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Splat formation in plasma-spray coating process*

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Abstract: The paper describes recent developments in modeling formation of plasma-spray coatings. This is a stochastic process in which particle-impact conditions, thermophysical properties, substrate topology, and temperature all play important roles in determining the structure of coating. Specific attention is paid to the simulation of droplet impact and solidification under plasma-spraying conditions. Results of 3-dimensional models show that on a flat surface solidification may cause splashing and break-up of the impacting particle. Undercooling effects result in faster solidification and, thus, smaller extent of spreading. More recent works investigate the effect of surrounding gas on dynamics of impact. It is shown that this could result in entrapment of a bubble under the droplet.

INTRODUCTION

Macroscopic properties of plasma-spray coatings, such as hardness, porosity, and mechanical strength, are determined by their microstructure. Understanding what parameters affect microstructure of coatings and, for example, what causes formation of porosity, could result in better design of the process.

A fundamental aspect of plasma-spray coating process is the deposition of molten or semi-molten particles on a surface. It is the shape of these individual deposits and their interactions with each other that determines much of a coating's properties. Individual impacts may result in the formation of round thin disks, disks with fingers, or they may break up.

Plasma-spray coating is a stochastic process in which a stream of molten, semi-molten, or even some solid particles strikes the surface of the work piece where they undergo rapid deformation and solidification to form disk-like splats. The shape of these splats plays a crucial role in determining the physical properties of the coating. Splat shapes depend on many factors such as size, velocity, and thermophysical properties of the impacting particles, as well as the topology and physical properties of the substrate. On-line measurement of these parameters for all impacting particles would be enormously complex, but their statistical distributions can be easily determined.

Modeling formation of plasma-spray coatings requires the development of a stochastic model. Recently, Ghafouri-Azar *et al.* [1–3] used a Monte-Carlo approach to model coating formation. Given particle size, velocity, and temperature distributions as well as spray gun velocity and substrate conditions, they predicted coating thickness, porosity, and surface roughness. Results for porosity, surface roughness, and coating thickness compare favorably with experimentally measured values. The model, however, uses analytical expressions to relate particle impact conditions to the final splat shapes. Additionally, porosity is assumed to be solely due to the curl-up of the splats as a result of thermal

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stresses. This model can be improved by employing a more rigorous model of droplet impact and solidification.

DROPLET IMPACT AND SOLIDIFICATION

A considerable amount of literature is available describing numerical models of droplet impact on a solid surface. In addition to plasma spray, these models find application in other industrial processes such as agricultural spraying, ink-jet printing, spray painting, spray cooling of hot surfaces, fire-fighting, and solder deposition on circuit boards. Computing fluid flow and heat transfer during droplet impact is a complex problem since it involves modeling free surfaces undergoing large deformations and moving liquid–solid–gas contact lines. Heat transfer calculations must include convection in the liquid and conduction in the solid, while accounting for steep temperature gradients in a rapidly deforming liquid layer, coupled with conduction in the substrate.

Bussmann *et al.* [4,5] developed a 3-dimensional, finite-volume, fixed-grid Eulerian model that used a volume-tracking algorithm to locate the droplet-free surface. They presented a method for considering fingering and splashing of a droplet impacting a solid surface. Their predictions agreed well with photographs of corresponding impacts. Heat transfer and solidification was not, however, considered in this work. Pasandideh-Fard *et al.* [6,7] extended the model of Bussmann *et al.* and included a heat transfer model, which also considered solidification and phase change. The model is based on the following assumptions: laminar, incompressible flow; negligible viscous dissipation; solidification occurs at the equilibrium temperature; the gas around the droplet is passive and at uniform pressure. The model combines a fixed-grid control volume discretization of the fluid flow and energy equations with a volume-tracking algorithm to track the droplet-free surface and an improved fixed velocity method to track the solidification front. Surface tension is modeled as a volume force acting on fluid near the free surface. Contact angles are applied as a boundary condition at the liquid–substrate and the liquid–solid contact lines. Energy equations in the liquid and solid phases of the droplet are solved using the enthalpy method. Within the substrate there is only conduction heat transfer. Thermal contact resistance at the droplet–substrate interface is included in the model. Figure 1 shows a comparison between com-

