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Deposition features of cold sprayed copper particles on preheated substrate

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A R T I C L E   I N F O

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A B S T R A C T

In this study, finite element analysis combined with experimental observation was conducted on copper particles depositing on preheated copper substrates to clarify the deposition mechanism of cold sprayed particles on the thermally softened substrate. The numerically predicted results indicate that with increasing the substrate preheating temperature, substrate deforms more and more intensively and the metal jet formed at the rim of the interface becomes increasingly prominent due to the enhanced thermal softening effect. Additionally, the substrate maximum local temperature increases gradually with the substrate preheating temperature, which means the viscous-like metal jet is more likely to form at the interface of the high temperature substrate. For the experiment, some crumple-like features near the particle–substrate interfacial region can be clearly observed at the surface of the preheated substrate. The crumple can be recognized as a sign of plastic flow, which further indicates that thermal softening is easy to occur for high temperature substrate. Besides, the experimental results also suggest that particles are more likely to deposit on the preheated substrate surface. The amount of the successfully deposited particles, including both large and small-scale particles, increases with the substrate preheating temperature.

1. Introduction

Cold spraying (CS), also called cold gas dynamic spraying (CGDS) or kinetic spraying (KS), is a relatively new material deposition technique, which has been developed for more than two decades. In this process, powder particles are accelerated to a high velocity normally ranging from 300 to 1200 m/s in a supersonic jet flow and projected onto the substrate or already deposited coating at an entirely solid state. Intensive plastic deformation induced by the high velocity impact occurs in cold sprayed particle, substrate (or already deposited coating) or both, enabling the low oxidized cold sprayed coating to be formed [1,2]. Generally, particle velocity prior to the impact is an important factor that determines whether particles can adhere on the substrate surface. It has been widely accepted that there exists a material-dependent critical velocity for a given condition (e.g. specific particle size, temperature and material properties), only above which bonding at the particle/substrate interface can take place and the CS coating can be formed on the substrate surface [3–5].

As for the bonding mechanism, currently, the most acceptable view can be regarded as the occurrence of adiabatic shear instability (ASI) at the interface which results from the high strain rate and the intensive localized deformation during the particle deposition process. At the region where ASI occurs, adiabatic heating-induced thermal softening is dominant over work hardening, and then metals behave like a viscous material, extruded from the interface, forming an outward metal jet at the rim [3,4]. Such viscous-like metal jet helps to clean up the cracked native oxide film which originally exists on particle and substrate surfaces, allowing the metal-to-metal contact and thus the metallic bonding to occur [6].

In some studies, it is reported that substrate surface temperature plays an important role in particle deposition and coating formation process. Fukumoto et al. reported that increasing the substrate temperature contributes to the particle deposition and significantly improves the formation of the first layer coating [7]. The work of King et al. further confirmed that substrate preheating promotes the occurrence of interfacial melting and thus enhances the bonding between particles and substrate [8]. Legoux et al., however, indicated that substrate preheating truly influences the deposition efficiency of the cold sprayed coating, but depends on the properties of the powder particles [9]. Besides, some numerical and experimental investigations on the temperature distribution within the substrate after preheating were also performed by different researchers [9–13]. Despite the fact that the already existing studies provided some meaningful findings in regard with the substrate preheating process, further researches are still needed to well understand the effect of thermally softened substrate on the deposition mechanism of cold sprayed particles. Therefore, in this study, numerical

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simulation combined with experimental observation is performed with copper particles to clarify the bonding mechanism of the cold sprayed particles depositing on the preheated substrate.

2. Computational descriptions

The high velocity impacting process is modeled by using ABAQUS [14] with the Lagrangian algorithm. The detailed description of this model can be found in Ref [15]. The copper particle has a diameter of 20 μm. The impacting velocity is 600 m/s based on the principle of exceeding the critical velocities of a 20 μm copper powder [16,17]. As for the particle initial temperature, our previous CFD results indicated that the particles can be slightly heated to 100–200 °C by the carrier gas before they impact on the substrate [18], thus particle initial temperature in this study is set as 100 °C. For preheated substrates, six different temperatures ranging from 100 °C to 600 °C are considered with an increment of 100 °C, while for the non-preheated substrate the initial temperature is set as 25 °C. The material of particle and substrate is described as a Johnson and Cook plasticity model which accounts for strain, strain rate hardening, as well as thermal softening [19]. A linear Mie–Grüneisen equation of state is employed for the elastic behavior. The properties of copper material used in this study can be found elsewhere [15].

