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General aspects of interface bonding in kinetic sprayed coatings

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Abstract

In this study, different engineering materials are classified into four impact cases according to their physical and mechanical properties, i.e., soft/soft, hard/hard, soft/hard, and hard/soft (particle/substrate). Based on finite-element modeling, impact behaviors of the four cases were numerically analyzed. For soft/soft and hard/hard cases, the size variation of the thermal boost-up zone (TBZ), accompanied with the different aspects of adiabatic shear instability, was numerically estimated and is theoretically discussed. Meanwhile, for soft/hard and hard/soft cases, the specific aspect of shear instability, which has a very high heat-up rate, is always observed on the relatively soft impact counterpart where a thin molten layer is expected as well. Based on these phenomenological characteristics, bonding aspects are characterized, and a database for numerically estimated critical velocities of different particle/substrate combinations was developed for kinetic spraying process.

Keywords: Kinetic spraying; Finite-element modeling (FEM); Impact behaviour; Coating; Bonding

1. Introduction

In this decade, kinetic spraying, or cold gas dynamic spraying, has been developed as a novel coating technology to obtain dense and high-quality coatings, which have low oxygen content and high bond strength. These properties can be achieved because the technique is a low-temperature and high-pressure coating process and is therefore unique when compared to conventional thermal spraying processes. Besides the many metallic coatings used, bulk metallic glass coatings [1], various composites coatings [2–4], and unique coatings for restoration of worn metals [5] have shown potential for various industrial applications.

In kinetic spraying, adiabatic shear instability (hereafter referred to as ASI) has been understood as one of the dominant mechanisms for successful bonding between micron-sized particles and the substrate (or previously deposited layer). This phenomenological characteristic is directly related to the abnormal temperature/strain rise and stress collapse, which is attributed to severe and localized plastic deformation at the impacting interface [6,7]. Based on this theoretical concept, some investigators have numerically examined deformation behaviors and have also estimated critical velocities for different impact cases using computational simulations [6–9]. Copper has often been employed as standard material to describe high-strain-rate deformation behaviors, such as the ASI, because it is feasible to simulate its behavior, and highly reliable high-strain-rate material data are available [6]. However, these high-strain-rate thermomechanical behaviors, especially the ASI characteristic of copper, cannot be applied for all other cases, because the onset of material instability depends upon the thermal-softening and strain-rate hardening characteristics of a material. Thus, it is important to consider how mechanisms operating within the materials may affect the initiation of shear instability upon a high-strain-rate impact. Furthermore, ASI behaviors need to be characterized as fundamental aspects. Additionally, it is quite challenging to numerically estimate the critical velocities for pure metals, let alone various engineering metallic alloys that are candidates for kinetic spraying.

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Previous research has focused mainly on examining the cohesive bonding (between the similar metals) through numerical modeling. However, the impact behaviors and mechanisms of adhesive bonding (between the dissimilar metals) have not been sufficiently investigated due to the one-time process characteristic of first layer coating. As regards both cohesion and adhesion, one should also consider the physical phenomenon that can affect adhesive bonding using available sophisticated numerical modeling techniques.

In this study, 22 kinds of engineering materials were classified into four impact cases (soft/soft, hard/hard, soft/hard, and hard/soft), according to their physical and mechanical properties. The impact behaviors of each case were numerically analyzed through finely tuned finite-element dynamic thermomechanical modeling. As a result, ASI aspects different from the conventional copper case were revealed. In accordance with the findings, the existence of a thermal boost-up zone (TBZ) is theoretically proposed. In view of ASI, general bonding features of the four cases were also characterized with respect to recoverable strain energy, plastic dissipation energy, contact area and contact time (which were evaluated based upon the energy balance concept). Furthermore, critical velocities for different particle/substrate combinations were numerically estimated.

