COMPUTATIONAL PREDICTION OF COLD SPRAY NOZZLE PERFORMANCE FOR THE DEPOSITION OF TITANIUM

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ABSTRACT

Cold spray is a novel technology for the application of coatings onto a variety of substrate materials. In this method, melting temperatures are not crossed and the bonding is realized by the acceleration of powder particles through a carrier gas in a converging-diverging nozzle and their high energy impact over a substrate material. The critical aspect of this technology is the acceleration process and the multiphase nature of it. The accurate assessment of the nozzle performance with simulation techniques is complex. In order to demonstrate the limits of current numerical tools, experiments with three different nozzle designs were conducted under constant conditions. The Deposition Efficiency was measured and it was shown that it decreases with the cross-sectional throat area of the nozzle. Computational results based on a one-way coupled multiphase approach did not concur with this, while more sophisticated modelling techniques with two-way couplings can partially provide high-quality outcomes, in agreement with experimental data.

KEYWORDS: Cold Spray, CFD, Multiphase Modelling, Coatings, Titanium

1. INTRODUCTION

New required standards and tolerances come along with an increasing demand of enhanced surface properties, making a new generation of coating technologies inevitable, that apply high quality layers of advanced materials [1] onto substrates of other metals or alloys.

An alternative to conventional deposition technologies [2] [3] [4] is Cold Spray (CS). This method is free of melting and therefore avoids the detrimental effects of those techniques which operates under high temperature levels [5]. High pressure gas is accelerated in a converging-diverging supersonic nozzle to velocities in the order of 1000m/s. The coating material is injected as powder into the nozzle and accelerated by the gas flow. As the powder particles strike against a substrate placed at a distance from the nozzle exit, they deform plastically and bond with the substrate material.

The ratio of particle mass that is deposited successfully over the paricle mass fed into the nozzle is called Deposition Efficiency (DE). It is evident that DE strongly depends on the impact velocity of the particles. Despite the simple design and working principle, the flow characteristics are very complex, e.g. trans- and supersonic velocities, boundary layer instability, turbulence, and particularly the presence of multiple phases. The most critical factor is the rapid change that the flow variables undergo from the inlet to the outlet of the nozzle.

This complexity makes the nozzle dynamics sensitive to manufacturing inaccuracies [6]. There are not conclusive studies which compare and explain the DE performances of different nozzle geometries based on the predicted flow phenomena. This paper aims to show that the DE prediction capabilities with numerical methods can be limited. In this regard, experiments when depositing titanium onto aluminium tubes, are compared to numerically computed multiphase flows and discussed taking into account the features of more complex approaches found in literature.

2. EXPERIMENTAL RESULTS

The general set-up for the CS process is shown in Figure 1. The experiments were conducted within the University of Cambridge (UK) utilizing a nitrogen type CS apparatus with an open loop powder feeder. The handling system was capable of delivering a working pressure of up to 3 MPa. A load cell reads the powder mass flow rate, as well as a flow meter measures the gas flow rates in both the powder feeder line and the main line, where a gas heater was installed. This component is used to generate a higher inlet temperature, i.e. nozzle exit speed. Titanium powder (CP-grade 2, -45µm size, spherical) was injected in the subsonic region of the nozzle and deposited onto 50mm diameter tubes (Al 6082-T6) using three nozzles in order to assess their DE performance.

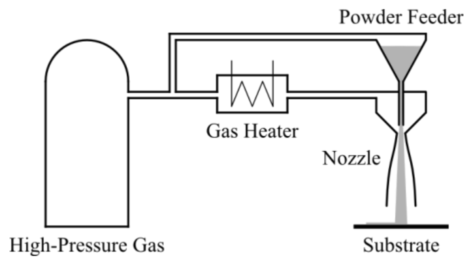

Figure 1: CS process set-up

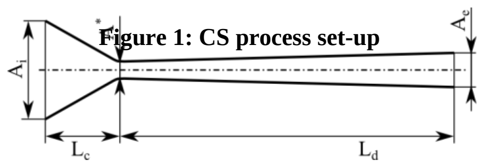

Figure 2: Nozzle Geometry

Nozzle	A_i [mm^2]	L_c [mm]	A^* [mm^2]	L_d [mm]	A_e [mm^2]
N 1	314	30	3.1	180	28.3
N 2	44.2	15.5	5.7	190	47.8
N 3	314	20	5.7	190	47.8

