Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 18
ISSUE 1-2
September-October
2006

Thermomechanical modeling of a single splat solidification in plasma spraying

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Received 15.03.2006; accepted in revised form 30.04.2006

Analysis and modelling

ABSTRACT

Purpose: In plasma spraying, the residual stress is one of the important factors that reduce the strength and shorten the service lifetime of the spray coatings. It is therefore essential to investigate the evolution of the temperature and the distribution of the residual stresses, which are primarily induced by initial temperature difference and thermal expansion coefficient mismatch between the splat and the substrate.

Design/methodology/approach: As the plasma spraying process involves the solidification and cooling of extremely tiny molten metal droplets in a very short time, it is very difficult to observe the procedure directly. In this paper, a finite element model involving the temperature and residual stress simulation of a single NiCoCrAlY particle splat in plasma spraying when cooled on the carbon steel substrate is presented.

Findings: The numerical analysis results show that the temperature rise is more evident within the interior than on the top surface of the substrate. The maximum residual stresses of about 170 MPa appear at the central part of the splat.

Research limitations/implications: Future work should integrate the flattening process with the solidification and cooling of the droplet.

Practical implications: It will be helpful to the understanding and control of residual stresses in plasma spraying.

Originality/value: This research simulates the evolution temperature and residual stress distribution during the solidification and cooling process on the single splat level in plasma spraying.

Keywords: Numerical techniques; Plasma spraying; Finite element analysis

1. Introduction

Plasma spraying is a very promising manufacturing method characterized with short production time and low manufacturing cost in the three categories of thermal spraying methods[1-3]. But because plasma spraying involves the solidification and cooling of extremely tiny molten metal droplets in a very short time[4-6], the evolution of the temperature and residual stresses is difficult to be observed directly. Therefore, numerical simulation becomes the feasible method to understand the process. This paper addresses the issues of microcosmic temperature and residual stress evolution in plasma spraying process when a single molten droplet deposits on the substrate.

Ng et.al[7] investigated the temperature and residual stress field in plasma spray coatings, but their study is more from the macroscopic point of views: coatings are assumed to be fabricated layer by layer instead of splat by splat. Chin et.al[8] modeled the temperature and residual stress distribution of a single molten metal droplet cooled on the substrate in microcasting, which is similar to the thermal spraying process, but differentiated from the materials, geometrical scale and time scale involved. In their model, the molten metal droplet is 6 millimeters in diameter and 0.8125 millimeters in thickness, which is much larger than the size of splats in plasma spraying ranged from several tens micrometers to a few hundreds micrometers in diameter and several micrometers in thickness typically[4-5].

This study will model the temperature and residual stress field of a single molten NiCoCrAlY spray droplet splat by finite element analysis when cooled off on a carbon steel substrate.

2. Model

In plasma spraying, the molten droplet of high temperature is propelled by the plasma jet and impacts on the substrate with a velocity of several hundred meters per second[9-11]. The droplet then flattens and obtains a thin splat shape eventually[12-13]. Therefore, the analytical model of a single splat cooling off on the substrate are based on the following assumptions:

a The splat is simplified to be a flat cylinder of 160 micrometers in diameter and 5 micrometers in thickness;

b The solidification and cooling processes take place after the flattening of the droplet[4];

c The splat is of uniform temperature (at the melting point of the liquid phase of the splat material) before cooling;

d Only one single splat is considered in this study.

To save computation time and memory, the splat and substrate system is simplified to a two-dimensional axisymmetric model as in [8]. The geometric model and boundary conditions are illustrated in Fig. 1.

The transient heat transfer within the splat or the substrate can be formulated as an unsteady-state heat conduction equation[14]. The nonuniformity of the temperature field, as well as the mismatch of coefficients of thermal conductivity, result in the thermal stress within the splat and the substrate[7]. Since the splat is cooled from the liquid state of temperature higher than the melting point to the solid state of room temperature, both plastic deformation and elastic deformation present during the different phases of cooling process[15].

The splat is meshed to 30 quadrilaterals and the substrate 1200 quadrilaterals. To get the resolution with higher accuracy near the interface of the splat and substrate, the mesh of the substrate is biased toward the splat/substrate interface as indicated in Fig. 1.

