Simulation of Cold Spray Nozzle Accompanying a Water-cooling Adjustment

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Abstract

Cold spraying is a coating process which enables production of metallic and metallic ceramic coatings with dense (very low porosity level) and pure (low oxygen content) structures. Several coating applications such as corrosion resistance and electrical conductivity rely on these properties. Generally, cold spraying is based on higher particle velocities and lower process temperatures than other thermal spray processes. The coating is formed in a solid state when feedstock particles impact on a substrate with high kinetic energy, deform and adhere to the substrate or the previous deposits. Therefore a high pressure gas is usually necessary to accelerate the particles to a sufficient kinetic energy terms of velocity to obtain an intensive plastic deformation. Also, quality of the coating depends on particle size distribution and shape, gas pressure, gas temperature, gas molecular weight, nozzle shape and so on. In commercial cold spray applications where the cost efficiency is mostly considered, continuous flow of work is required. However during the deposition, the nozzle of a cold spray system operating high pressure and temperature will foul with the metallic powder causing system failure and rework removing damaged nozzle. To solve that problem number of nozzle assemblies are introduced accommodating venturi adjustments or adoption of synthetic fiber (PBI) instead of typical nozzle materials including brass, stainless steel or tool steel. In our experience based on commercial practices, a water-cooling nozzle assembly will also help to achieve to provide continuous deposition without clogging.

In this work we focus on a water-cooling convergent-divergent nozzle design and its effects on particle velocity which is the most important parameter in cold spray practice. A computational fluid dynamic (CFD) model of the cold gas dynamic spray process is presented. The gas dynamic flow fields within both typical adiabatic and water cooled de-Laval nozzles as well as in the immediate surroundings of the nozzle exits is simulated. Predicted particle velocity results at the nozzle exit are compared with experimental data which are obtained using a commercially available in-flight particle condition monitoring system. In addition details of predicted nozzle wall temperature values and particle velocities are visualized in a graphical manner.

1. Introduction

Coating technology is growing because of its important role in improving, e.g., corrosion resistance, conductivity, and other properties of material in order to decrease costs and increase service life and safety. Thermal spray processes, including flame, arc, plasma, high velocity oxygen fuel (HVOF) and cold spraying, are the techniques to produce coatings from powder or wire feedstock by spraying molten, semi-molten or solid particles on the substrate and forming the coating. Acceleration of particles can be done by several ways based on energy used: electrical (arc and plasma spraying), chemical (flame and HVOF spraying), or kinetic (cold spraying) energy [1].

Cold spraying is a relatively new spraying method, which has many advantages compared with the other thermal spraying. The advantages are high deposition efficiency, low residual stresses, minimal heat input to substrate, phase and compositional stability, and reduced need for masking [2]. Furthermore, cold spraying is a cost-effective and environmentally-friendly process, alternative to e.g., soldering, electroplating, and painting [3]. Cold spraying was developed in the former Soviet Union in the 1980´s at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences, ITAM SB RAS, (Novosibirsk, Russia). This latest thermal spray technique is based on the use of significantly lower process temperatures with high particle velocities than those present in other thermal spray techniques [2,6]. During the past decades, the trend has turned from the use of thermal energy to the use of increasing amounts of kinetic energy. This opens new advantages, e.g., pure and dense coating, formation due to the low or zero-level oxidation during the cold spray process. In addition, heat input is significantly low therefore, not changing the substrate properties, and avoiding oxidation during spraying [3,6]. The other advantages are that phase transformations caused by melting and porosity formation caused by solidification in the other methods can be eliminated by the use of cold spray process [4]. Temperature of the gas needed to provide sufficient coating op is below the melting point of the sprayed material, in this way, particles are not melted in the gas flow [5]. Figure 1 shows a diagram of gas temperatures and particle velocities in different thermal spray processes.

