanding of the process fundamentals and to develop a practical tool for product design and analysis, as well as process optimization and control. The particle energy distribution along the direction of spray can be given by the following model. The model is based on the energy conservation principle. The model includes a plasma torch in front of which micron size powder particles of coating material is feed and become molten droplets. Hence model helps to understand energy transfer mechanism during coating process.

## The Tailor-Chandra model

The total energy of the moving drop before it is deposited on the substrate is the algebraic sum of four heads. They are namely the Thermal Energy ($E_{Th}$), Surface Energy ($E_S$), Kinetic Energy ($E_K$) and the energy lost by way of radiation ($E_R$). The mathematical expression for these different energies is given as:

*Thermal energy (ETh)*

$$E_{Th} = mL_f \tag{1}$$

where $m$ is mass of drop and $L_f$ is latent heat of fusion i.e. energy taken up by particle to get converted into droplet.

Now, $$E_{Th} = \frac{4}{3}\pi r_S^3 \rho_S L_f \tag{2}$$

where $r_s$ is average particle radius and $\rho_s$ is density of coating material in solid state (feed stock powder).

*Surface energy (ES)*

Now surface energy of the droplet is equal to the surface tension times the surface area of the drop formed melting of particle. It is given as-

$$E_S = 4\pi r_l^2 S \tag{3}$$

where $r_l$ is radius of liquid droop and S is surface tension. Now we can be calculate from equity the masses of drop and particle. This means Volume of powder particle x Density of coating material in solid state (powder) = Volume of drop x Density of coating material in liquid state (droplet)

$$\frac{4}{3}\pi r_l^3 \rho_l = \frac{4}{3}\pi r_S^3 \rho_S \tag{4}$$

$$r_l = r_s\left(\frac{\rho_s}{\rho_l}\right)^{\frac{1}{3}} \tag{5}$$

Now standard data are available for $\rho_s$ and $\rho_l$ and $r_s$ is measured by CILAS particle size analyzer.

Let us denote,

$$\left(\frac{\rho_s}{\rho_l}\right) = \alpha \tag{6}$$

$$r_l = r_s(\alpha)^{\frac{1}{3}} \tag{7}$$

*Kinetic energy ($E_K$)*

The kinetic energy ($E_K$) part of the particle is deduce in the following form

$$E_K = \frac{1}{2}\left(\frac{4}{3}\pi r_l^3 \rho_l\right)V^2 \tag{8}$$

Now it is common that the velocity of the drop decreases as it moves away from torch, the reason is that as it moves for it encounters resistive forces arising out of turbulence, viscosity as well as recoil radiation pressure exerted on the drop when it radiates energy. We consider that the velocity decreases in some exponential factor of distance from torch to the substrate

$$V = V_0 x^{-\lambda_K} \tag{9}$$

where, $\lambda$ is a positive quantity and $V_0$ is the velocity at torch along $x$ direction. Therefore the kinetic energy is given by

$$E_K = \frac{2}{3}\pi r_l^3 \rho_l V_0^2 x^{-2\lambda_K} \tag{10}$$

*C.1. First order correction of volume:*

The volume of the drop decreases in size during propagation by a very small but finite factor. This may be considered a correction in the volume of the droplet.

$$r_l(x) = r_l(0)\left[1-\gamma\left(T(x)-T(0)\right)\right]^{\frac{1}{3}} \tag{11}$$

where $\gamma$ is the volume expansion coefficient. Therefore the Surface Energy ($E_S$) and Kinetic Energy ($E_K$) slightly get modified as

$$E_S = 4\pi S r_l^2(0)\left[1-\gamma\left(T(x)-T(0)\right)\right]^{\frac{2}{3}} \tag{12}$$

and

$$E_K = \frac{2}{3}\pi\rho_l r_l^3(0)\left[1-\gamma\left(T(x)-T(0)\right)\right]V_0^2 x^{-2\lambda_K} \tag{13}$$

*Radiation loss ($E_R$)*

The radiation loss is simply calculated by using Newton's law of cooling or to a better approximation from Stefan's law of radiation. Obviously the rate at which radiation loss occurs is directly proportional to the surface area of the drop and temperature difference. i.e.

$$E_R = \varepsilon 4\pi r_l^2 \sigma\left[T^4(x) - T_a^4(x)\right] \tag{14}$$

where σ is Stefan's constant, T(x) is temperature at a distance x, $T_a(x)$ is the ambience temperature. ε is the emissivity of the material in liquid state which are consider to be independent of temperature to a first approximation.

