JTTEE5 15:559-562
DOI: 10.1361/105996306X146956
1059-9630/$19.00 © ASM International

Measurement and Numerical Simulation of Particle Velocity in Cold Spraying

Wen-Ya Li, Chang-Jiu Li, Hong-Tao Wang, Cheng-Xin Li, and Hee-Seon Bang

(Submitted February 27, 2006; in revised form April 27, 2006)

The velocity of cold spray particles was measured by a diagnostic system designed for thermal spray particles that is based on thermal radiation. A laser beam was used to illuminate the cold spray particles in cold spraying to obtain a sufficient radiant energy intensity for detection. The measurement was carried out for copper particles of different mean particle sizes. The particle velocity was also estimated using a two-dimensional axisymmetric model developed previously. The simulated velocity agreed well with the measured result. This fact indicates that particle velocity in cold spraying can be predicted reasonably by simulation. Therefore, it is possible to optimize the cold spray process with the aid of the simulation results.

Keywords cold spraying, measurement, numerical simulation, particle velocity

1. Introduction

In cold spraying, spray particles are accelerated to a high velocity by a supersonic gas flow that is generated through a converging-diverging de Laval nozzle. A coating is deposited through the intensive plastic deformation of solid particles impacting on a substrate at a temperature well below the melting point of the spray material (Ref 1). In this process, the particle velocity prior to the impact is one of the key parameters for a successful deposition of spray particles. It is widely accepted that there exists a critical velocity at which the transition from the substrate erosion to the particle deposition takes place for a given spray material. Therefore, to realize a sufficient deposition efficiency, a majority of spray particles have to be accelerated to a velocity higher than this critical velocity. Although some other factors, such as particle size (Ref 2), particle temperature (Ref 3, 4) and surface oxidation (Ref 4) influence this critical velocity value besides the mechanical properties of spray materials, it is still essential to understand the accelerating behavior of spray particles in cold spray.

The velocity of particles in cold spray can be experimentally measured using a laser two-focus velocimeter (Ref 5). Recently, Jodoin et al. (Ref 6) reported an optical diagnostic method to measure the cold spray particle velocity, which combines a fast-shutter CCD camera with a high-power pulsed laser diode to illuminate cold particles. However, a systematic measurement of the particle velocity is time consuming and expensive in many cases. The well-developed gas-solid two-phase flow technique based on computational fluid dynamics (CFD) method made it possible to simulate gas-solid two-phase flow precisely. The measured results by Gilmore et al. (Ref 5) and Jodoin et al. (Ref 6) agreed with their calculated results by CFD method. As a result, many numerical investigations on particle acceleration in cold spraying have been carried out by different investigators (Ref 5-13). Based on the simulation results, it has been reported that many factors influence the particle velocity in cold spray, including the geometry of the spray gun nozzle, the accelerating gas conditions, and the properties of the particle material (Ref 5-13). Although the results reported by Gilmore et al. (Ref 5) and Jodoin et al. (Ref 6) have shown that it is feasible to use CFD approach to obtain reasonable results in certain cases, it is still necessary to measure the particle velocity experimentally. Many diagnostic systems for particle velocity measurement in thermal spraying are available and are based on the thermal radiation of high-temperature particles. However, owing to the cold feature of particles in cold spraying, those systems cannot be used directly. Cold particles must be illuminated to a sufficient reflective intensity to use the system for thermal spray particles.

In this study, a measurement system of in-flight particle diagnostics developed in Xi'an Jiaotong University for thermal spray particles was used to measure the velocity of cold spray particles. This system is equipped with a laser beam to illuminate cold particles. Velocities of copper (Cu) particles of different mean sizes under different accelerating conditions were measured. The measured results were compared with the calculated values under different spray conditions. Results from the comparison can be used to validate the simulated method and to optimize the cold spray conditions.

2. Numerical Method

Numerical modeling was performed using a commercial software FLUENT (ver. 6.0, FLUENT Inc., NH) to determine the flow field of the driving gas inside and outside the nozzle, and subsequently, the accelerating and heating of particles in cold spraying. Due to the axisymmetric characteristic of the flow

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This article was originally published in *Building on 100 Years of Success, Proceedings of the 2006 International Thermal Spray Conference* (Seattle, WA), May 15-18, 2006, B.R. Marple, M.M. Hyland, Y.-Ch. Lau, R.S. Lima, and J. Voyer, Ed., ASM International, Materials Park, OH, 2006.

Wen-Ya Li, Chang-Jiu Li, Hong-Tao Wang, and **Cheng-Xin Li,** State Key Laboratory for Mechanical Behavior of Materials, School of Materials Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, P.R. China, and **Hee-Seon Bang,** Department of Naval Architecture and Ocean Engineering, Chosun University, Gwang-ju, 501, Republic of Korea. Contact e-mail: licj@mail.xjtu.edu.cn.