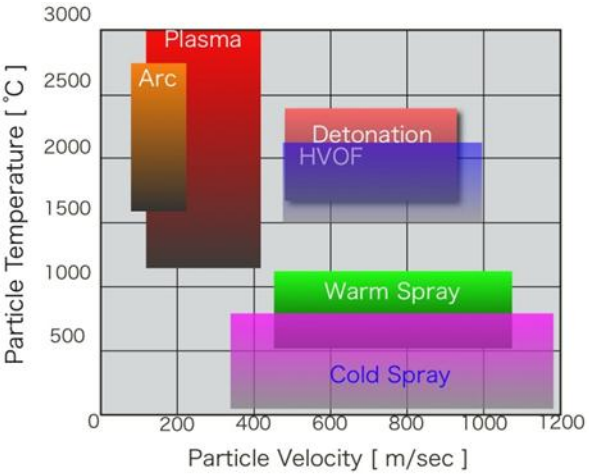


Fig.1. *Gas temperatures versus particle velocities in the thermal spray processes.*

In cold spray process, a coating is deposited through the intensive plastic deformation of solid ductile particles impacting on a substrate at a temperature well below the melting point of spray material. As shown in figure 2, the supersonic jet is generated through a converging-diverging de-Laval nozzle. Spray particles are feed axially from the back of the spray gun. The operating temperature and the pressure of the accelerating gas are monitored by thermocouple and pressure gauge mounted on the spray gun. As a result, phenomena inherent to thermal spray at high temperatures, such as oxidation and phase transformation are avoided in cold spraying [7]. Formation of a cold-sprayed coating depends on the velocity of powder particles. Each material has a specific critical velocity. Above the critical velocity particles adhere to the substrate, causing plastic deformation and formation of the coating, whereas at velocities lower than critical velocity only erosion and particle rebounding occur without coating building up [6]. Furthermore, higher velocity leads to stronger deformation and therefore coating structure becomes denser and mechanical properties are improved [8]. However, in many commercial applications, increasing particle temperature results with the clogging of cold spray gun nozzle. Many different nozzle assemblies have been introduced in the prior art. Despite efforts, most of the state-of-art designs fail to provide a cold spray nozzle assembly that is commercially feasible. There are number of cold spray gun nozzle assemblies are available on the market. In this present paper, a water-cooling cold spray nozzle design and its effects on the particle velocity is investigated and compered with a typical adiabatic nozzle assembly concerning both numerical simulation and experimental data.

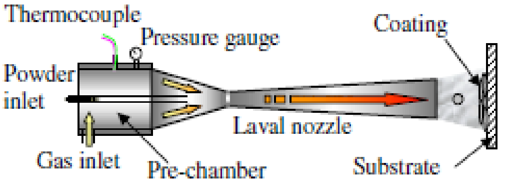
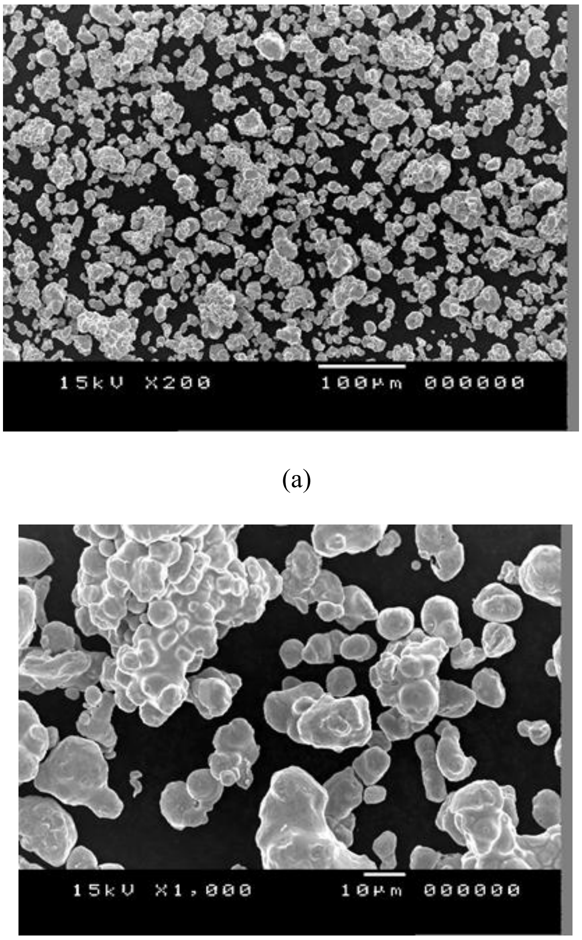


Fig.2. *Schematic diagram of cold spray gun.*

2. Experimental procedure

Three sets of parameters are involved in this study: powder structure, geometry of the spray gun nozzle, driving gas conditions.

