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Feed rate effect on particulate acceleration in Cold Spray under low stagnation pressure conditions

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ABSTRACT

Cold Spray (CS) is an emerging coating process, which is attracting the interest of research and industry due to its rapid solid-state particle deposition mechanism and the advantages over conventional high temperature spray technologies. The acceleration of solid particles by means of a gas flow expanding to supersonic regimes is critical to process efficiency; previous studies rarely address the particle feed rate as an influential parameter for the acceleration. Higher particle feed rates typically result in high solid volume fractions in critical areas of the supersonic nozzle, such as at the throat cross-section. In this study, Particle Image Velocimetry (PIV) was employed to study the feed-rate relationship with particle velocity in CS at low stagnation pressure conditions. The experimental observations were compared against a 2D–axisymmetric Eulerian–Lagrangian model using ANSYS-Fluent v14.5. It was experimentally found that the mean particle velocity in the jet decreases with increasing particulate loading. Moreover, the particle velocity distribution depends on the particle material and shape. It was therefore possible to evaluate the effect of particle loading on exit-nozzle particle speed, and simulate this using Computational Fluid Dynamics (CFD).

1. Introduction

Cold Spray (CS) is a coating manufacturing process, in which a feedstock material in the form of powder is deposited onto a substrate by means of high velocity impacts. The micron–sized powder particles ($5-100\ \mu$m) are accelerated to velocities ranging from 300 to 1200 m/s by an expanding process gas in a supersonic de–Laval nozzle. As the process makes use of the high kinetic energy of the particles rather than their thermal energy, it allows for very low temperature levels compared to other coating technologies and eliminates or minimizes the disadvantages of melting such as thermal distortion and Heat Affected Zones (HAZ). Hence, it provides a possibility to coat oxidisation–sensitive materials and material combinations with different melting temperatures [1,2]. It is generally accepted that for deposition to occur, a critical impact velocity must be crossed. This represents a threshold value that makes the particle acceleration a critical aspect of the technology [3,4]. Each material is characterized by a specific critical speed level.

Both experimental and numerical studies on the two–phase nozzle flow were conducted in the past decades, yielding to the main parameters for gas and particulate acceleration. Primarily, the gas stagnation pressure and temperature [5,6], the gas species [7,8] and the powder injection conditions [9,10] are important. Another critical parameter is the particle material and size, as the larger and heavier particles are less susceptible to the flow, having a much higher characteristic reaction time [11–13] whereas the particle shape is connected to the drag coefficient [14,15].

With the objective of analysing the gas and particle dynamics, different optical measurement techniques were employed in CS. Schlieren photography was frequently used to visualise the flow features. Only resolving the density gradients of the gas phase however impedes quantification of the velocity and particle motion [8]. Therefore, non–intrusive velocity measurement techniques were used, firstly by Gilmore et al. [16] who recorded the particle velocity by a *laser-two-focus* (*L2F*) apparatus and, inter alia, could observe a particle feed rate link to exit velocity. Due to the low spatial resolution and precision of L2F, many researchers subsequently concentrated on *doppler picture velocimetry* (*DVP*), which is described in detail in [17] and is used for small particle densities, such that the particle loading effect was not of interest. *Particle image velocimetry* (*PIV*) or similar techniques, such as tracking techniques, could be used to record instantaneous particle velocity distributions throughout the field of measurement without any scanning procedure. As a result, several researchers facilitated results based on a single–frame triple–pulse particle tracking technique [18–21]. In particular, Pardhasaradhi et al. [22] used this approach to measure the particle exit speed of different nozzles under varying conditions. It was found that the effect of the particle loading had a

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negligible counter-effect on the particle dynamics within the scope of measurement, attributed to a low mass fraction of the discrete phase. Nevertheless, depending on the particle feed rate and the relative gas consumption, the discrete phase loading can increasingly affect the acceleration process at higher feed rate levels. Samareh et al. [20] measured this in terms of a particle velocity decrease due to increased particle loading and a corresponding change in gas flow features in the jet. This could be assessed by an Eulerian-Lagrangian computational approach. However, the influence of other factors, such as material properties, particle shape, particulate mass distribution, were not reported. Accordingly, a study by Lupoi [23] showed that a number of experimental observations with various nozzle geometries could not be explained by the most widely used 1-way coupling CFD techniques. An improvement of the computations was shown to be achievable when increasing the detail of phase coupling for such experiments by Meyer and Lupoi [24]. As for higher particle feed rates, a work by Pattison et al. [25] showed an experimental optimisation involving a full 2D-velocity field deduction using PIV in its usual sense. Similarly, Zahiri et al. [26] demonstrated particulate plume characteristics in CS with PIV. Although a sufficiently high particle density is required to enable field measurements with PIV, these studies did not study the links to velocity results. There is no doubt that the higher the feed rate the faster the processing time can be. A cost analysis of the CS process by Stier [27] provides evidence that it is important to understand the mass loading effect also on an economical level, as it enables the optimisation of gas and powder consumption without loss of deposition efficiency.

