Particle Image Velocimetry (PIV) of Cold Spray particles in supersonic nozzles

R. Lupoi

Trinity College Dublin, the University of Dublin, Department of Mechanical and Manufacturing Engineering, Parsons Building, Dublin 2, Ireland.

ABSTRACT

Cold Spray (CS) is an emerging manufacturing technique for the formation of coatings. The process work by accelerating micron-sized particles up to supersonic speed in a nozzle, and it is not thermal-driven. When particles strike on a surface they plastically deform and bond to it. This paper reports and explain experimental particle speed measurements at the nozzle exit using the Particle Imaging Velocimetry (PIV) technique using Alumina and Stellite-6 as powder materials.

Keywords: Cold Spray, PIV, Particle speed, laser.

1. INTRODUCTION

Cold Spray (CS) is a manufacturing process for the application of coatings. A feedstock material in the form of powder is deposited onto a substrate by means of high velocity impacts. Micronized powder particles (5−100μm) are accelerated by an expanding process gas (inert) to supersonic velocities to form a bonding layer. In this manner, the process makes use of the kinetic energy of the particles rather than their thermal energy, which allows for very low temperature levels compared to other coating technologies. This results in a solid-state deformation and a process that is completely free of melting. Consequently, typical high temperature effects, such as oxidation, evaporation, high residual stresses, gas release, crystallization, and others are eliminated or minimised [1,2]. The method was firstly discovered and initially developed at the *Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences* in Novosibirsk by a group of researchers lead by Dr. Anatolii Papyrin [2]. Over the past decades, the technology was further developed from a raw method into a more advanced process for complex applications by a rapidly growing number of research groups, at first located in Russia and the United States, but also in several European and Asian Countries, and Australia [3].

In CS high pressure gas (Helium or Nitrogen) is firstly fed from a supply into the main line and heated to a desired temperature, as shown in Figure 1. It is subsequently expanded in a converging-diverging De-Laval nozzle, accelerating to supersonic speeds. The powder is injected either into the converging or the diverging section of the nozzle and accelerated due to the forces acting on it by the gas flow to 300 - 1200m/s. This two-phase flow system is now characterised by additional interactions of the combined gas-particle motion. The powder particles must achieve velocities above a certain value, the "critical velocity" in order to realize bonding upon impact. Each material is characterized by its own threshold value.

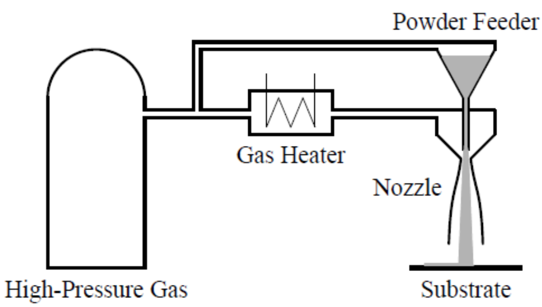

Figure 1. Generic CS system schematic.

To engineer an efficient process, the parameters and the nozzle design were studied carefully. In the mid to late 1990s, Dykhuizen and Smith [4] quantified the increasing effect of the particle velocity on the Deposition Efficiency (DE) and used it for a nozzle optimisation calculation. DE quantifies the efficiency of the process by comparing the proportion of deposited particle mass over all injected particle mass [2]. Dykhuizen and Smith used a one-dimensional isentropic flow assumption and a drag law to determine the particle velocity as a function of the gas properties, as well as the particle material and size. In addition, they stated that the performance is more sensitive to the nozzle length than its shape. These calculations are often referred to as the basis for numerical models of the time.

The same authors published a work with D. Gilmore [5], in which the velocity of the particles in the jet normal plane was measured by a laser-two-focus velocimeter, using air and Helium as process gases. Because of the lower molecular mass and the higher heat capacity ratio, the achievable velocities using Helium were more than twice as high as for Nitrogen at the same temperature level. This is an example of Helium as the favourable process gas, at the expense of high costs. Van Steenkiste et al. [6] stated that the most influential additional parameters are the gas pressure and temperature, the powder feed rate, and the substrate stand-off distance from the nozzle exit. Similarly, Stoltenhoff et al. [7] analysed a strong dependency of the pressure and temperature on the DE, both having a nit negligible effect. A result of increased temperature is a generally decreased coating porosity and enhanced tensile strength [8]. Particles need to impact at speeds above the critical velocity but below a second threshold, the erosion velocity, where the impact becomes so strong that the particle is destroyed and material is lost from the substrate. The range of velocities in between those values forms the deposition window. Schmidt et al. [9] summarised the findings in this context.