Owing to commercial availability of Copper particles, in this study copper particles diameters ranging from 5 to 45μm are used. The morphology of the powder is presented in Figure 3. The powder size distribution was characterized by laser diffraction particle size analyzer (Seishin Trading Co., Ltd. Kobe, Japan). The volume and number distributions of diameters are shown in Figure 4. The volume average diameter is about 30 μm, and the number average diameter is about 18 μm. In this study, a commercial cold spray system called PCS-305 designed by PLASMA GIKEN CO. LTD. was used to obtain experimental results. PLASMA GIKEN’s PCS-305 system enables the use of pressure as high as 5 MPa and preheating chamber gas temperature of max 1000°C. The system included gas pressure regulators, gas preheater, powder feeder and spray gun. The gun developed by Plasma Giken Co. Ltd was used in this experiment as well, it employs prior art water-cooling, converging–diverging nozzle which allow the particles to reach the high velocities required in the process. Water-cooling nozzle is shown in Figure 5. This cold spray nozzle assembly includes a tubular set up is connecting to converging and



(a)

(b)

Fig.3. *Micrograph of Cu powder morphology.*

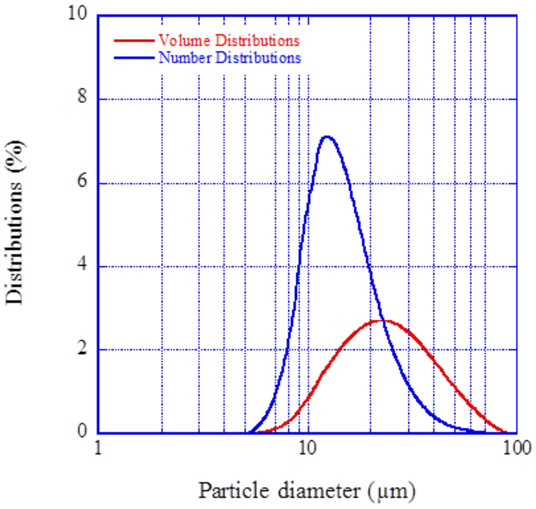


Fig.4. *Size and distribution of Cu powder.*

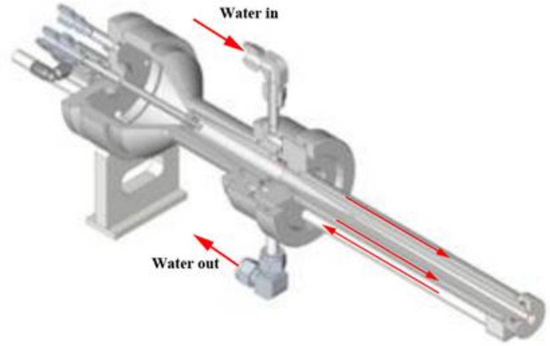


Fig.5. *Water-cooling cold spray gun nozzle.*

diverging portions interconnected at a throat. A water pump is supplying coolant and lets it circulate through the tubular set up placed outer walls of nozzle. This modification provides median reduced temperature of both inner and outer walls of the nozzle. As a result, temperature adjustment helps particles travel at high velocities without adhering to the walls of the nozzle. In the current study, nitrogen gas is used as the propellant; the pressure was set to 3MPa and temperature ranged from 200°C to 1000°C.