2. Numerical modeling

2.1. Finite-element methodology

Non-linear transient finite-element (FE) modeling of the high-velocity micron-sized particle impacting process was performed using a commercial finite-element package, ABAQUS 6.7-2. In order to conduct the non-linear transient dynamic analysis of the particle bonding process, which has relatively short dynamic response times and large deformations, the explicit time integration algorithm [10] was chosen. An axisymmetric model was used to reduce computational costs, and fully coupled thermal-stress analysis was performed to obtain the thermomechanical responses of the particle impacting process. Fig. 1 shows the FE model constructed for the present work. Four-node bilinear axisymmetric quadrilateral mesh elements with reduced integration and hourglass control (CAX4R) from the ABAQUS element library were used, and a surface-to-surface penalty contact algorithm with balanced contact pair formulation [10] was applied between particle and substrate. Refinement of mesh at the impacting interfaces was subsequently performed for more accurate computations. Arbitrary Lagrangian Eulerian (ALE) adaptive remeshing [10] was also performed to avoid mathematical truncation errors due to severely distorted elements.

2.2. Numerical model

The Johnson–Cook plasticity model, which includes strain hardening, strain-rate hardening, and thermal-softening effects, was employed to describe the rate and temperature dependence of material behavior during plastic deformation. The model can be written as follows [11]:

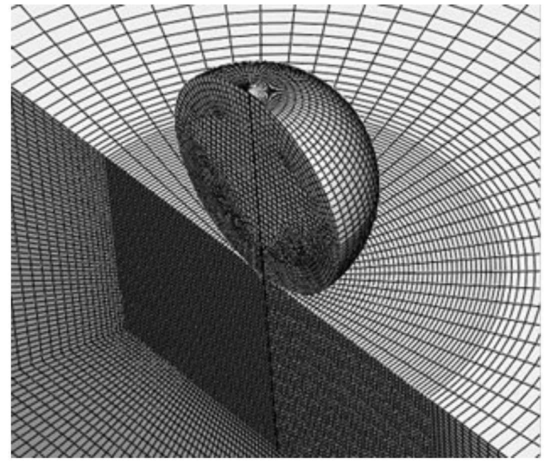

Fig. 1. Finite-element model for particle/substrate impact simulation.

$$\sigma = [A + B\varepsilon_{\mathrm{p}}^n]\left[1 + C\ln\left(\frac{\dot{\varepsilon}_{\mathrm{p}}}{\dot{\varepsilon}_0}\right)\right][1 - (T^*)^m] \tag{1}$$

where σ is the equivalent flow stress, ε_{p} and $\dot{\varepsilon}_{\mathrm{p}}$ are the equivalent plastic strain and strain rate, respectively, and $\dot{\varepsilon}_0$ is the normalizing reference strain rate. Parameters A, B, C, n, and m are material specific parameters; A is the yield stress in a quasi-static simple tension or compression test, B is the strain-hardening parameter, whereas C is the dimensionless strain-rate hardening coefficient. Parameters n and m are power exponents of the strain hardening and thermal-softening terms. T^* is the normalized temperature defined as follows:

$$T^* = \begin{cases} 0; & T < T_{\mathrm{trans}} \\ (T - T_{\mathrm{trans}})/(T_{\mathrm{melt}} - T_{\mathrm{trans}}); & T_{\mathrm{trans}} \leqslant T \leqslant T_{\mathrm{melt}} \\ 1; & T_{\mathrm{melt}} < T \end{cases} \tag{2}$$

where T_{melt} is the melting temperature above which the material is fluid and the hardening effect should totally vanish. T_{trans} is a reference transition temperature at or below which there is no temperature dependence of the response [10].

In the modeling, the particle/substrate interaction is assumed to be an adiabatic process. Theoretical calculations [6,8] and numerical experiments [12] have shown that heat conduction is negligible during the high-strain-rate deformation process due to its relatively short thermal diffusivity distance as compared to the characteristic system dimension. The balance of internal energy with heat conduction neglected can be written as follows:

$$\rho c_{\upsilon}\,\mathrm{d}T = \beta \cdot \sigma\,\mathrm{d}\varepsilon_{\mathrm{p}} \tag{3}$$

where ρ is the mass density, c_{υ} is the specific heat, and $\beta(\approx 0.9)$ is the Taylor–Quinney constant that equals the fraction of the viscoplastic work converted into heat.