Mathematical tools, particularly Computational Fluid Dynamics (CFD), have become an important instrument for design aspects in spray technologies. A majority of the numerical work is associated with nozzle shape and injection optimisation, which suggests a review of the respective developments. For completeness, work that was mentioned in previous sections needs to be addressed here as a starting point: in earlier publications, one-dimensional isentropic flow analysis was used to optimise the nozzle shape by virtue of maximal particle acceleration [4, 10, 11]. To go one step beyond, the Method of Characteristics (MoC) - giving the respective type of nozzles their name - was applied to the nozzle design in order to find a wall contour of the divergent section, which produces a flow field free from discontinuities [12, 13, 9, 14]. Progressively, CFD was employed in the design procedure of nozzles [15].

The 2D-modelling approach with simple particle tracking, as used commonly, was applied by Li et al. in order to optimise the nozzle geometry with given or limited nozzle length, mainly by finding the optimal exit diameter and expansion ratio [16, 17]. Jung et al. [18] faced the endeavour of the optimising the section lengths with a model of similar type. Long converging sections were discovered to be detrimental for the particle velocity but increase its temperature.

The diverging section length of the nozzle (the supersonic section), in contrast, showed the opposite influence. An exceptional design idea was investigated experimentally by Klinkov et al. [19]: A double-edged oblique cut was added at tip of the divergent section with the purpose to form a jet that spreads out in one direction. The behaviour was tested in combination with increasing flow swirl in order to create various spray spot sizes and shapes. Likewise, others generated better powder spot shape control by enhancing the partial permeability by means of slots in the nozzle wall. Recently, Lupoi [20] numerically and analysed the behaviour of four different nozzle designs under constant operating conditions. The performance in terms of DE was of primary interest. A common 2D-CFD simulation with a one-way coupled Lagrangian tracking was employed, but could not explain the measured trends.

To summarize, the design of efficient CS nozzles involves the detailed understanding of the particle acceleration process, and such is mainly accomplished by CFD simulations. However, the current state of the art lacks of comprehensive experimental measurements of particle speed to validate numerical modelling and for further developments.

This paper reports the Particle Imaging Technique (PIV) applied to the measurements of CS particles under a variety of parameters and particle material, Stellite-6 and Alumina.

2. PARTICLE IMAGE VELOCIMETRY APPARATUS

2.1 Measurement principles

Particle Image Velocimetry is a measurement technique for the acquisition of velocity field data [21]. It is an optical method and, when very light and small tracer particles are used, quasi non-intrusive. A flow is seeded with such particles which 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 post-processed by a cross-correlation algorithm, obtaining the displacement of the particles or particle groups.

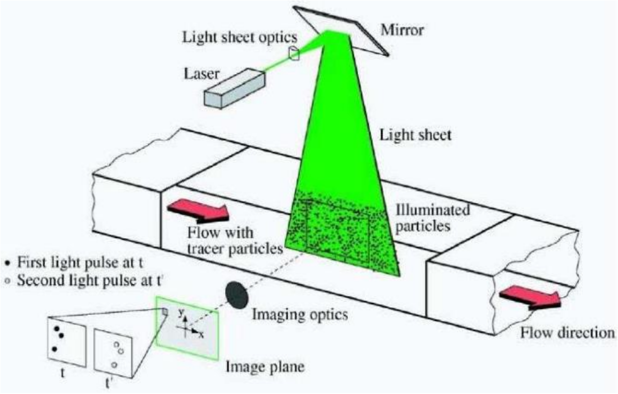

Figure 2. Principle of Particle Image Velocimetry.

By knowledge of the inter-pulse time, the displacement data can be interpreted as velocity information. This principle is illustrated in Figure 2. The information that is obtained by measurement does not correspond to the fluid flow, but to the particle motion. Consequently, the dispersed phase is commonly favourably light and small, in order to achieve minimal Stokes numbers such that the relative flow can be assumed negligible. However, different from usual PIV applications, the particle motion is the focus of interest in the present study. Although it can differ greatly from the gas flow, no additional seeding is required in CS and the particle motion can be obtained directly. Table 1 shows the specifications of the PIV system used in the experiments in TCD.

