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Strong effect of carrier gas species on particle velocity during cold spray processes

Xinkun Suo [a], Shuo Yin [a,b,*], Marie-Pierre Planche [a], Taikai Liu [a], Hanlin Liao [a]

[a] IRTES-LERMPS (Laboratoire d'Etudes et de Recherches sur les Matériaux, les Procédés et les Surfaces), Université de Technologie de Belfort-Montbéliard, Site de Sévenans, 90010 Belfort Cedex, France

[b] School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, Liaoning, China

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ABSTRACT

This study is a comprehensive investigation into the effect that the carrier gas species has on particle velocity during cold spray processes. Numerical simulations were the main method adopted to achieve this objective. A computational fluid dynamics (CFD) model was developed to predict the gas flow and particle velocity both inside and outside the nozzle. This model was experimentally validated and agreed well with the measured data. The carrier gas species was an important factor of the particle velocity. For an air propellant gas, using helium as the carrier gas increases the particle velocity due to the low average molar mass of the mixed propellant gas. Similarly, increasing the helium carrier gas pressure increases the molar fraction of helium in the mixed propellant gas and, thus, the particle velocity.

1. Introduction

Cold spray is an emerging coating technology in which a high pressure and temperature propellant gas (also called main gas) is accelerated through a de Laval nozzle. Powder particles are injected into the nozzle by a carrier gas and then accelerated by a propellant gas. This new coating technique can minimize the adverse effect caused by a molten or semi-molten state and provides the possibility of coating oxygen-sensitive materials; therefore, it has attracted interest from the industrial community. The existence of a material-dependent critical velocity for given conditions (e.g., specific particle size, temperature and material properties) above which bonding at the particle/substrate or interparticle interfaces forms a dense coating due to intensive plastic deformation has been widely accepted [1–3].

Therefore, because the particle velocity prior to impact plays a significant role, much effort over the past few years has been devoted to study how the working parameters affect the particle velocity [4–9]. A large body of work has reported that increasing the propellant gas temperature or pressure increases the particle impact velocity [10–12]. Furthermore, using helium as the propellant gas improves the particle acceleration and impact velocity due to its low molar mass; however, it always costs too much [13,14]. To lower the high cost of helium while guaranteeing a high particle velocity, Irissou et al. attempted to use an air and helium mixture as the propellant gas and found that the particle impact velocity gradually increases with the helium volume percentage [15].

The effect of the carrier gas on the particle acceleration and coating formation has recently attracted increasing attention from researchers. Higher carrier gas temperatures normally contribute to the particle deposition and coating formation due to heat effects on the powders before spraying [16–18]. More recently, the effect of carrier gas pressure was numerically studied by Tang et al., who reported that the particle velocity decreased with increasing carrier gas pressure [19]. Despite these studies provide meaningful conclusions regarding the carrier gas properties, we noticed that they all considered the same carrier and propellant gases. Therefore, the current work pays special attention to the effect of the carrier gas species on the particle velocity. The effect of the carrier gas pressure was also investigated, but the carrier gas species differs from the propellant gas species.

2. Numerical methodology

2.1. Computational domain and boundary conditions

Numerical simulations using the commercial software ANSYS-FLUENT 14.5 were performed to predict the gas flow and particle velocity. A commercial MOC nozzle (CGT GmbH, Germany) with the dimensions listed in Table 1 was used in this study and exactly matched the real gun in the experimental validation test. A two-dimensional axi-symmetric model was used to save computational time. A schematic of the computational domain, the corresponding boundary conditions and selected local grids are shown in Fig. 1. The injector outlet was 20 mm downstream from the propellant gas inlet. The computational

* Corresponding author at: IRTES-LERMPS, Université de Technologie de Belfort-Montbéliard, Site de Sévenans 90010, Belfort Cedex, France. Tel.: +33 3 84 58 37 36; fax: +33 3 84 58 32 86.

E-mail address: s.yin1984@hotmail.com (S. Yin).

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Table 1
Nozzle dimensions used in this study.

Configuration	Dimensions, mm
Gas inlet diameter	18.2
Particle inlet diameter	2.0
Convergent length	54.0
Throat diameter	2.7
Divergent length	120.0
Outlet diameter	6.0

Table 2
Working conditions used in the simulations.

	C1	C2	C3
Carrier gas species	Air	Air, argon, helium	Helium
Powder material	ZK61	ZK61, copper	ZK61, copper
Propellant gas pressure, MPa	2.750	2.800	2.800
Propellant gas temperature, K	673, 823, 873	873	873
Carrier gas pressure, MPa	2.800	3.000	2.850, 3.000
Carrier gas temperature, K	300	300	300
Particle size, μm	58	30	30

domain was meshed into 123,500 quadrilateral cells to obtain a grid-independent solution. The grids in certain key regions were refined to guarantee the computational accuracy. The working parameters for the different cases are given in Table 2.

