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Numerical analysis of particle impacting and bonding processes during high velocity oxygen fuel spraying process

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ABSTRACT

In this paper, the dynamic impact behavior of a particle and a substrate under different particle temperatures and velocities as well as using different materials for the particle and substrate were systematically studied. We found that the highest temperature occurred at the side edge of the particle after the collision, which is consistent with the distribution of equivalent plastic strain. The deformation of the particle and substrate was very severe at the first 40 ns, slowed down after 40 ns and remained almost unchanged after 80 ns. With the increase in the particle velocity, the effective combination area became larger, the equivalent plastic strain of the substrate is increased, and the equivalent plastic strain of the particle is decreased. As the initial temperature of particles increased, the effective combination area between the particle and substrate increased, and higher temperature and larger equivalent plastic strain of the particle could be obtained. With the increase in the substrate strength, the temperature and the equivalent plastic strain of the particle is increased, whereas the plastic deformation of the substrate is decreased.

1. Introduction

Thermal spray process is one of the most widely used surface treatment methods. It is used to protect surfaces against wear, corrosion and thermal barrier [1]. In high velocity oxygen fuel spraying, the sprayed particles are heated to soften and accelerated to high velocity by heat and momentum interaction with the flame flow, impacting the substrate and forming a coating layer structure. A coating is formed through the intensive plastic deformation of particles impacting on a substrate at a temperature well below the melting point of the spray material [2]. The adherence of these coatings to the substrate is strongly influenced by the residual stresses generated during the coating deposition process [3]. Therefore, studying the residual stresses during the impacting process is highly important.

Numerical simulation has become an important tool for process control and optimization in many engineering applications. A clear understanding of the dynamic thermal-physics impingement process when droplets make contact with the substrates is critical for controlling and optimizing the spray process. Nowadays, progress has been made in the study of impacting particle dynamics on the substrate including the fully molten droplet [4–6], partially molten droplet [1] and solid particle [7–13]. Although the impact phenomena have been studied for a long time using both numerical and experimental methods, the deformation behavior and the bonding mechanism during the impacting process are still not well understood.

The bonding of particles in spraying is generally considered to be the result of the extensive plastic deformation and related phenomena at the interfaces [14]. The current work attempts to study systematically study the dynamic evolution of particle temperature and plastic deformation under different substrate materials, particle temperatures and particle velocities. The dynamic evolution of the combination area and reaction force imposed on the particle were predicted using the finite element program ABAQUS.

2. Finite element model

2.1. Basic assumption

(1) Because the time of the dynamic impact process is very short and the size of the particle is small, the heat transfer between the particle and the substrate is not considered.

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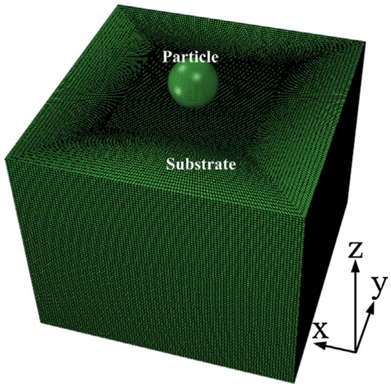

Fig. 1. 3D model of particle and substrate.

(2) The geometry of the particle is assumed to be spherical and the temperature distribution within the particle is uniform.
(3) The particle is no longer isolated upon contact with the substrate.

2.2. Numerical model

Fig. 1 shows a 3D model of a particle and a substrate. The diameter of the particle is 30 μm and the lengths of the substrate in the *x*, *y*, and *z* directions are 120, 120 and 210 μm, respectively. Because the particle-impact process is symmetrical, a quarter of the model was used in order to reduce the CPU processing time. The mapped mesh represents for the particle and substrate with reduced integrated hexahedral elements. The entire constraint was applied to the bottom surface. The penalty-based contact algorithm based on the ABAQUS software was chosen owing to its momentum conservation accuracy. The trace points set at the bottom of the particle were used to monitor the force in this process.