Camera			Laser		
Resolution	1280x1024	$[px]$	Wavelength	532	$[nm]$
Pixel size	6.7x6.7	$[\mu m]$	Pulse energy	100	$[mJ]$
Repetition set (max.)	4 (8)	$[Hz]$	Repetition set (max.)	4 (15)	$[Hz]$
Interframe time set (min.)	5 (0.2)	$[\mu s]$	Pulse length	6	$[ns]$
Dynamic range	12	$[bit]$	Beam diameter	3	$[mm]$

Table 1. Laser and PIV camera specifications.

2.2 Experimental apparatus

An experimental apparatus, shown in Figure 3, was developed so as to allow for the application of PIV to CS particle speed measurements. The nozzle is mounted on a vertical direction, and sprays the mixture of gas and particles in the test section channel. The laser beam is fired through an array

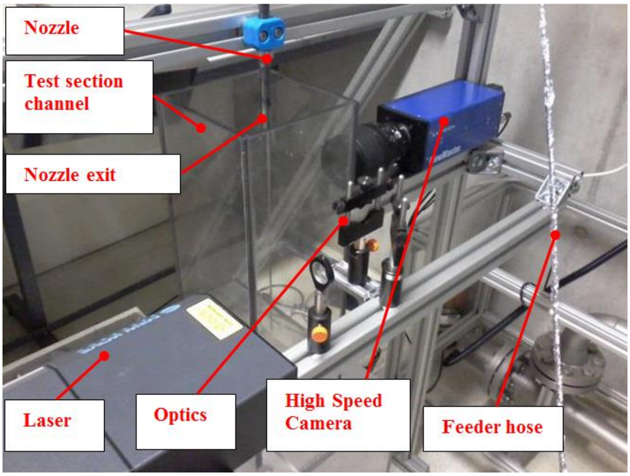

Figure 3. Experimental set up and apparatus.

of optical lenses so as to direct it towards the nozzle, and to re-shape it into a sheet type of geometry. The nozzle in the figure is not the actual CS nozzle used in the experiments, the final set up does not however differ from the assembly in Figure 3. Images of the particle are captured by the high speed camera. The test section channel leads to a containing chamber shown in

Figure 4, that allows to capture the material which was sprayed. This way, it is possible to measure the particle mass flow rate that was generated during each experiment by the feeder.

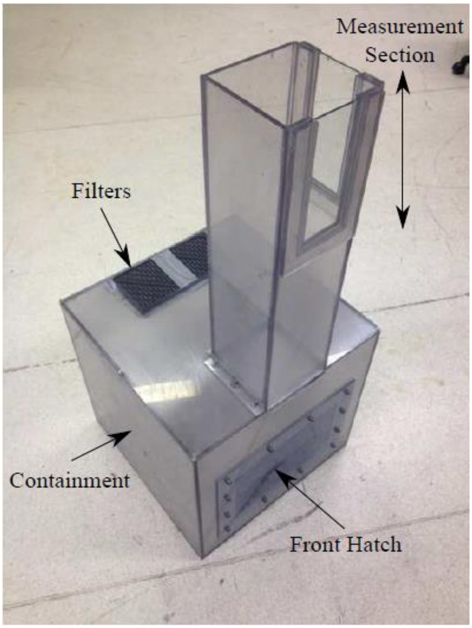

Figure 4. Particle capturing chamber below the test section.

3. EXPERIMENTAL VELOCITY MEASUREMENTS

The time step between images must be short enough to minimise the amount of particles that can exit the illuminated plane but long enough to make the particle images distinguishable. The time scale that determines the capturing of the subsequent image frame pair is the repetition rate of the system (in this case set to 4*Hz*). The camera system requires a minimum time for the image read-out from the CCD sensor, which inherently limits the respective rate at which images can be captured. Even in case of the maximum repetition rate of 8*Hz* corresponding to a time of 0.125*s*, the particles would travel more than 30 metres at CS typical speeds. As a consequence, the particles are not tracked through the field and the image pairs are independent measurements, i.e. the camera is always looking at the same location.