There is however temperature gradients both along the axial as well as radial direction. It is a common notion that the temperature will decrease in both directions. The simplest picture will be by considering an exponential decay.

Let the temperature decay with radial direction as-

$$T \propto e^{-\lambda_{R_1} r} \tag{15}$$

and with axial distance as

$$T \propto e^{-\lambda_{R_2} x} \tag{16}$$

using the principle of joint variation we get

$$T(r,x) = ce^{-(\lambda_{R_1} r + \lambda_{R_2} x)} \tag{17}$$

since we will be considering only the axial motion , we discard the former variation. Radiation loss *($E_R$)* is given by

$$E_R = 4\pi r_l^2(0)\sigma\left[1-\gamma\left(T(x)-T(0)\right)\right]^{\frac{2}{3}}\left[T^4(x)-T_a^4(x)\right] \tag{18}$$

where $r_l(0) = \alpha^{\frac{1}{3}} r_s$

We also consider that radiation is perpendicular to the axial direction. This mean

$$T_a(x) = T(x)e^{-\lambda_{R_1} r} \tag{19}$$

so we sum up our total energy heads:

$$
\begin{aligned}
E_{Tot} &= E_{Th} + E_S + E_K - E_R \\
&= \frac{4}{3}\pi r_s^3 \rho_s L_f + 4\pi S r_s^2 \alpha^{\frac{2}{3}} \left[1 - \gamma T(0)\left\{e^{-\lambda_{R_2} x} - 1\right\}\right]^{\frac{2}{3}} \\
&+ \frac{2}{3}\pi \frac{\rho_S}{\alpha} r_s^3 \alpha \left[1 - \gamma T(0)\left\{e^{-\lambda_{R_2} x} - 1\right\}\right] V_0^2 x^{-2\lambda} \\
&- 4\pi\sigma r_s^2 \alpha^{\frac{2}{3}} \left[1 - \gamma T(0)\left\{e^{-\lambda_{R_2} x} - 1\right\}\right]^{\frac{2}{3}} \left[T^4(x) - T^4(x) e^{-\lambda_{R_1} r}\right]
\end{aligned} \tag{20}
$$

Equation 20 represents the total energy during the plasma spray process.

## Conclusion

In this study authors described a model of the plasma spray process that integrates a description of the plume, the plasma/particle interaction, and the build-up and solidification of the deposited coating by energy-transformation. This model supposed to be validate against experimental measurements and help to resolve many coating failure factors such as poor adhesion strength, thermal expansion mismatch between coating material and substrates etc. Beside the model gives the macroscopic prediction of the energy-transfer thermal evolution of the coating process which is crucial for identifying the process parameters to which the formation of the coating is most sensitive and hence, for the design of optimal spraying sequences (e.g. number and frequency of spraying passes as well as the design of cooling arrangements. On a more fundamental level, the model explains the prediction of the overall thermal history effects is critical to understanding the energy-transport phenomena responsible for the formation of the overall coating structure. The model shows predicted temperatures in the coating are also key to the successful prediction of thermal stresses and strategies for process optimization and control.

## Used parameters

| Parameters | Symbol | Parameters | Symbol |
|---|---|---|---|
| *Thermal Energy* | $E_{Th}$ | *Volume expansion coefficient* | $\gamma$ |
| *Surface Energy* | $E_S$ | *Stefan's constant* | $\sigma$ |
| *Kinetic Energy* | $E_K$ | *Temperature at a distance x* | $T(x)$ |
| *Energy lost by way of radiation* | $E_R$ | *Ambience temperature* | $T_a(x)$ |
| *Mass* | $m$ | *Emissivity* | $\varepsilon$ |
| *Latent heat* | $L_f$ | | |
| *Particle radius* | $r$ | | |
| *Density of coating* | $\rho$ | | |
| *Radius of liquid* | $r_l$ | | |
| *Surface tension* | $S$ | | |
| *A positive quantity* | $\lambda$ | | |
| *Velocity* | $V_0$ | | |

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