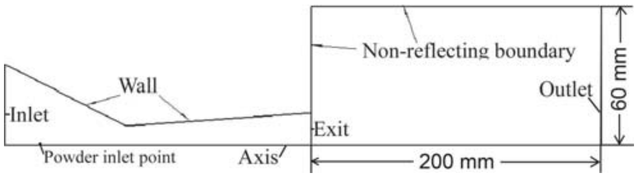

Fig. 1 Diagram of the computational domain and boundaries

in this study, a two-dimensional symmetrical model was used. The schematic diagram of the computational domain and boundaries is shown in Fig. 1. The outside domain was a cylinder of 60 mm in radius and 200 mm in length from the nozzle exit along the nozzle axis, as shown in Fig. 1.

The gas is taken as an ideal and compressible gas. The standard K-ε turbulence model is used in the simulation. The accelerating and heating of particles are computed using the discrete phase model (DPM) of FLUENT. The effect of powder feeding on the gas flow is not considered in this study. All the results illustrate the change of the particle velocity along the central axis of the nozzle. Other detailed descriptions of the simulation can be found elsewhere (Ref 12, 13).

In this simulation, spherical Cu particles having different diameters are used. The initial axial particle velocity and temperature are 50 m/s and 27 °C, respectively. The gas inlet conditions are determined by experiment. The particle velocity at the standoff distance of 20 mm is used for comparison with the measured results.

3. Particle Velocity Measurement

The diagnostic system developed at the Xi'an Jiaotong University for thermal spray particles (Ref 14, 15) was used to measure the particle velocity in cold spraying. The measurement by this system is based on the thermal radiation of high-temperature in-flight particles as reported previously (Ref 16). Due to very weak thermal radiation from the particles in a "cold" state in cold spray, the cold spray particles were illuminated using a laser beam. The laser has a wavelength of 808 nm and a CW output power of 2 W. The system setup is shown schematically in Fig. 2. In this diagnostic system, the reflected radiation of the laser by the in-flight particles is modulated by a single filtering window and the optical signal is transferred through an optical fiber. The measurement volume determined by the optical head was about 1.4 × 1.4 × 1.7 mm. The optical signal is then converted opto-electronically to an electrical signal and amplified. The signal is converted from analog to digital by an A/D converter and processed by a computer to calculate the particle velocity.

With a single filtering window modulating, the evolution of the signal peak from a cold sprayed particle can be described as shown in Fig. 3 (Ref 14, 15). The effective diameter of the image spot of the cold sprayed particle on the filtering mask plane is defined as D and the width of the filtering window as B. In the case when D is less than B, as the image spot changes positions from a → b → c → d → e → f, the effective signal intensity will change with a waveform of a trapezoid shape, as shown in Fig. 3. When the time interval (t) corresponding to the full width at half maximum (FWHM) of the signal peak is obtained, the particle velocity (V_p) can be calculated using the equation:

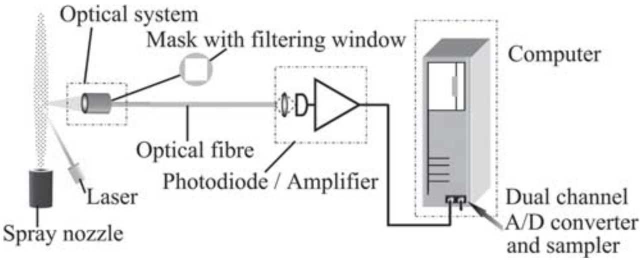

Fig. 2 Diagram of the modified setup for the velocity measurement of the cold sprayed particles with a laser

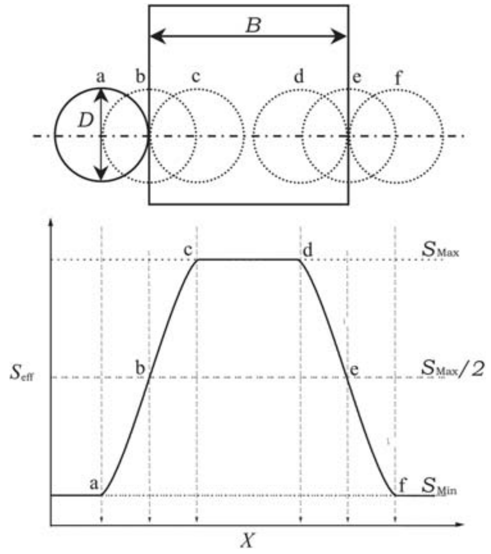

Fig. 3 Diagram of the change of the signal intensity during the image spot of a cold sprayed particle passing through the filtering window

$$V_p = M\frac{B}{t} \quad \text{(Eq 1)}$$

where M is the magnification of the lens set. For a fixed spray condition, a sufficient number of signal peaks of individual particles are obtained to estimate statistically the average particle velocity. During the measurement, signals in pulse form were recorded. After smoothing using 64 points adjacent averaging, five parameters defining a trapezoid are obtained through trapezoid fitting, that is, center position of the signal peak, widths, and heights of the upper and bottom lines of the trapezoid (Ref 14, 15). Accordingly, the FWHM of the peak was measured for the calculation of the particle velocity by Eq 1.