3. Experimental details

Cold sprayed splats were produced by using a home-made cold spray system (LERMPS, UTBM, France) with an optimal de-Laval type converging–diverging nozzle. The nozzle has a rectangular cross-section with an expansion ratio of about 3.8, held by a robot arm. High pressure compressed air was used as the propellant gas with the inlet pressure and temperature of 2.5 MPa and 500 °C, respectively. The pressure and temperature of the injection gas is controlled as 3.0 MPa and 27 °C to guarantee the successful injection. Powders were axially injected to the cold spray nozzle at the position of 10 mm downstream from the nozzle inlet. The standoff distance from the nozzle exit to the substrate surface was 30 mm. The cold spray gun travels only one pass with a high speed of 500 mm/s to produce the individual cold sprayed splat. Substrate was preheated by a flame gun which is held and controlled by a robot arm. A thermal couple was inserted into the substrate from the center of the back surface to measure the preheating temperature. The distance between the substrate front surface and the thermal couple was limited to less than 5 mm in order to guarantee the accuracy of the temperature measurement. When the target temperature was achieved, the flame gun moved away quickly and then the spray process started.

Copper powder with a spherical morphology was selected as the feedstock. Fig. 1 shows the scanning electron microscope (SEM) morphology of the copper particles used in this experiment. In order to clearly observe the morphology of the deformed particles, relatively large powders were employed in this study. The powder size distribution was measured to be between 0 and 150 μm with the averaged particle diameter of 75 μm by a laser diffraction sizer (MASTERSIZER 2000, Malvern Instruments Ltd., UK). The copper substrate was manufactured as a cylinder shape with the height and diameter of about 10 and 30 mm, respectively. The substrate surface was polished to 0.05 μm in roughness before spraying. The powder and splat surface morphologies were examined by SEM (JSM5800LV, JEOL, Japan).

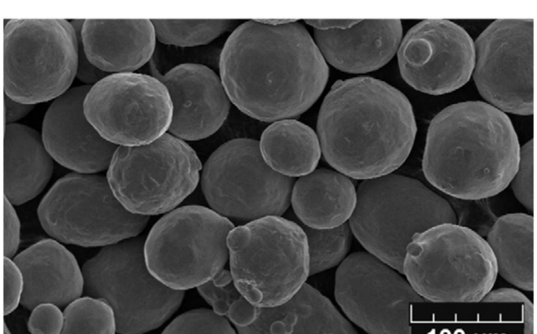

Fig. 1. SEM morphology of the copper powders used in this study.

4. Results and discussion

4.1. Finite element analysis of the particle deformation behavior

Fig. 2 shows the contours of the temperature and effective plastic strain of a single copper particle depositing on the copper substrate with different substrate preheating temperatures. For each case, it is seen that the cold sprayed copper particle strongly flattens with a deep crater forming on the substrate surface after high-velocity impact. Localized plastic deformation takes place at the interfacial region during the impact process, which results in the adiabatic temperature rise at the corresponding region due to the plastic work dissipation. As a consequence, viscous-like metal jet is formed at the rim of the interface, helping to clean the interface and then facilitating the metal-to-metal bonding between particle and substrate. By comparing different cases, significant difference also can be noticed from Fig. 2. As the substrate temperature increases, substrate experiences increasingly intensive deformation. The depth of the crater on the substrate surface shows an increasing trend with the substrate preheating temperature. The increase in substrate deformation level is attributed to the gradually enhanced thermal softening effect of the preheated substrate which can eliminate the work hardening effect and enable the metals to deform easily. As can be seen in Fig. 2, for substrate with higher preheating temperature, higher local temperature and also larger area of the high temperature zoon are achieved at the interfacial region. Therefore, thermal softening is easier to be triggered and is more intensive. Stronger thermal softening effect can eliminate more working hardening effect, hence larger plastic deformation, in other words, deeper crater, can be expected in the high temperature substrate. In addition, if the thermal softening effect is sufficiently strong to dominate the work hardening effect, plastic flow can take place and the viscous-like metal jet is formed. Therefore, for the same reason, the metal jet formed at the rim of the crater must become more and more prominent with increasing the substrate preheating temperature as can be seen in Fig. 2. As for the particle, negligible difference is observed, which means its deformation seems to be insensible to the substrate preheating temperature.

Interfacial temperature is a greatly important factor that can determine the atomic diffusion level [20]. Normally, higher interfacial temperature benefits the metallic bonding between particle and substrate. In order to further evaluate the local temperature at the interfacial region, Fig. 3 provides the variation of the local maximum temperature and temperature rise of the substrate with the substrate preheating temperature. As expected, the substrate maximum temperature increases gradually with increasing the substrate preheating temperature. This fact suggests that the atomic diffusion level and the consequent metallic bonding strength should be more considerable at the condition of higher substrate temperature. Besides, it is interesting to notice that the maximum temperature rise follows a reverse trend. Temperature rise is known as a consequence of the dissipation of the plastic deformation work. As already discussed, for higher temperature substrate, thermal softening is easier to be triggered, hence the plastic work required for triggering the thermal softening should be relatively smaller. On the other hand, as indicated in Fig. 3, substrate maximum temperature increases with the preheating temperature, which implies that the intensity of the thermal softening is higher for high temperature