2.3. ALE adaptive grid technique

In the calculation process, the arbitrary Lagrange–Euler (ALE) method was used to overcome the mesh distortion impact due to large deformation. The ALE adaptive grid technique can accurately describe the moving interface of objects using a suitable mesh while maintaining a reasonable shape of the finite elements. The ALE method is widely used in solving large deformation problems, such as elastic fracture, contacts, forming, and crashes as well as in other fields. In recent years, the ALE method has been widely used in the simulation of spray particles [9,13].

2.4. Johnson–Cook material

In the dynamic impact process, a Johnson–Cook material is suitable for dynamic impact model considering the significant strain rate hardening and softening of the material [15]. The Johnson–Cook model is widely used in large finite-element software. The specific forms of the Johnson–Cook model are the following:

$$\tau = (A + B(\varepsilon_e^p)^N) \times [1 + C \ln \dot{\varepsilon}^*] \times [1 - (T^*)^M] \quad (1)$$

$$T^* = \frac{T - T_0}{T_m - T_0} \quad (2)$$

$$T = T_0 + \frac{\beta}{\rho c_p} \int \tau d\varepsilon_e^p \quad (3)$$

where A is a static yield strength, B strain hardening coefficient, C strain rate hardening coefficient, N is the strain hardening exponent, M is material-related constants, τ is yield stress, ε_e^p is the equivalent plastic strain rate, $\dot{\varepsilon}^*$ is the effective plastic strain rate normalized with respect to a reference strain rate, T^* is non-dimensional temperature, T is the temperature of the material, T_0 is the reference material temperature, T_m is the melting temperature of the material, c_p is specific heat, β is plastic dissipated energy conversion factor (0.9 based on empirical assumptions).

Four different substrate materials, namely, 45 steel, IN718, Ti-6Al-4V, and WC-17Co, were selected as substrate materials to investigate the impact process. WC-Co coating [16,17] has been widely used in various applications with excellent wear resistance and mechanical properties, which has gained large interest from the researchers. IN718, which is often used as a substrate material [18], can maintain higher tensile, fatigue, and creep strength under high-temperature environment. No. 45 steel, which has been widely applied in machinery manufacturing and transportation, is a high-quality carbon structural steel with good mechanical properties. Ti-6Al-4V, which is widely used in aerospace, automotive and biomedical fields, has good heat-treatment and wear properties. The material properties of the particle and substrate are listed in Table 1.

3. Results and discussion

3.1. Prediction of the surface deformation

Fig. 2 shows the dynamic evolution of the equivalent plastic strain of a 30 μm particle at 20, 40, 60 and 80 ns. In the calculation, the particle and substrate materials were WC-17Co and IN718, respectively. The particle and substrate temperatures were set at 1590 K and 297 K, respectively, and the particle velocity was set at 720 m/s. The maximum equivalent plastic strain was not located at the center of the substrate and the particle, but at their edges, which indicated the position of the maximum dramatic deformation. This phenomenon is validated by the other simulation results [7,10,11]. For the IN718 substrate, the severe deformation occurred in the vicinity of the interface, but for the WC-17Co particle, the plastic strain was distributed throughout the particle because the particle experienced a more intense deformation.

Table 1
Material properties used in this study [19,20].

Parameter	Symbol	Unit	Steel 45	IN718	Ti-6Al-4V	WC-17Co
Static yield strength	A	MPa	546	900	1096	1550
Strain-hardening modulus	B	MPa	487	1200	1092	2200
Strain-hardening exponent	N	–	0.25	0.6	0.93	0.45
Strain rate sensitive coefficient	C	–	0.027	0.092	0.014	0.0312
Thermal softening exponent	M	–	0.631	1.27	1.1	1.34
Density	ρ	kg/m^3	7870	8190	4430	13,500
Specific heat	c_p	J/kg K	446	537	565	313
Solidus temperature	T_S	K	1420	1528	1604	1680
Liquidus temperature	T_L	K	1495	1610	1660	1768
Reference temperature	T_0	K	298	298	298	298