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Short communication

Influence of powder injection point position on efficiency of powder preheating in cold spray: Numerical study

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ABSTRACT

Cold spray is a material deposition technique based on the high velocity particle–substrate impact. The last researches in this field show that efficiency of deposition depends not only on the particle impact velocity but also on the impact temperature. In order to control the particle impact temperature, a special powder preheater installed between the powder feeder and the nozzle could be applied. In the current paper, an influence of powder preheating on the particle impact parameters is numerically studied. Two cases with powder injection to subsonic and supersonic regions of the nozzle are considered. It is shown that artificially preheated 10–50 μm copper particles axially injected to the supersonic region of the nozzle have higher impact temperature than the particles injected to the nozzle prechamber. This effect could be explained by the dependence of duration and intensity of gas–particle heat exchange on the location of powder injection point. It was also shown that in the case of powder injection to supersonic zone, the application of powder preheating could shift the particle impact parameters towards the deposition window without increasing the working gas stagnation temperature.

1. Introduction

Cold spray is a method of coating deposition using powders in solid state. In this process, the particles of powders are accelerated by the gas flow in a converging–diverging nozzle. During high-velocity (400–1200 m/s) impact with the substrate, the powder particles undergo significant plastic deformations and bond to the substrate that leads to coating formation [1]. It is known from the literature that the particle could bond to the substrate if their impact velocity is higher than the so-called critical velocity. In accordance with results published in [2], the critical velocity could be estimated using the following equation:

$$v_{crit} = \sqrt{\frac{4F_1\sigma_{TS}\left(1-\frac{T_i-T_R}{T_m-T_R}\right)}{\rho_p} + F_2c_p(T_m-T_i)}.$$

Here T_i is impact temperature, T_R is reference temperature (273 K), c_p and ρ_p are particle heat capacity and density, σ_{TS} is particle tensile strength, and F_1 and F_2 are empirical constants. One can see from the equation that the critical velocity depends not only on material properties of the particle but also on particle impact temperature. Therefore, the conditions favorable for particle bonding could be achieved not only by increasing the impact velocity but also by augmenting the impact temperature. Taking into account this equation, a parametric deposition window could be developed for any given type of spraying material [3]. In other words, the same powder could be deposited at higher velocity but lower temperature or inversely, at lower velocity and higher temperature. Schematically, the deposition window is presented in Fig. 1 [3]. It is also important that deposition efficiency and coating properties depend on what region of the deposition window the particle impact parameters are placed. In particular it is known that in order to reach high deposition efficiency and high coating strength, the particle impact parameters should lay fairly above the line of the critical velocity [3].

Technologically, the particle impact velocity and temperature are defined by type of working gas, gas stagnation temperature, gas stagnation pressure and nozzle geometry. Gas pressure in cold spray typically varies in the range between 0.6 MPa (low-pressure systems) [4] and 5.0 MPa (high pressure systems) [5] depending on the type of spraying material. High pressure systems permit to accelerate powders to higher velocities due to higher density of the working gas flow and therefore higher drag coefficient and possibility to apply nozzles with high exit Mach number. Using helium as a working gas permits to perform efficient cold spray deposition at a relatively low gas stagnation temperature due to high sonic speed in helium and therefore high absolute outlet velocity at the exit of supersonic nozzle [6]. However, the usage of helium is limited due to its high cost and therefore other working gasses such as nitrogen and air are widely applied for cold spray deposition. Sonic speed in nitrogen is significantly lower than that in helium, and therefore to achieve particle deposition at a favorable velocity–temperature range the gas heating is applied [1]. Typical range of gas stagnation temperature lies between 100 °C and 1000 °C. It is important to note

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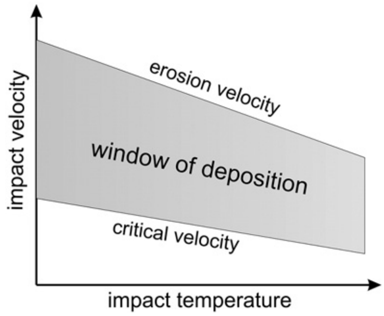

Fig. 1. Schematic illustration of parametric cold spray deposition window dependent of particle impact velocity and temperature.

that gas heating plays two roles. Firstly, increasing the temperature increases gas flow velocity and consequently augments particle impact velocity. Secondly, increasing the gas temperature permits to increase particle impact temperature that also leads to amelioration of bonding conditions.

Besides the gas flow parameters, the particle impact conditions could be controlled also by location of powder injection point. Injection of powder in cold spray nozzle could be performed in subsonic [7,8] and supersonic parts [8,9] coaxially or radially.