4. Materials and Experimental Procedure

A gas-atomized spherical Cu powder was sieved with a 400 mesh sieve to two different feedstocks, P-1 and P-2. Figure 4 shows the morphologies of these two powders. For an accurate simulation of the particle velocity, the size distributions of the Cu feedstocks were characterized by a laser diffraction sizer (MASTERSIZER 2000, Malvern Instruments Ltd., UK). Figure

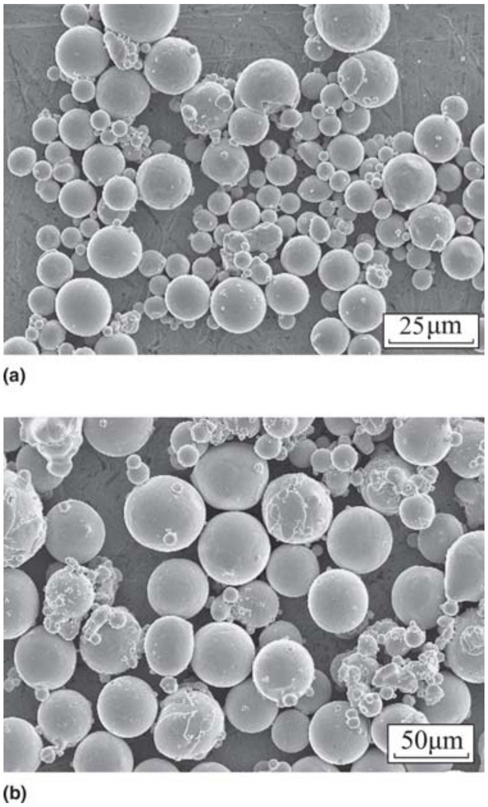

Fig. 4 Morphologies of the Cu powders used. (a) P-1. (b) P-2

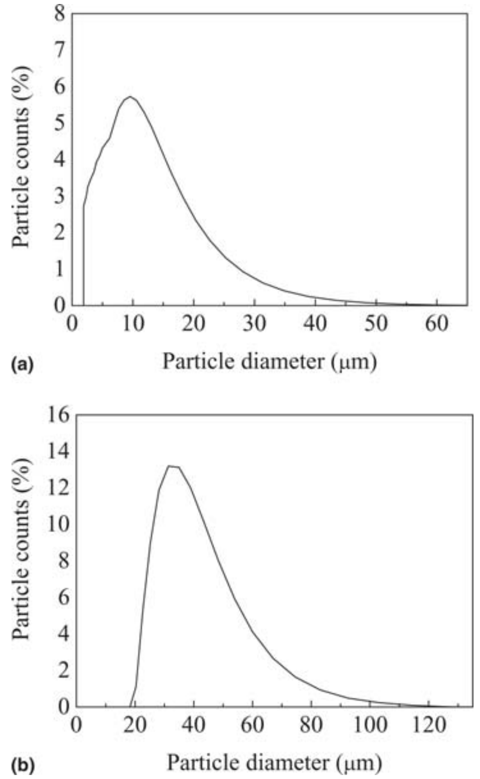

Fig. 5 Size distributions of the Cu powders used. (a) P-1. (b) P-2

5 shows the particle size distributions of P-1 and P-2. The mean particle sizes of P-1 and P-2 were 9.6 and 32.6 μm, respectively.

A cold spraying system developed at the Xi'an Jiaotong University was used to generate cold sprayed particles having a high velocity. The design of the system has been described in detail elsewhere (Ref 17). A converging/diverging de Laval nozzle of a conical shape was adopted. The inlet, throat, and exit diameters, and the convergent and divergent section lengths of the nozzle were 16, 2, 6, 30, and 100 mm, respectively. Nitrogen was used as process and powder carrier gas under different conditions. For P-1, the N_2 inlet pressure and temperature were 2 MPa and 230 °C, respectively. For P-2, the N_2 inlet pressure was 2 MPa and the temperatures were 10 and 265 °C. Velocity measurements were conducted at a standoff distance of 20 mm.