Consequently, in order to promote understanding the detailed effect of the particle feed rate as a process parameter, this work aims to investigate the particle velocity in the jet of a Cold Spray system working under low pressure conditions in dependence of the particle feed rate using PIV, in combination with a tracking algorithm for the identification of single particle vectors. Feedstock materials with different densities and geometries are used to show influences of changing materials. The experimental observations were compared against a 2D–axisymmetric Eulerian–Lagrangian model. This work is considered an initial but comprehensive study on the topic, towards the full understanding of gas-solid phase interactions in CS.

2. Equipment, materials, and methods

2.1. Experimental procedure

PIV is a measurement technique for the acquisition of velocity field data. It is an optical method and, when the flow is seeded with very light and small tracer particles, quasi non–intrusive. These particles are illuminated with two (or a sequence of) subsequent laser pulses formed to a light sheet in the plane of measurement. A camera system captures two (or a sequence of) images of the scattered light respectively. These images are processed by a cross–correlation algorithm, deducing the displacement of the particle collection within the interrogation window. At lower particle image densities, it is possible to identify single particle displacements and hence track particles through the field of measurement. By knowing the inter–pulse time, the displacement data can be interpreted as velocity information. In case of CS, the feedstock particles are an inherent part of the observed system and their Stokes number $St = \tau_p/\tau_f$, expressed as the ratio of the particle reaction time and a characteristic fluid time, can be in the order of unity or higher. This means that the particle is affected by the flow, but due to significant differences, no information about the fluid motion can be directly measured. Since the CS–particle motion is the focus of interest in the present study, no additional seeding is required and such can be obtained directly using the classical imaging technique. Table 1. summarises the specifications of the PIV system used in the present study. Both hardware and software was produced by LaVision. A 532 nm Nd:YAG Laser set to 4 Hz repetition rate at a 5 μs pulse separation time delivered consecutive image pairs. The repetition rate was limited by the CCD readout time of the camera, such that the entire evolution of the particles though the flow field could not be tracked at the present velocities. The light sheet thickness and width were approximately 1 mm and 60 mm respectively. The camera exhibited a resolution of 1280 × 1024 pixels for grey–scale images. The image pre–processing included a background subtraction and high–pass filtering to reduce stationary image features and low–frequency background variations. This was required due to scattering effects produced by the shape irregularities, although it increased the uncertainty of the measurement. The processing involved a multi–pass cross–correlation with reducing interrogation window size and an additional tracking algorithm, which identified single particle vectors.

Table 1
Laser and PIV camera specifications.

Camera		Laser	
Resolution	1280 × 1024 [px]	Wavelength	532 [nm]
Pixel size	6.7 × 6.7 [µm]	Pulse energy	100 [mJ]
Repetition rate	4 [Hz]	Repetition rate	4 [Hz]
Dynamic range	12 [bit]	Pulse separation	5 [µs]
		Pulse length	6 [ns]
		Light sheet	1 × 60 [mm]

Fig. 1 illustrates a schematic of the experimental arrangement, including PIV and the CS process. The gas flow was provided by an air supply, delivering a constant pressure of 0.58 MPa at the nozzle inlet. The pressure value was limited in the current set-up due to the compatibility of the optical measurement system with the high pressure operating environment. Studies to follow will involve intermediate and high pressure conditions, although stagnation pressure values between 0.5 and 1 MPa are used in low pressure CS systems for the deposition of number of materials; the level of pressure used in this study is therefore still representative of the process. The gas was first fed into the powder feeder. The gas–solid mixture was then injected into the CS nozzle (de-Laval converging/diverging design - 210 mm long, 2 mm throat diameter, 6 mm exit diameter). The measurement plane was oriented within the longitudinal direction and with a length of 50 mm from the nozzle exit. The particle jet was sprayed into the measurement section of an enclosed area, which ensured undisturbed flow and allowed for a measurement of the particle feed rate at a precision of approximately 2%. Fig. 2(a) shows the experimental set-up, a close-up of the measurement equipment is shown in 2(b).

In terms of the particle material, two powders with different properties were chosen. The first material was Stellite–6, having a density of 8440 kg/m^3, in the form of spherical particles. This material is a cobalt–chrome alloy highly relevant for CS applications with well-known corrosion resistance characteristics. In addition, Alumina (Al_2O_3) was used as second set of powder material, which represents a rather light-weight ceramic with a density of 3890 kg/m^3 and irregular shape. The powders were analysed by imaging and size distribution techniques. Firstly, SEM images were created with a Zeiss Ultra Plus Scanning Electron Microscope and used for an investigation of the particle morphology. Secondly, particle size distribution of the powders was evaluated using a Sympatec HELOS laser diffraction particle size analyser. Each measurement was carried out in quadruplicate on three different samples of each powder. The powder was dispersed in water using a magnetic stirrer rotating at 1200 RPM in tandem with an ultrasonic probe.

2.2. Numerical methodology

The conducted experiments were compared against CFD simulations. The modelling approach was chosen to be similar to most computational works in CS, in order to survey its capabilities to estimate the experimentally detected behaviour. The nozzle flow was calculated in ANSYS-Fluent v14.5 by solving steady 2D–axisymmetric Reynolds–