Table 1: Geometrical details of the nozzles

Nozzle	DE [%]
N 1	16.3
N 2	32.5
N 3	33.3

Table 2: Experimental results

of DE for each nozzle

The geometrical details of the nozzles can be seen in Figure 2. Correspondent values of the three designs (N1, N2, N3) are summarized in Table 1. A_i and A_e represent the inlet and exit cross-sectional area, respectively. L_c and L_d are the length of the converging and diverging sections of the nozzles and A^* quantifies the cross-sectional throat area. For all test runs the same processing conditions were applied, i.e. the substrate was placed at a standoff distance of 40mm from the nozzle exit, the inlet pressure and temperature were set to 3MPa and 350°C, the powder feed rate was measured to be 55±9 g/min.

The measured feedstock powder mass flow enables the direct calculation of DE. The respective results are summarised in Table 2. Comparing N1 and N3, the DE of 16.3% is almost doubled to a value of 33.3%, despite the processing conditions were kept constant. An analysis is provided in the section to follow.

3. SIMULATION AND MODEL VALIDITY

All three nozzles were simulated with ANSYS Fluent v14.0. The operating fluid nitrogen was set to be an ideal gas. The problem was reduced from a full 3D flow to an axisymmetric flow. Moreover, the calculations included a k-ε-turbulence model, assuming fully turbulent flow. The conservation equations for the gas phase were assumed to be steady state and, due to the compressibility, solved by a density-based solver with a second-order discretisation. Boundary conditions applied to the inlet of the grid (ca. 120000 elements), were set to the same values as in the experiments (3MPa, 350°C). The outlet pressure was defined to be atmospheric pressure, sufficiently far downstream from the actual nozzle exit.

Concerning the particle phase modelling, a one-way coupled Lagrangian approach is chosen. In this respect, each particle (45μm diameter in the model) is released in the inlet zone and further described in a frame of reference that moves with the particle, solving the particle equations based on the local fluid properties. Nevertheless, the change of the gas state variables due to momentum and energy transfer to the particles is not taken into account, as it would require a two-way coupled multiphase model. The one-way coupling is often used in CS simulations, because it provided acceptable results under set conditions [7]. Mostly, it is claimed that this simplification is justified due to high Stokes numbers ***St*** and low momentum interaction parameters Π_{mom} [8].

Figure 3 presents the gas velocity profiles along the axial position for nozzle N1 to N3. The gas phase acceleration is most intense in the transonic region. Each profile shows the typical alternating pattern for over-expanded flows downstream of the nozzle. In all three types the gas reaches similar maximum values, although the acceleration in the transonic region differs.

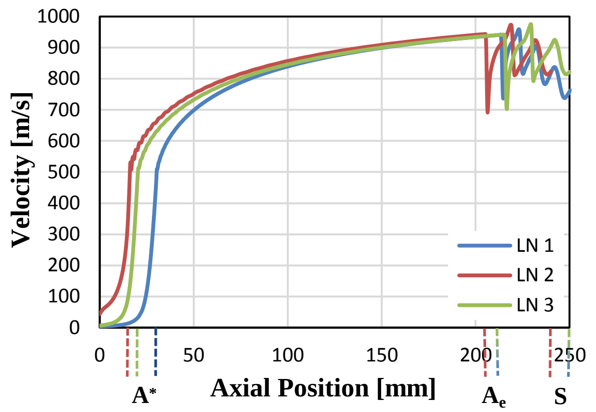

Figure 3: Gas velocity profiles along the nozzle axis for N1 to N3

Figure 4 shows representative velocity profiles for particles in all nozzle design configurations. The drag force (that accelerates each particle) is directly related to the relative velocity of the fluid. As can be seen in Figure 4, this drag increases dramatically in the transonic region and reduces in the diverging section due to the fading expansion. Since particle and gas speeds are still of different levels at nozzle exits A_e, the acceleration is maintained downstream of those points. The shock pattern does not affect the 45µm-particles because of their relatively high inertia. Interestingly, the particles all show very similar profiles and maximal velocities of approximately 595m/s or 63% of the carrier gas speed.

