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Analysis of deposits formation in plasma spraying with liquid precursors

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HIGHLIGHTS

► A 3D model is applied to study the vaporization of solution sprays in a plasma jet.
► Individual deposits impacting on the substrate are collected experimentally.
► The forming mechanism of each type deposit is discussed.

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ABSTRACT

The coating deposited by plasma spraying with liquid precursors has nano- and submicron-metric features. Its microstructure highly depends on the injection history of the solution droplets. To increase the understanding of the formation mechanism of the deposits, a 3D model is applied to study the statistical characteristics of the trajectory and heating of the solution spray in a plasma jet. The temperature and size distributions of the particles upon impacting on the substrate are predicted. Individual deposits of precursor droplets or synthesized particles impacting on the substrate are collected experimentally. The deposits are classified into five types based on the computed temperature distribution and experimental observations: (1) melted or half-melted particles; (2) small sintered particles; (3) dry agglomerates; (4) wet agglomerates; and (5) wet droplets. The forming mechanism of each type is discussed.

1. Introduction

In the field of thermal spray, the atmospheric plasma spraying (APS) is a well-established technology. It has been widely used to produce various coatings, such as wear, corrosion resistant, hydroxyapatite, and thermal barrier coatings. For conventional plasma spray, powder particles of the coating material in the micrometer size range (10–100 μm) are injected into the plasma jet, in which powder particles are melted and accelerated to the substrate to form the coating. The deposit resulting from the particle is near circular lamellae of a few tens to a few hundreds of micrometers in diameter and a few micrometers thick. The microstructure of coatings deposited by the conventional plasma spray is characterized with large splat boundaries/cracks parallel to the substrate interface, which may lead to spallation failure of the coating and is not desirable in applications. To gain better quality and performance of the coating, liquid precursors are sprayed into the plasma jet to generate finely structured coatings [1]. In this process, liquid solution feedstocks of desired resultant materials are injected into the plasma jet either by atomization or by a liquid stream. Rapid heat-up and vaporization of precursor droplets result in the formation of particles with different morphologies, which are heated and accelerated to the substrate to generate coatings. This technology has been used to deposit Yttria-Stabilized Zirconia (YSZ) for application as thermal barrier coatings [2], Ni–YSZ anode and $(La_{1-x}Sr_x)MnO_3$ cathode for solid oxide fuel cells (SOFC) [3,4], and semiconductor oxide gas sensors [5]. The microstructure of the coatings deposited by this process typically has ultra fine splats and particles, vertical cracks to the substrate, and controlled micrometer and nanometer porosity, which can provide some unique thermo-chemical–mechanical properties (such as improved strength and hardness, higher durability and lower thermal conductivity, etc.) for the coatings [6]. Previous studies have revealed that the deposition mechanism in plasma spraying with liquid precursors differs from that in the conventional plasma spraying [7–14]. The coating has a variety of compositions and its microstructure highly depends on the injection history of the precursor droplets. The droplets injected into the plasma jet

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experience a sequence of thermal, physical, and chemical processes. These include droplet breakup and collisions, solvent vaporization, solute precipitation and pyrolysis, formation of the product particles, sintering, and perhaps melting of the product particles. Depending on the injection parameters (droplet size, velocity, solution concentration, and injection modes) and the properties of the solvent and solute, different particle morphologies result. Generally, bigger precursor droplets injected into the periphery or cold regions of the plasma jet may form hollow spherical particles. Small precursor droplets injected into the core of the plasma jet may form solid particles experiencing melting and solidification, and deposit on the substrate as splats. These splats appear identical to the molten splat structure of conventional air plasma spray, except that these splats are ten times smaller. Moderate precursor droplets passing through the moderately hot volume of the jet may form half-melted spherical particles. The desirable nano- and sub-micrometric microstructure only can be achieved under certain spraying conditions [6–9]. Therefore, it is necessary to investigate the heating and trajectory history of solution sprays and to understand the formation mechanism of deposits in plasma spraying with liquid precursors.