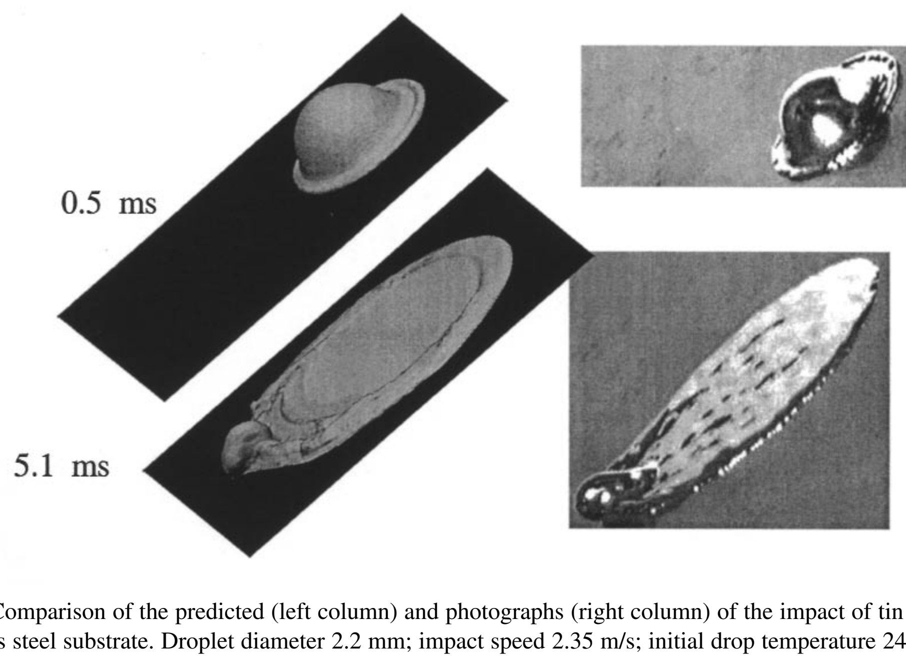

Fig. 1 Comparison of the predicted (left column) and photographs (right column) of the impact of tin droplet on stainless steel substrate. Droplet diameter 2.2 mm; impact speed 2.35 m/s; initial drop temperature 240 °C; initial substrate temperature 25 °C; incline angle 45°.

puter-generated images of predicted splat shape and photographs of relatively large (2.2 mm diameter) tin droplets impacting on a stainless steel plate inclined at 45° to the horizontal. Figure 2 shows the excellent agreement between the predicted and measured values of the spread factor (defined as the instantaneous splat length normalized by the initial droplet diameter), measured both along and across the incline.

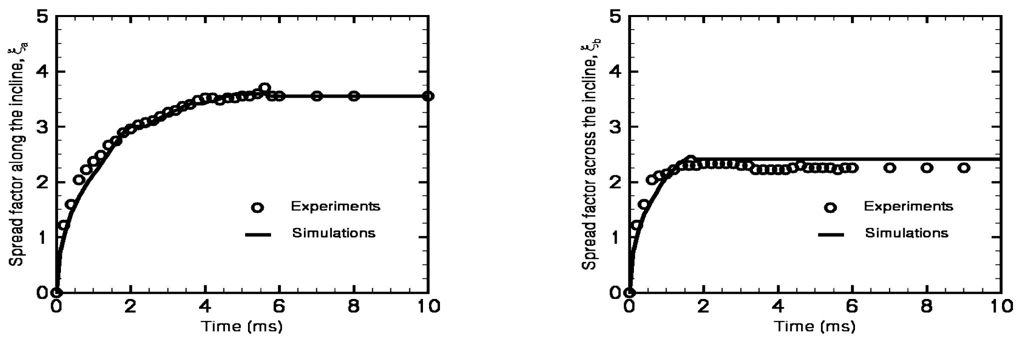

Fig. 2 Comparison of the predicted and measured values of spread factor for tin drop impact of Fig. 2 (left: along the incline; right: across the incline).