1.1. Injection to subsonic zone

In the case of injection to subsonic zone of the nozzle, the fluidized powder is caught up by room-temperature carrier gas from the feeder, also kept at room temperature, and injected coaxially to the subsonic region of the nozzle (nozzle prechamber). Due to high intensity of heat transfer between particles and hot high-density subsonic working gas flow, the particle temperature rapidly increases and, if the length of prechamber is enough, reaches the value of the static gas temperature in prechamber [3]. After that, the heated particles are carried by the gas flow to diverging (supersonic) region where their velocity increases but the temperature drops down following the diminishing of the gas static temperature. However, the particles "preserve" some amount of the heat captured in subsonic nozzle area and their impact temperature still higher than the gas static outlet temperature but at the same time lower than the gas stagnation temperature or the particle temperature in prechamber [3]. It is important to note that the key factors permitting the particles not to cool down dramatically in supersonic zone have low time of residence in the diverging zone and low Nusselt number of the particles accelerated in supersonic gas flow [10]. Therefore, the main advantage of injection to prechamber is the possibility to increase the particle impact temperature due to intensive heat exchange interaction with working gas in prechamber.

The main technological disadvantage of prechamber injection is the necessity to keep the stagnation pressure of the carrier gas flow higher than the static pressure of working gas in nozzle prechamber. Therefore, specially developed high-pressure powder feeders have to be applied.

1.2. Injection to supersonic zone

In the case of injection to supersonic zone of the nozzle, the outlet of the powder injection tube is placed coaxially or radially in the diverging part of the nozzle. An important advantage of such type of injection is that the static pressure in the point of injection is significantly lower than that in the nozzle prechamber and therefore application of convenient low-pressure feeders is allowed.

However, it is known that spraying of relatively hard metals as steels and titanium demanding severe impact conditions to create a bond with substrate cannot be performed by cold spray systems with powder injection to supersonic region. Typically, this fact is explained by shorter accelerating path of the particles injected in supersonic region in comparison with subsonic injection case. However, it is important to note that the particle impact temperature in the case of injection to supersonic zone is also significantly lower, that was clearly demonstrated in [10]. In particular it was shown that in this case particles are injected in zone with low gas static temperature that, in combination with low residence time and low Nusselt number, leads to poor changing of particle temperature.

1.3. Powder preheating before injection

In order to increase particle impact temperature, the artificial powder preheating before injection to the gas flow could be applied. In this case, an additional preheater between powder feeder and nozzle prechamber is mounted (Fig. 2). For example, in [11] and [12], authors developed a special cold spray system where the particles of WC–Co are preheated during movement from the powder feeder to the nozzle injection point by hot carrier gas. In this work, injection was performed in subsonic region and the carrier gas stagnation temperature was at 500 °C, whereas the working gas stagnation temperature was at 600 °C. Authors mentioned that without artificial powder preheating, the deposition did not occur at the same spraying parameters. It is important to note that the temperature of powder preheater was lower than the gas temperature in the nozzle prechamber and preheating was made only to facilitate following powder heating in subsonic region of the nozzle by working gas.

One can suggest that in the case of powder injection to subsonic region, the artificial powder preheating to the temperatures higher than the gas stagnation temperature in nozzle prechamber is not effective. Due to intensive gas–particle heat exchange in subsonic zone the particles lose the "excess" of the heat accumulated in preheater and their temperature gets to the balance with static temperature of the gas flow in prechamber. However, one can suggest that in the case of injection to supersonic region, the preheated particles could preserve this additional temperature more efficiently and therefore their impact temperature will be higher.

The aim of the current paper is to estimate the influence of the type of powder injection on the efficiency of artificial powder preheating before injection and therefore on particle impact parameters using numerical simulation methods.

2. Numerical simulation method

2.1. Models

At present, mainly two types of numerical simulation methods are applied for simulation of gas/particle biphasic flow in converging–diverging nozzle and free jet. The first type is the one-dimensional simulation of gas flow parameters based on application of isentropic equations [13]. In some cases, additional equations describing the behavior of boundary layer are added to the system of isentropic equations in order to take into account the viscosity of the gas flow resulting in the rise of the thickness of boundary layer near the nozzle walls [14]. After definition of parametrical flow field of the gas flow, the particle velocity and temperature are calculated using a Lagrangian approach (one way

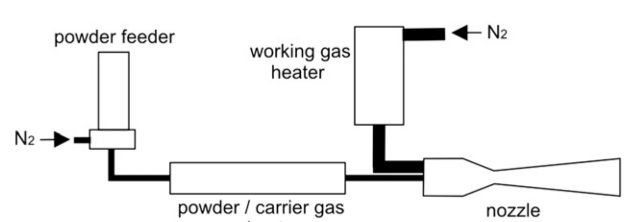

Fig. 2. Schematic of cold spray equipment with additional powder preheating.