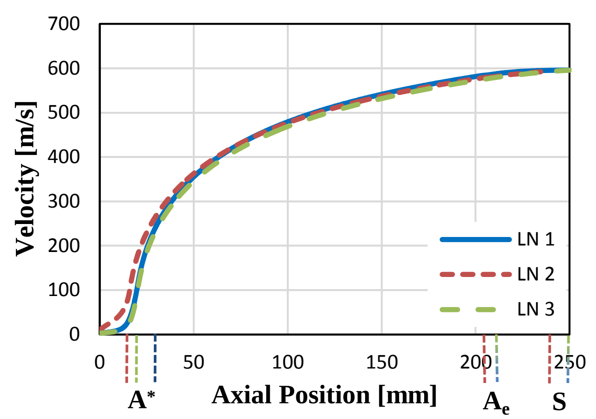

Figure 4: Particle velocity profiles along the nozzle axis for N1 to N3

Not only the simulated gas phase, but also the particulate material behaves in similar ways in the considered designs. However, in reality, the deposition performances are different as reported in Table 2. This mismatch can only be explained through the model inaccuracy in the prediction of gas-phase interactions. The fluid-particle coupling is therefore shown to play a more decisive role in CS nozzle dynamics.

4. MODELLING ALTERNATIVES

If a significant fluid-particle interaction exists, it must have larger effects in N1 than in N2 and N3. The reason is a higher volume fraction of the particulate phase, originating from the smaller A^* and a lower gas flow rate. A work published by [9] provides this claim with further numerical explanation. In this case, the interphase relations were modelled in a more sophisticated manner, using an Eulerian approach. Here, both the fluid and the particulate phase were modelled as immiscible, interacting continua in the same reference frame. The authors showed a significant decrease in gas velocity at the exit due to the gain in momentum of the particulate phase as the loading was increased. This suggests significant interactions, at least on a theoretical level. A limit of this type of model is the dependency of its validity on particle density and distribution.

The same authors contributed with another publication [10] that is focused on the simulation of the shock pattern in the jet using a two-way coupled Lagrangian approach. It was found that flow patterns could be predicted with high accuracy, including effects of high particle loading in the jet. Using a particle size distribution of mostly small particles ($<10\mu m$), the calculated exit velocities were within the error range of the measurements. According to the authors, this agreement originated form the complex RSM turbulence model and the two-way phase coupling.

However, in [8] the real particle velocities were considerably overestimated despite a two-way coupling. This was explained by pointing out the limits of the k-ε-turbulence model and, particularly, the dispersion of the particles which is dependent on the nozzle geometry. The validity of complex couplings is also a question of local conditions, such as turbulence and particle distribution.

5. CONCLUSIONS

In this work, the deposition performances of three different De Laval nozzle designs under constant process conditions were investigated and explained by comparing them to numerical results. Titanium was deposited onto aluminium 6082-T6 tubes. It was found that the N1 nozzle, with the smallest throat cross-sectional area, performs the worst in terms of DE.

Numerical simulations were performed based on fluid dynamic observations, using steady axisymmetric equations with a k-ε-turbulence model and a one-way coupled discrete phase model. The computed results showed very similar velocity profiles for both phases in all nozzles. The variations in nozzle performance were therefore not numerically reproducible and the insufficiency of the interphase coupling was derived as the main reason.

The comparison with more sophisticated modelling showed that those provide promising results. However, the vast amount of factors, especially the nozzle design, the extreme changes in velocity, turbulent kinetic energy, and volume fraction along the axis makes overall theoretical predictions difficult. Although more elaborate turbulence and multiphase models can deliver more reliable results, such are still initial studies, which will require further development stages to achieve full validation.

Acknowledgements

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