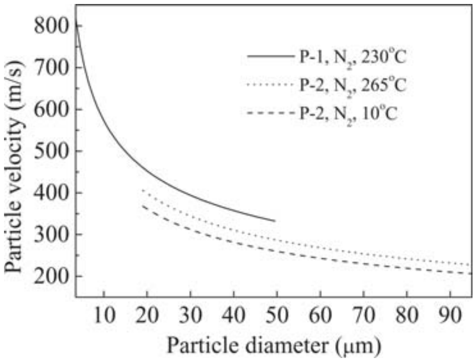

Fig. 6 Change of the particle velocity as a function of the particle size under different spray conditions

5. Results and Discussion

Figure 6 shows the changes of the particle velocity as a function of the particle size under three spray conditions obtained by simulation. It is clearly seen that the particle velocity increases significantly with a decrease in the particle diameter, especially when the particle size is less than 20 μm as for P-1 powder. This finding is similar to those reported in previous studies (Ref 12, 13). As a result, particle velocities of the P-1 powder are higher than those of the P-2 powder as shown in Fig. 6. On the other hand, for the P-2 powder, particles yield a higher velocity at an elevated gas preheating temperature, because the gas velocity increases with an increase of the gas temperature.

Velocity measurement was carried out under the same spray conditions as those used for the numerical simulation. Figure 7 shows a typical detected signal from the P-2 powder with N_2 at 10 °C and the processed result following the method reported previously (Ref 14, 15). It is found that the processed data represents a well-defined trapezoid shape waveform. The time interval corresponding to the FWHM of this signal peak is 9.43 μs. For the measurement system used, the magnification and the width of the filtering window are 2 and 1.4 mm, respectively. Therefore, according to Eq 1, this particle yielded a velocity of 297 m/s. This velocity value is reasonably within the velocity range obtained by the simulation for this spray condition of the P-2 powder, as shown in Fig. 6.

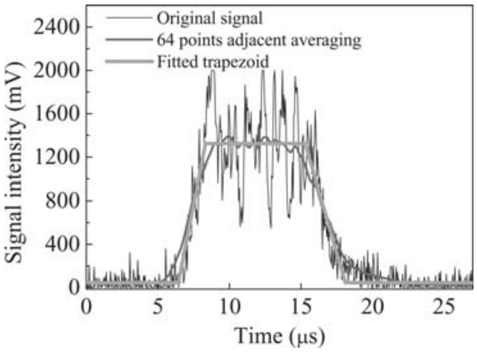

Fig. 7 Typical individual signal peak and processed results for P-2 particle under a N_2 temperature of 10 °C

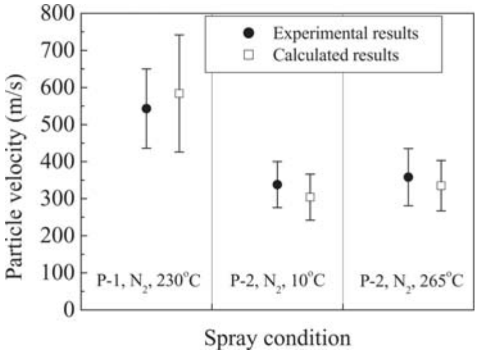

Fig. 8 Comparison of the measured velocities with the calculated results under three spray conditions

For each spray condition, more than 100 particle signals were used to calculate particle velocities. The velocity measurement results for both Cu powders are shown in Fig. 8. The spread of the particle velocity (shown as error bars in Fig. 8) at each condition is a result of the particle size distribution. The error bars of the simulated particle velocities were estimated according to the size distributions of P-1 and P-2, as shown in Fig. 5. Figure 8 shows that particle velocities obtained by simulation agreed well with the measured results for both the mean velocities and its distributions. It can be shown from Fig. 8 that as the driving gas was preheated, the average particle velocity was increased.

Results presented in this study showed that the simulation results were validated by the experiment. Gilmore et al. (Ref 5) and Jodoin et al. (Ref 6) also proved that their simulation results agreed well with their measurements. Therefore, the simulation models can be used to predict the particle velocity in cold spray. The optimization of the cold spray process can be conducted based on the simulation results for practical applications.

6. Conclusions

A laser-aided velocity measurement method for cold spray particles was developed based on a thermal radiation diagnostic system used for thermal spray particles. The measured Cu particle velocities agreed well with the calculated results using a two-dimensional axisymmetric model developed previously. Both the measurement and simulation results indicate that the particle velocity increases significantly with a decrease of the particle size and an increase of the preheating temperature of the driving gas. The proposed measurement method in this paper is reliable. It is confirmed that the particle acceleration behavior in cold spraying can be accurately predicted through the simulation method developed previously. The optimization of the cold spray process can be conducted using results obtained from the simulation method.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (NSFC) (No. 50171052) and the Doctoral Foundation of Xi'an Jiaotong University.

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