The substrate is assumed to be 25 °C before spraying, and the right vertical surface and the bottom surface are constrained to be the same constant temperature T=25 °C during the cooling process. The splat is supposed to be at the temperature 1400 °C, which is the melting point of NiCoCrAlY[7]. At the top surface of the splat as well as the exposed part of the top surface of the substrate, the heat is transferred to the surroundings by radiation and convection of the ambient flowing air. To make the computation more efficient, the radiation to the surroundings is converted to additional heat convection. Therefore, a heat convection of 350W/(m^2K) boundary condition is imposed on the surfaces mentioned above.

The material properties of the carbon steel and NiCoCrAlY[7] are as follows: the thermal expansion coefficients are 13.0×10^{-6}/ °C and 14.0×10^{-6}/ °C respectively; the thermal conductivities are 49.8 W/(m· °C) and 4.3 W/(m· °C); the specific heat coefficients are 465 J/(Kg· °C) and 501 J/(Kg· °C); the Young's modulus are 206 GPa and 225 GPa; the latent heat of NiCoCrAlY is 2.56 GJ/m^3; the yield stresses are 215 MPa and 300 MPa.

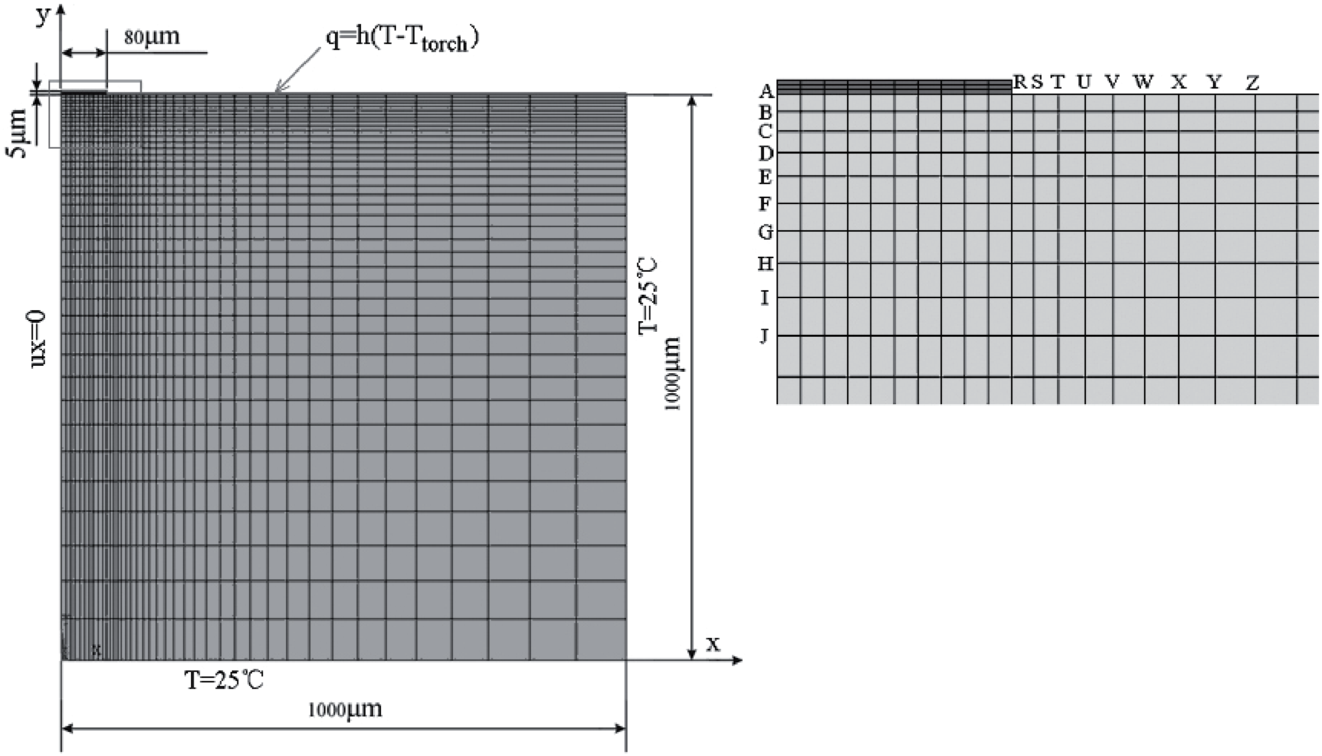


Fig. 1 Geometric model and boundary condition

3. Results and analysis

Fig. 2 and Fig. 3 show the temperature history of points along the centerline direction and radius direction of the splat and substrate respectively (illustrated in Fig.1). It can be learned that the solidification of the splat (defined by a temperature drop of 50 °C from the melting point) finishes within3 microseconds. To a single splat of the size studied in this project, the substrate reaches a gentle temperature drop state (defined by a temperature drop rate less than 10^6 °C/s) within 120 microseconds, while the splat reaches such a state in about 150 microseconds. The verifies the common assumption that the solidification and cooling time is relatively short compared to the flattening time, which is