Particle velocities were measured with DPV-2000 and CPS-2000 system (Tecnar Automation Ltd., St-Bruno,Québec, Canada), a commercial laser in-flight diagnostic system commonly used in thermal spray particle diagnostic. While a continuous laser (laser diode power of 3 W) illuminates an interrogation volume (of approximately 4mm radius), a dual-slit photomask captures the signal generated by individual particles passing in front of the sensor. The signal from the photosensor is amplified, filtered and analyzed. In-flight diagnostic of each individual particle that crosses the interrogation volume is performed by determining the time between the two peaks of the particle signal. Particle velocities are then obtained by dividing the distance between the two-slits by their time of flight. Furthermore, no substrate was positioned in front of the spraying gun since the resulting coating build-up would quickly mask the interrogation region [7]. In this study, the velocity measurements were taken at a point 30 mm from the spraying gun exit; which is far enough away so as not to affect the solution of the flow field.

The dimension for the simulation is base on the system of PCS-305 manufactured by Plasma Giken Co. Ltd. To simulate the flow field of driving gas inside and outside of nozzle, and consequently accelerating and heating of particles, FLUENT 12.01(ANSYS,Inc.,Canonsburg, PA), computational fluid dynamics (CFD) software is used. Models describing the dynamic and thermal behavior of in-flight particles during the two-phase flow have been well documented in the FLUENT manual [9].

3. Results and discussions

3.1. Grading Simulation and Experimental Results

Figure 6 shows the comparison of particle velocity obtained by DPV-2000 and FLUENT adjustments using water-cooling nozzle at the standoff distance 30mm, at a gas pressure of 3 MPa and gas temperatures ranging from 200°C to 1000°C. Considering the limit of the DPV-2000 to measure the cold particle, the particle diameter cannot be measured correctly, thus the number average velocity was argued instead of the volume average velocity. The particle diameter of copper for the numerical calculation was set to 20 µm in order to match with the copper powder size 5-45 µm used to obtain experimental results. The powder particle size and morphology has been confirmed to be an important factor influencing particle velocity. The particle can be accelerated more easily with the decrease in particle diameter and a more irregular shape [10]. Therefore, owing to relatively fine particles used in the experiment, particle velocities of simulation is little lower than experimental values. It can be clearly seen that the simulation and experiment have the similar tendency of particle velocity increasing with the increase of gas temperature.

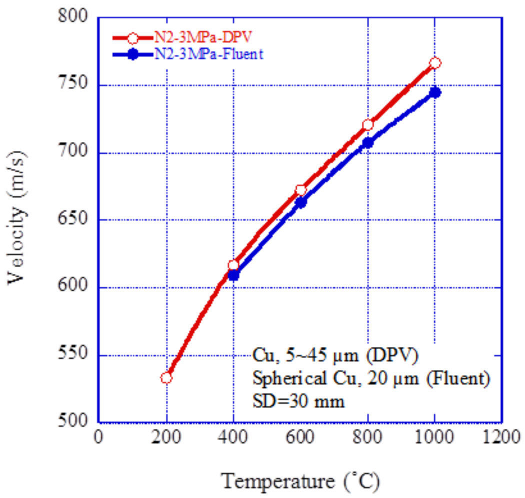


Fig.6. *Average particle velocity obtained by DPV-2000 and FLUENT.*

Figure 7 reveals the effect of standoff distance on particle velocity using nitrogen as the accelerating gas at the pressure of 3 MPa and the temperature of 600°C. It is seen that for the experimental results, there exits an optimal value of standoff distance for the maximum acceleration of particles. On the other hand, this optimal value measured is not same for the values calculated with the numerical methods. As shown in figure 7 gas velocity keeps increasing according to the numerical calculation after leaving the nozzle while the experimental results indicates a decrease upon the standoff distance of 80 mm.