Numerical models have been developed to study the heating and trajectory history of solution sprays [15,16], interactions between the transient plasma jet and the droplets [17–19,23], and heat and mass transfer within a solution droplet injected into a plasma jet [20–24]. Characterization of the coatings was also performed to investigate its microstructure and thermal–mechanical properties [1–8,11,13,14,25]. However, little information regarding the droplets/particles statistical behavior (such as temperature and size distributions) upon impacting on the substrate was provided to analyze the formation mechanism of deposits due to difficulties in experimental measurements. To this end, the present work applies a 3D mathematical model to study the injection and vaporization of solution sprays in the deposition of $La_{0.85}Sr_{0.15}MnO_3$ (LSM) coatings for SOFC cathode application. The temperature and velocity fields of the plasma jet are simulated. The statistical characteristics of the sprays upon impacting on the substrate are investigated. Furthermore, the individual deposits of precursor droplets or synthesized particles impacting onto the substrate are collected experimentally. The deposits are classified into five types based on the model results and experimental observations. The formation mechanism of each type is discussed.

2. Statistical behavior of solution sprays

The system for plasma spray with liquid precursors consists of a solution injector, an atmospheric plasma spray system, and a substrate as shown in Fig. 1. The plasma torch generates a high velocity and high temperature jet discharging into the surrounding air. The solution injector injects measured quantities of the solution precursor into the high temperature plasma jet. For a gas blast injector, the solution is atomized into a log-normal droplet size distribution centered around 15–30 μm. For liquid stream injection, the stream interacts with the plasma jet and atomized into droplets, which are bigger than that of the gas blast injector [16]. The jet turbulence and torch arc fluctuation also have significant effects on droplet collisions and breakup of the sprays. Heat and momentum transfer from the plasma to the atomized droplets leads to acceleration and vaporization of the precursor droplets resulting in the formation of a coherent deposit. To understand the formation mechanism of the deposits, it is necessary to investigate heat transfer and fluid dynamics of the plasma jet and the vaporization of solution sprays injected into the jet. In this section, a mathematical model is described to simulate the statistical characteristics of solution sprays in a plasma jet. The model has been validated in the previous publication [15]. The droplet/particle size and temperature distributions of the spray upon impacting on the substrate are predicted and analyzed.

2.1. Model description

The model consists of the plasma jet model and the solution spray model. The former provides temperature, velocity, and species concentration fields for the calculation of the trajectory, heating and vaporization of solution sprays in the jet.

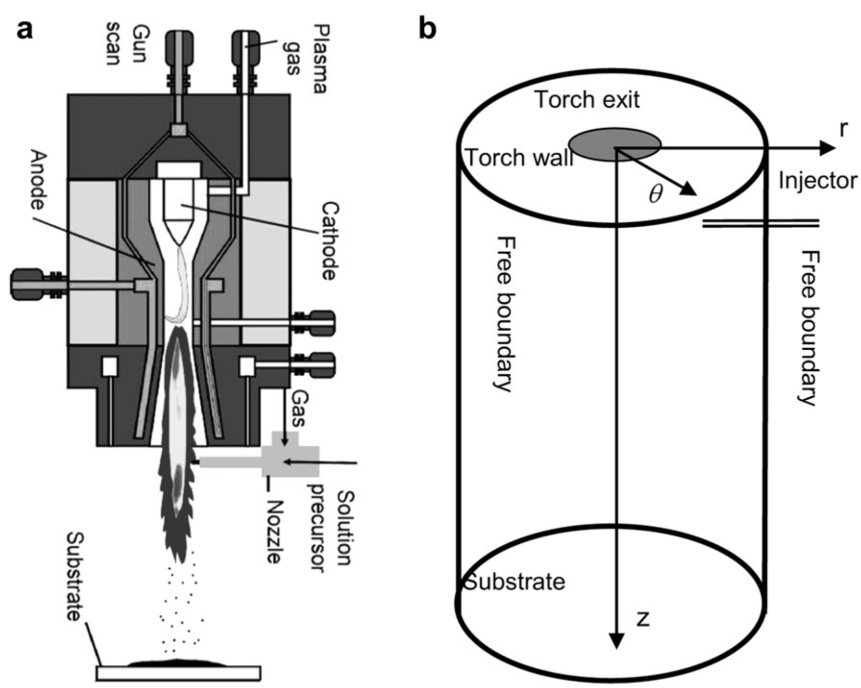

Fig. 1. Schematic of plasma spraying setup (a) and computational domain (b).