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A theoretical model for prediction of deposition efficiency in cold spraying

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Abstract

The deposition behavior of a spray particle stream with a particle size distribution was theoretically examined for cold spraying in terms of deposition efficiency as a function of particle parameters and spray angle. The theoretical relation was established between the deposition efficiency and spray angle. The experiments were conducted by measuring deposition efficiency at different driving gas conditions and different spray angles using gas-atomized copper powder. It was found that the theoretically estimated results agreed reasonably well with the experimental ones. Based on the theoretical model and experimental results, it was revealed that the distribution of particle velocity resulting from particle size distribution influences significantly the deposition efficiency in cold spraying. It was necessary for the majority of particles to achieve a velocity higher than the critical velocity in order to improve the deposition efficiency. The normal component of particle velocity contributed to the deposition of the particle under the off-nomal spray condition. The deposition efficiency of sprayed particles decreased owing to the decrease of the normal velocity component as spray was performed at off-normal angle.

Keywords: Cold spraying; Deposition efficiency; Off-normal angle; Copper; Coating

1. Introduction

Cold spraying is an emerging coating technology. A coating is formed by plastic deformation of sprayed particles in a solid state during impact in cold spraying. The temperature of spray particles prior to impact is much lower than their melting point and spray materials experience little microstructure change, oxidation or decomposition [1,2]. Most metals including Cu, Al, Ni, Fe, Ti and their alloys can be deposited by cold spraying [1–11], and even cermets [3] or ceramic particles [4] can be embedded into a metal substrate to form a thin layer coating.

The velocity of a spray particle prior to impact is one of the most important parameters. It determines whether deposition of the particle or erosion of the substrate occurs on impact of a spray particle. For a given material, there exists generally a critical particle velocity resulting in a transition from erosion of the substrate to the deposition of particle. Only those particles achieving a velocity higher than the critical value can be deposited to produce a coating. The particles having a velocity lower than the critical one will lead to shot peening or erosion of the substrate. The critical velocity is associated with the properties of the spray material [1,5] and substrate [5–7]. On the other hand, the particle velocity of a material is related to the physical properties of the driving gas and its pressure and temperature in operation, as well as nozzle design of the spray gun [8–10]. The characteristics of the metal powder, such as density, particle size [8–10] and morphology [11] will influence the particle acceleration and subsequent deposition.

Most investigations on deposition behavior in cold spraying were focused on the normal approaching of spray particles with respect to the substrate surface. Practically, owing to the profile of the substrate and even surface roughness, spray particles may impact at an off-normal angle with respect to the substrate surface. As a result, particle deposition will be influenced by the off-

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normal angle as reported by Gilmore et al. [8]. Naturally, the normal component of particle velocity will be less than that of vertical impact. Because the plastic deformations of both impacting particles and substrate mainly depend on the normal component of particle velocity, the spray angle in cold spraying will influence plastic deformation through the change of the velocity components. With thermal spray, the microstructure and properties of the deposits are influenced by the off-normal angle, particularly at an angle less than 45° [12–15]. In comparison with conventional thermal spray, the particles in cold spraying are of solid state rather than molten state, so the particle velocity is more vital in cold spraying. However, there were few papers investigating the effect of spray angle on deposition behavior in cold spraying.

In this paper, the deposition characteristic of a spray particle stream with a particle size distribution was theoretically examined using deposition efficiency as a function of particle size distribution parameters and spray angle. The established model is confirmed by the experimental correlation between the relative deposition efficiency and spray angle of cold spraying.

2. Theoretical analysis

Practically, the sizes of powder particles for spray deposition are not identical and usually distribute in a wide range. When the particles are fed into a spray gas stream, the acceleration of each particle depends on its size. A small size particle achieves high acceleration, while the one of a large size achieves less acceleration. Consequently, the accelerations of spray particles by driving gas yield a velocity distribution of particle stream. Only the particle of the velocity higher than its critical one contributes to the deposition of the coating in cold spraying based on the understanding up to now. In this study, the deposition of the particles will be considered through taking account of the particle size distribution and its effect on particle velocity, along with the normal component of the particle velocity. As a first approximation, the critical velocity for particle deposition is independent on particle size and the erosion effect caused by those metallic particles with the velocities less than the critical value is neglected in this study.

The distribution of particle size can be expressed by the following Rosin–Rammler formula [16]:

$$f_m = \left\{1 - \exp\left[-\left(\frac{d_p}{d_0}\right)^m\right]\right\} \cdot 100\% \qquad (1)$$

where d_p is the particle diameter, f_m is the cumulative mass fraction of all particles with the diameter less than d_p, d_0 and m are constants dependent on the powders used and can be determined experimentally.

In the present study, we take truncation of the size range and Eq. (1) is modified as follows:

$$f_m = \left\{1 - \exp\left[-\left(\frac{d_p - d_{min}}{d_0}\right)^m\right]\right\} \cdot \left\{1 - \exp\left[-\left(\frac{d_{max} - d_{min}}{d_0}\right)^m\right]\right\}^{-1} \cdot 100\% \qquad (2)$$

where d_{max} and d_{min} are the maximum and minimum cut-off diameters of the particles, which means that the size of all particles is between d_{min} and d_{max}.

The particle velocity is obtained by numerical simulation using Discrete Phase Modeling (DPM) in a computational fluid dynamics (CFD) program FLUENT [16]. Owing to the axisymmetrical characteristic of flow in this study, a two-dimensional symmetrical model is used. The gas is taken as an ideal and compressible one. A coupled implicit method is used to solve the flow field and the result in the steady state is obtained. The standard K-ϵ turbulence model is utilized. Spray particles are introduced into the gas flow at the position of 10 mm upstream away from the nozzle throat. The initial temperature and axial velocity of spray particle are 300 K and 50 m/s, respectively. The more detailed description of simulation method has been given elsewhere [17]. All the results illustrate the change of particle velocity along the central axis of the nozzle [17].

According to the simulation results, besides particle size, the particle velocity mainly depends on nozzle geometry, particle density, standoff distance from the nozzle exit and parameters of driving gas including type of the gas, its pressure and temperature in cold spraying [17]. The particle velocity obtained by the simulation for a converging/diverging spray nozzle of a conical shape can be expressed by an empirical function [17]. Consequently, the relation between particle velocity and individual parameters, i.e. particle size, can be obtained.

Therefore, for a spray nozzle operating at a given gas condition with a particular standoff distance, the particle velocity of a specific spray material is a function of particle size. When a uniform accelerating fluid of an identical velocity is used and the wall effect of the nozzle is neglected, the particle velocity obtained is inversely related to particle diameter as far as the velocity of the fluid is larger than that of the particle. In this case, according to the simulation result, the particle velocity can be expressed empirically as follows [17]:

$$V_p = \frac{k}{d_p^n} \qquad (3)$$

where V_p is the particle velocity, k and n are the coefficients related to driving gas conditions for a certain material. For given spray conditions, k and n can be determined via numerical simulation or experiment.

When spray powder holds a certain size distribution ranging from a minimum diameter d_{min} to a maximum one