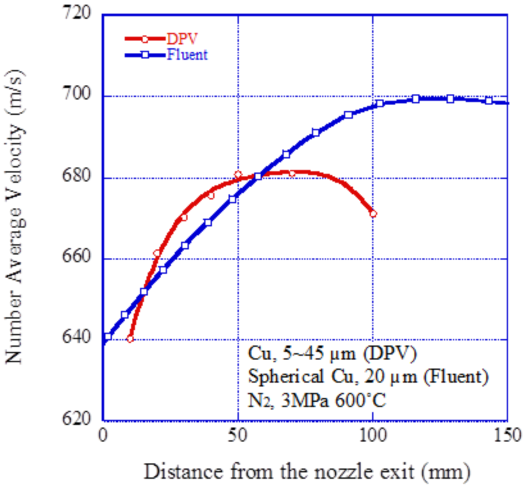


Fig.7. *Effect of standoff distance on particle velocity.*

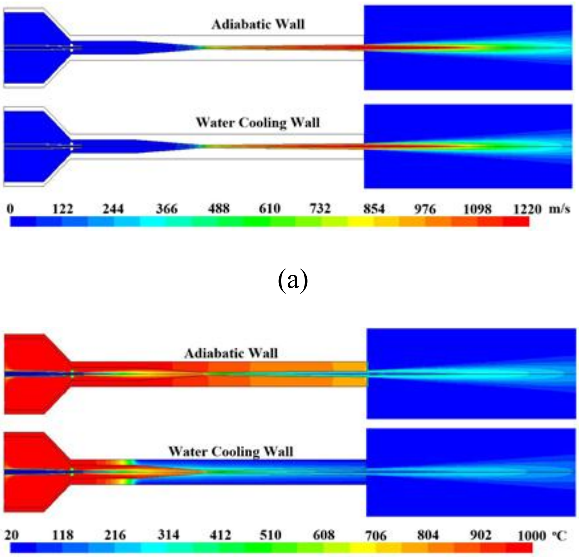
The results show that the computational model can provide a satisfactory prediction of the supersonic gas flow, which is consistent with the experimental and can meet the needs of this study.

3.1. Effect of water-cooling cold spray nozzle gun design on particle velocity

The gas velocity and temperature distributions calculated are shown in the figure 8 under the conditions of 3 MPa gas pressure and 1000°C gas temperature. It seems that there is no significant difference of the gas temperature and velocity distributions between the typical adiabatic nozzle and the water-cooling one in spite of the lower boundary temperature of the water-cooling nozzle wall compared with the adiabatic wall.

In addition, figure 9 shows the radial distributions of gas velocity and temperature including the thick wall temperature under the conditions of 3 MPa gas pressure and 1000°C gas temperature as a function of distance from the axisymmetric center of the nozzle. It can be seen that the gas velocity calculated at the four typical cross-sections of de-Laval nozzle, presents almost no tendency to change due to the significantly lower temperatures of the water-cooled nozzle wall. Although the gas temperature shows a substantial drop at the boundary of nozzle wall, it has no considerable effect on gas velocity.

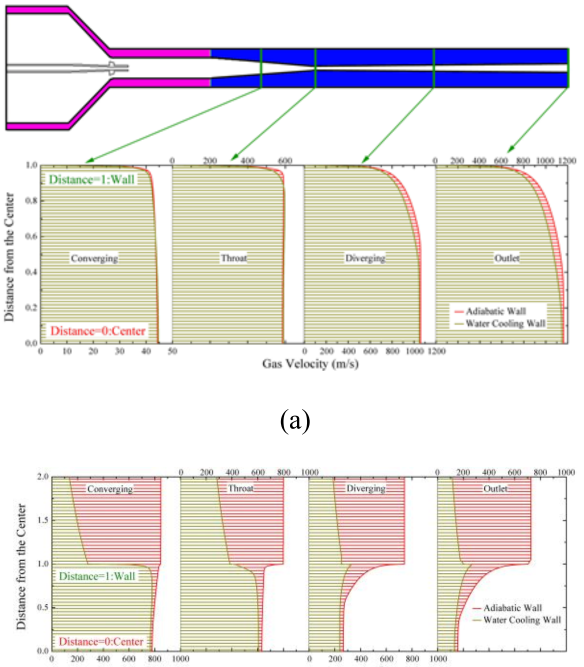
Figure 10.a presents the velocity of the accelerating gas and the particle at the axisymmetric center of adiabatic and water-cooling nozzle designs. It is Seen that the acceleration of the particle and gas



(a)

(b)