usually considered to be in the range of 10^{-7}-10^{-6} seconds. The maximum temperature rises along the centerline and the radius of the substrate are about 415 °C and 100 °C, while the remarkable influenced depth as well as the remarkable influenced radius (defined by a temperature rise less than 20 °C) is only 800 micrometres. It can be noticed from the comparison between Fig. 2 and Fig. 3 that the temperature rise at the interior is obviously bigger than that on the top surface within the substrate.

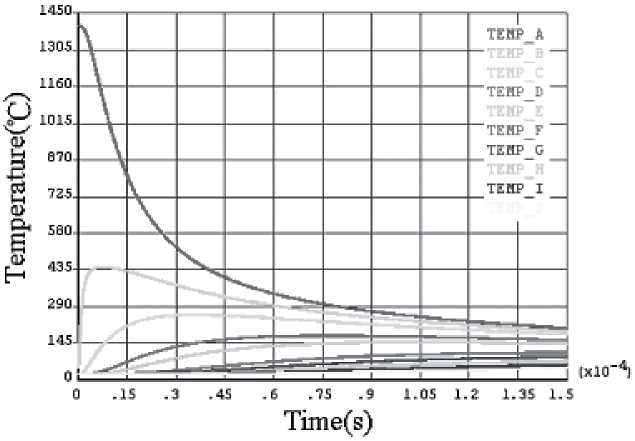


Fig. 2 The temperature history of points along the centerline

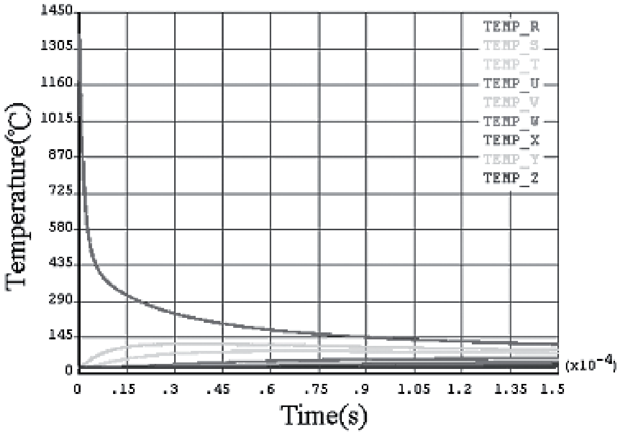


Fig. 3 The temperature history of points along the radius direction

The reason is that except heat transfer (which exists at the interior of the substrate), the heat is also carried off by both convection and radiation on the upper surface.

Fig. 4 demonstrates Von Mises stresses and X-Component stresses distribution around the splat after it reaches a steady state. It can be seen from the figure that the maximum equivalent residual stresses exist at the center of the splat, and the magnitude is about 170 MPa. As the elastoplastic model is employed for both the splat and substrate materials, the plastic deformation reduced the residual stresses greatly. On the other hand, the comparatively small difference of the thermal expansion coefficients between the splat and the substrate induces small material mismatch residual stresses. In the radius direction, the stresses decrease from the center to the rim, which can be observed more clearly from Fig. 5a. In the centerline direction, the stress decrease is from the upper surface to the interior. This explains the fact that the microcracks appear mostly at the center of the flattened droplet. As can be seen from the Fig. 4b, the X-Component stresses present as tensile stresses in the splat but compressive stresses in the substrate. Similar trend appears in Fig. 5b.