2.2. Gas and solid phases

Air, helium and argon were considered for the gas phases. The ideal gas law was used to calculate the gas density and account for compressibility effects. A steady-state, density-based, implicit solver was used to solve the flow both inside and outside the nozzle due to its better performance at solving supersonic flows. To accurately capture the turbulent flow features both inside and outside the nozzle, the re-normalized group (RNG) k-ε turbulence model was combined with the standard wall function for the near-wall treatment. The species transport equation was activated to characterize the heat and mass transfer between the different species. A second-order upwind discretization scheme was applied to the flow and turbulence terms.

Spherical magnesium alloy (ZK61) and copper particles were used as the solid feedstock. The trajectory of these particles was computed using discrete phase modeling (DPM), which requires the discrete phase to be present at a sufficiently low volume fraction. Both particle–particle interactions and the effect of particles on the gas phase were disregarded due to the low powder particle volume fraction during the cold spray process (solid phase volume fraction < 10%). The spherical drag law was used to compute the particle drag force. A detailed equation governing the particle motion can be found elsewhere [6,12,14,20]. Moreover, the turbulence-induced particle dispersion was accounted for using the Stochastic-Tracking model available in ANSYS-FLUENT. This approach uses the discrete random walk (DRW) model to predict the fluctuating components in the total particle velocity and their effects on the trajectory. Computing the path a sufficient number of times can realistically predict the random effects that turbulence has on the particle dynamics. For each computation, 240 particles were released from the injector exit into the nozzle, and the mean velocity was calculated at a cross-section 30 mm downstream from the nozzle exit using MATLAB code (MathWorks Inc.) developed in-house.

3. Results and discussion

3.1. Experimental validation of the numerical model

The numerical model was validated by comparing the in-flight particle velocity experimentally measured outside the nozzle using a DPV 2000 system equipped with a CPS (Technar Ltd, Canada) to the numerically predicted result for 30 mm from the nozzle exit. A detailed description of the measurement procedure can be found elsewhere [21]. Spherical ZK61 powders (TangShan WeiHao Magnesium Powder Co., Ltd, China) ranging from 34 to 93 μm and averaging 58 μm in diameter were used as the experimental feedstock. For the numerical model, the average diameter, 58 μm, was used to best fit the experimental condition. The same working conditions (C1) were used in both the experiment and the simulation. Fig. 2 compares the measured particle velocity with the predicted one. As indicated, the numerical data matches the measured data well, with a tolerable error below 8%. Both results exhibited the same upward trend with increasing propellant gas temperature. This positive comparison suggests that the numerical model used in the current work reliably predicts the particle velocity.

3.2. Effect of carrier gas species on particle velocity

The C2 working conditions were used in this section. Fig. 3 shows the ZK61 and copper particle velocities as a function of the carrier gas species. A significant difference can be observed for the different carrier gases. Specifically, helium exhibited the highest velocities of the three gases, followed by air, and the lowest velocity was provided by argon.

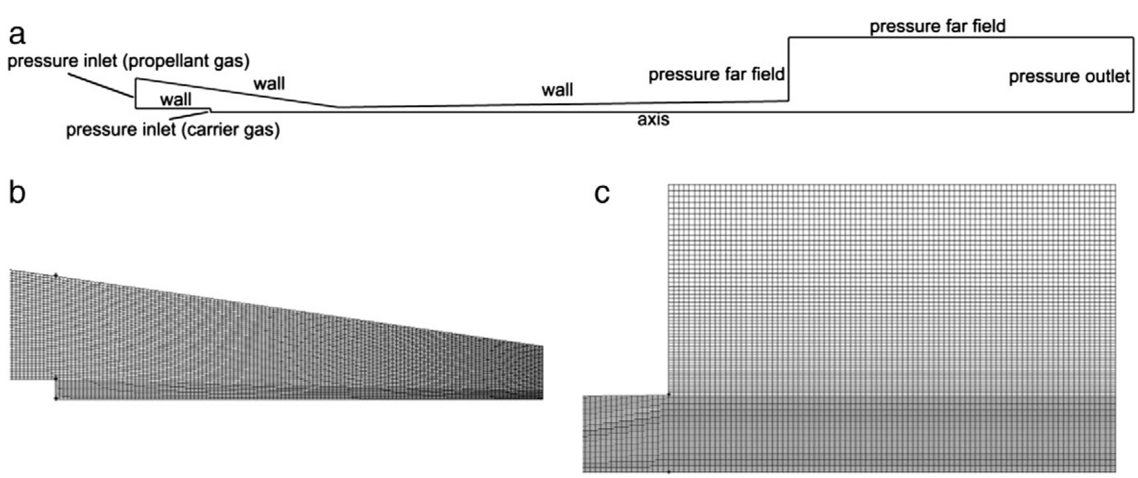

Fig. 1. Schematic of the (a) computational domain and the corresponding boundary conditions, (b) local grid at the divergent section and (c) local grid at the free jet region.