Fig.8. *Distributions of Gas velocity (a) and temperature (b) under the conditions of 3 MPa, 1000°C.*

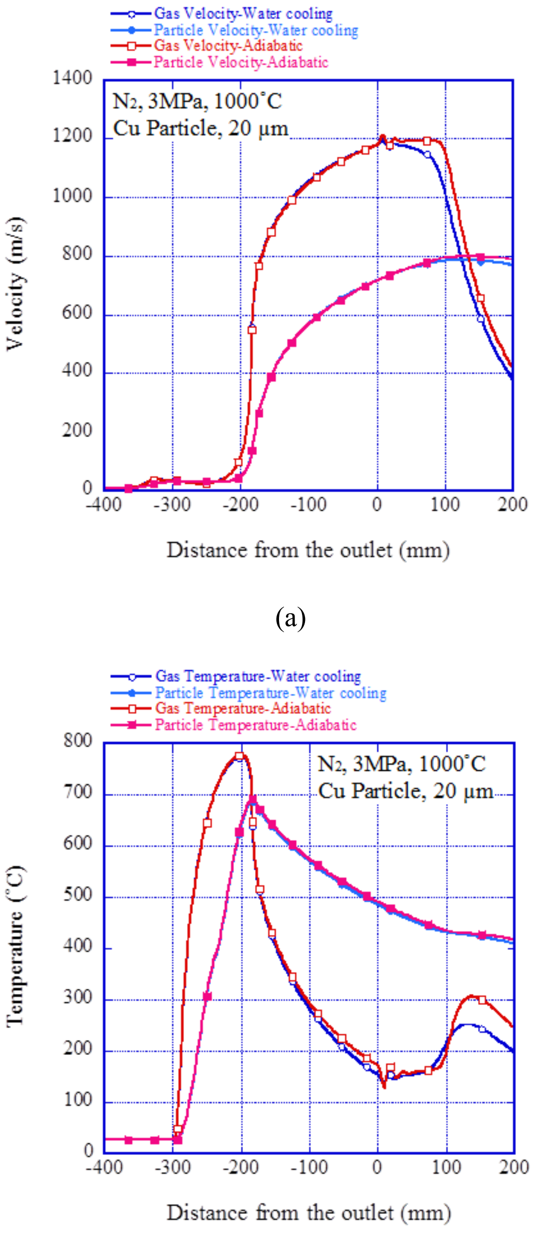


(a)

(b)

Fig.9. *Gas velocity (a) and temperature (b) of the radial distributions at different locations inside the nozzle.*

velocity takes place in the area of the nozzle throat, and it increases and reaches a maximum value at the nozzle exit of both adiabatic and water-cooled designs. In-flight particle velocity values exhibits similarities in both assemblies; however gas velocity at the water-cooling nozzle shows a negligible cutback compared with the adiabatic nozzle. In consistent Figure 10.b. shows that the particle temperature in typical adiabatic nozzle is almost identical with water-cooling nozzle; it starts to decline with the increasing of distance from throat. In consistent with the gas velocity value presented in figure 10.a, in-flight gas temperature in the water cooled nozzle stands lover than adiabatic nozzle starting from a distance of 10 mm from the nozzle exit.



(a)

(b)

Fig.10. *Velocity (a) and temperature (b) of particle and gas at the axisymmetric center.*

3. Conclusion

A two-dimension asymmetrical model was employed in velocity and temperature of gas and particle simulation of a water-cooling and typical adiabatic cold spray gun nozzle. In addition, particle velocity was measured using DPV-2000 system. The flow in the predicted profiles along both particle velocity and temperature match well with the experimental results. Based on the validity of the calculations, the effect of water-cooling process is simulated and it was found that it has no significant diverse effect on particle velocity which is considered to be the most important parameter in particle deposition. According to our practical commercial experience and know-how in the cold spray equipment field, reducing the temperature of the nozzle wall helps particles not to adhere to nozzle wall and prevents it from clogging. Considering the results presented at this paper, further studies can be conducted to produce many other modified assemblies which employ cooling of the nozzle wall.

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