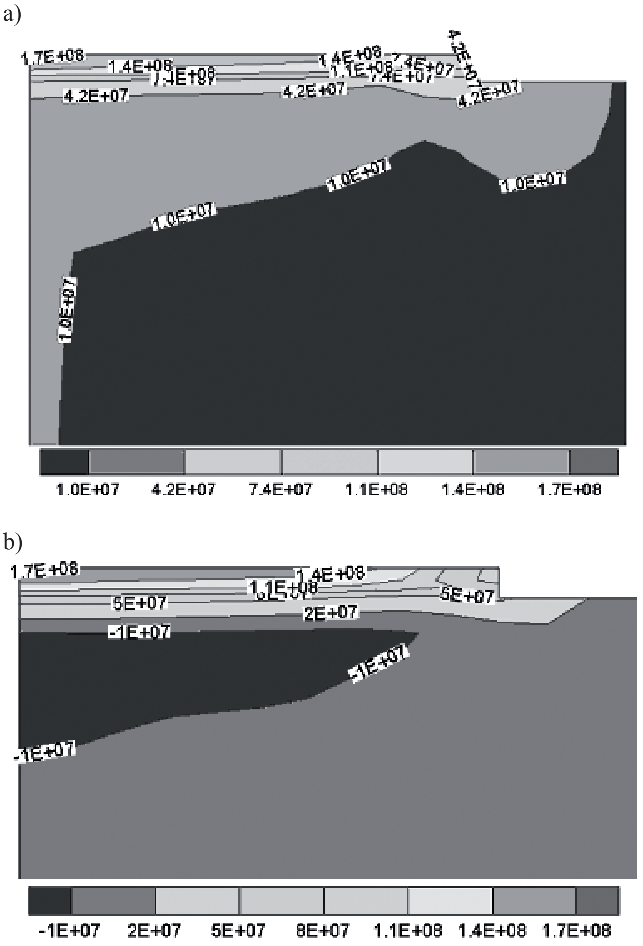
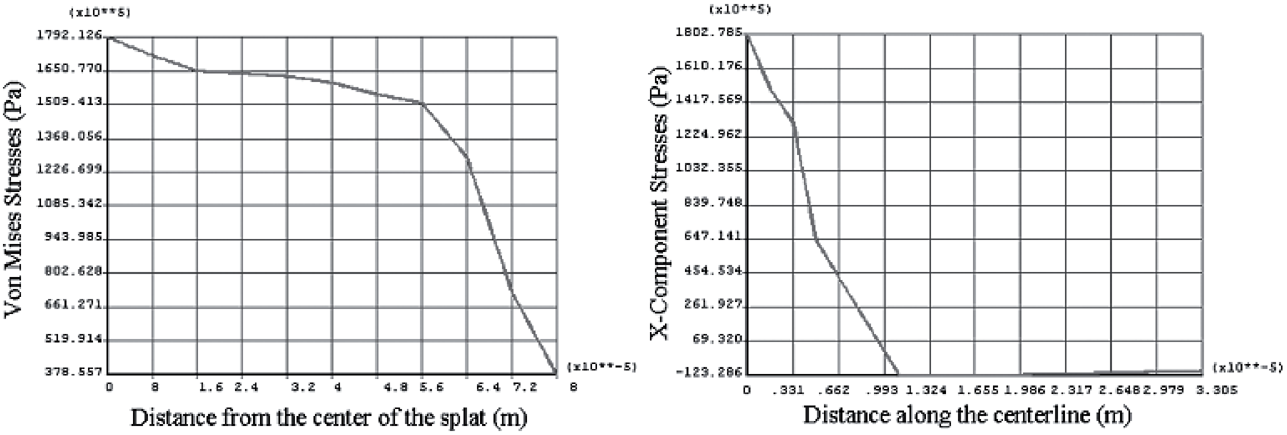


Fig. 4 The residual stress distribution near the splat: (a) Von Mises stresses(Pa), (b) X-Component Stresses(Pa)



a) Von Mises Stresses on the top of the splat

b) X-Component stresses along the centerline

Fig. 5 The residual stresses along the radius direction and centerline of the splat

4. Conclusions

This article presents the thermomechanical modeling of a single molten NiCoCrAlY splat cooling on the carbon steel substrate with finite element method. We arrive at the following conclusions:

1. According to the simulation results, it takes about 3 microseconds for the splat to finish solidification and 150 microseconds to reach a gentle temperature drop state.
2. The study also demonstrates that the temperature rise on the top surface is less obvious than that within the interior of the substrate because of the heat convection and radiation.
3. After the splat is cooled to approximately the room temperature, the maximum residual stresses present within the splat is around 170 Mpa, and it decreases from the center to the rim and top surface to the interior.

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