Thermal Spray: Practical Solutions for Engineering Problems, C. C. Berndt (Ed.), Published by ASM International, Materials Park, Ohio-USA, 1996

Droplet Impact and Solidification in a Thermal Spray Process: Droplet-Substrate Interactions

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Abstract

Experiments have shown that the mechanical properties of plasma-sprayed coatings depend to a large extent on the details of the spraying process, in particular, they are strongly dependent on the details of the solidification and deformation history of the individual droplets which are in turn highly affected by the substrate conditions such as its temperature, material, and surface thermal contact resistance. In this study, droplet-substrate interactions are investigated through a complete numerical solution of droplet impact and solidification for a typical thermal spray process. The energy equation is numerically solved for both droplet and substrate regions; the solution is based on the Enthalpy Method for the liquid and solidified parts of the droplet, and the conduction heat transfer in the substrate. The numerical solution for the complete Navier-Stokes equations is based on the modified SOLA-VOF method using rectangular mesh in axisymmetric geometry. The developed model is suited for investigating droplet impact and simultaneous solidification permitting any desired condition at the substrate. The splat shape, the solidification front, and the temperature profile in the entire droplet and substrate regions are obtained at any desired time elapsed after the impact. Through these results, the nucleation and growth of solidification and droplet-substrate interactions are extensively studied.

FLUID FLOW and heat transfer phenomena associated with the impingement, spreading, and solidification of liquid droplets are of broad importance in a number of materials processing applications. Typical examples include thermal plasma spraying of ceramics and metallic materials, high velocity oxy-fuel (HVOF) spraying, and spray forming processes such as Osprey spray forming process.

In this paper we focus on droplet-substrate interactions under conditions typical of thermal plasma spraying processes. Material powders are injected into a high temperature plasma region where they are rapidly melted and accelerated towards the surface of a substrate. This is a complicated problem because it involves substantial droplet deformation, and simultaneous solidification and heat interaction with the substrate in a short time. Calculations of heat transfer between the droplet and substrate require detailed information about droplet shape during impact, which can be obtained only by a complete numerical solution of the continuity, momentum and energy equations. To this end, several numerical simulations for the isothermal droplet impact can be found in the literature. These models and their applicability have been discussed elsewhere [1]. Bennett & Poulikakos [2] and Kang et al. [3] studied the solidification behavior of droplet impact based on an assumption that solidification starts when spreading is completed. The droplet first deforms to its maximum spread in the form of a flat disc, then the energy equation is solved. The validity of such an assumption depends on the impact of solidification on droplet spreading. Watanabe et al. [4], Liu et al. [5], Trapaga et al. [6], and Bertagnolli et al. [7] employed a computational method to study the simultaneous spreading and solidification of the droplet. No thermal contact resistance has been incorporated in their model. Moreover, the simultaneous heat interaction of the droplet with the substrate has not been modelled.

The splat formation and cooling rate of plasma sprayed molybdenum particles on different substrates were investigated experimentally by Moreau et al. [8,9,10]. Their work is concerned with the influence of substrate conditions and material on the coatings texture and the cooling rate of sprayed particles. There is a large scatter in their measurements which is the result of very difficult experimental conditions. Their measurements indicate that surface conditions play an important role in the solidification process. Vardelle et al. [11] and Bianchi et al. [12], using a different experimental set up,