SPLASHING AND BREAK-UP

Pasandideh-Fard *et al.* [6,7] used their model to study break-up of thermal-spray droplets under different impact and substrate conditions. They showed that break-up on a flat surface is primarily due to solidification. When solidification was artificially suppressed in their model, no break-up was predicted. This has also been demonstrated experimentally. It has been observed by a number of research groups that when substrate temperature is raised beyond the so-called "transition" temperature, splats become circular and no break-up occurs. Figure 3 shows an example of these predictions.

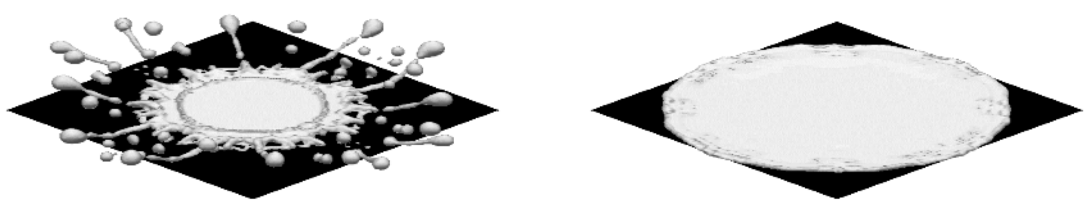

Fig. 3 Predicted nickel splat shapes at two different substrate temperatures. Left: 290 °C; right: 400 °C.

EFFECT OF SURROUNDING GAS

The models described so far assume that the gas flow about the droplet does not affect final splat shapes. Inspection of the underside of splats often reveals the presence of small air bubbles. The bubbles could be either due to nucleation of absorbed gases in the melt or the result of gas entrapment under the splat. To investigate the possibility of gas entrapment, Mehdi-Nejad *et al.* [8,9] included the effect of gas motion in a 2-dimensional axi-symmetric model of droplet impact. They showed that as the droplet approaches the substrate, the effect of viscosity in the thin gas film separating the two becomes significant, preventing the gas from escaping. As a result, gas pressure is increased in front of the impacting drop. Since the droplet is not rigid, the high gas pressure deforms the droplet surface, forming a cusp. Mehdi-Nejad *et al*. showed excellent agreement between their predictions with photographs of water and heptane drops [10]. Currently, efforts are underway to include heat transfer and solidification in this model.

UNDERCOOLING EFFECTS

The solidification models described so far assume solidification and phase change occurs under thermodynamic equilibrium, i.e., at a single melting temperature. Due to the high heat fluxes between substrate and the droplet, this assumption may not be valid. Chae *et al*. [11] recently considered the effect of undercooling. They showed that undercooling may result in a significant decrease in spread ratio, defined as the splat-to-droplet diameter ratio. They also showed solidification of the drop occurs faster than that predicted by equilibrium model. The model did not, however, predict dendritic growth, although this has been observed experimentally.

CONCLUSIONS

Existing models have successfully predicted many features of droplet impact and solidification during plasma-spray processing. The 3-dimensional models solve the governing equations for conservation of mass, momentum, and energy. In addition, the free surface of a drop is tracked via a volume-of-fluid (VOF) approach. The model has shown that:

1. Splashing and break-up are primarily caused by solidification. Delaying solidification by raising the substrate temperature results in disk-shape splats with no break-up.
2. Gases may be entrapped under an impacting drop, resulting in generation of small voids under the splat. This is caused by the rapid increase in gas pressure between an impacting droplet and the substrate. The rise in pressure deforms the drop and results in gas entrapment.
3. Undercooling effects may considerably decrease the spread ratio.

In spite of the great strides in modelling droplet impact, much remains to be done. The following effects need to be included in models:

1. Effect of shrinkage: Present models assume both fluid and solidified layers have the same density; in reality this is not the case. Shrinkage due to solidification results in residual stresses.
2. Marangoni convection: Variation of surface tension coefficient because of temperature results in an additional driving force for the flow.
3. Undercooling effect: Preliminary results have demonstrated the importance of rapid solidification effects. This effect should be further studied.
4. Thermal contact resistance is an important factor in determining splat shape. To date, this has been treated as an empirical parameter. A model for determining thermal contact resistance is needed.

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