The CS nozzle (De-Laval, converging/diverging design 210mm long) was loaded with 5.8bar-g pressure (air) at the inlet. This level is below the typical CS thresholds, >25bar-g; it is however practical as it does allow the use of compressed air rather than bottled gases. Two powder materials were used in these experiments, and injected in the nozzle: Stellite-6 (a CoCr alloy, average size 45µm) and Alumina (average size 60 µm). Alumina is not directly applicable to CS operations as being a ceramic, it is however light-weight hence interesting to compare against Stellite. The velocity of the particle stream was measured with the PIV system over a distance of 40mm from the nozzle exit, and averaged. Figure 5 shows the average particle velocity at different mass feed rates for the two materials. In the case of Alumina it was not possible to go beyond 120g/min as nozzle chocking would occur in the current set-up just above this level.

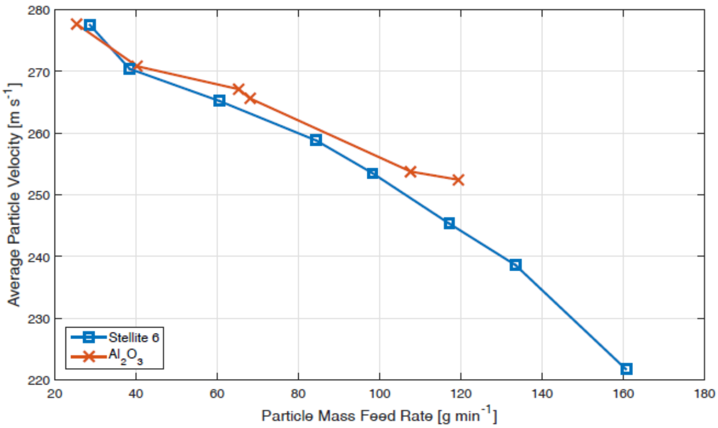

Figure 5. PIV of particle stream, average data over test section.

The air inlet pressure was kept constant in all experiments; it is interesting to notice that as the mass feed rate of the solids phase increases, the average particle speed decreases. This effect is typically not captured when modelling the process using CFD, as it requires the development of more sophisticated algorithms not yet available. The particle stream, especially at higher mass loadings, interacts with the gas phase; the overall effect is a reduction in gas exit velocity, i.e. particle speed. The same effect is shown to occur for both Stellite-6 and Alumina. Using high feed rates in CS is advantageous as that increases the process capabilities; this study shows that velocities may however fall below the critical values for deposition to be efficient at high loadings.

Figure 6 and Figure 7 show experimental velocity measurements from the nozzle exit (Axial Position = 0) to 45mm downstream for both Stellite-6 and Alumina. In the case of Stellite-6 the distribution is nearly constant, however the velocity levels decreases by as much as 24% as the feed-rate goes up. In the case of Alumina the trend is very different, as the velocity is shown to reduce with the axial position. This is because this material is low density (light weight) and particles will tend to lose their momentum as they exit the nozzle and the gas velocity decreases. Also in this case, as the particle loading increases the overall speed will reduce.

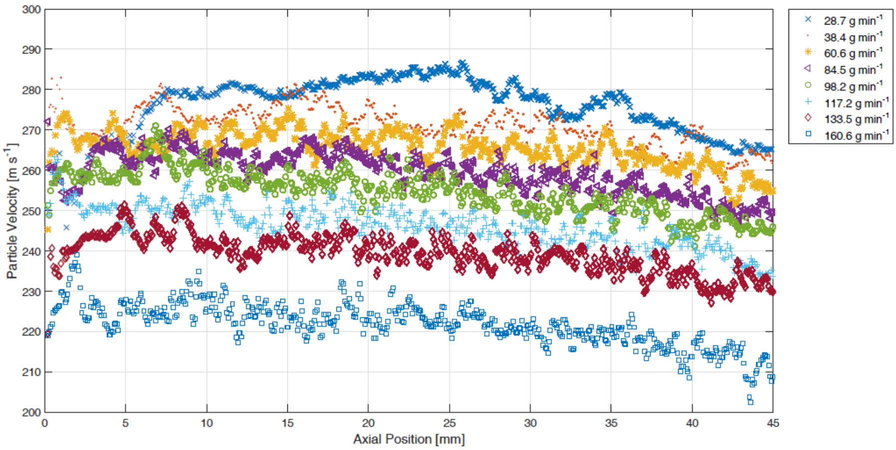

Figure 6. PIV of particle stream after the nozzle exit, Stellite-6.

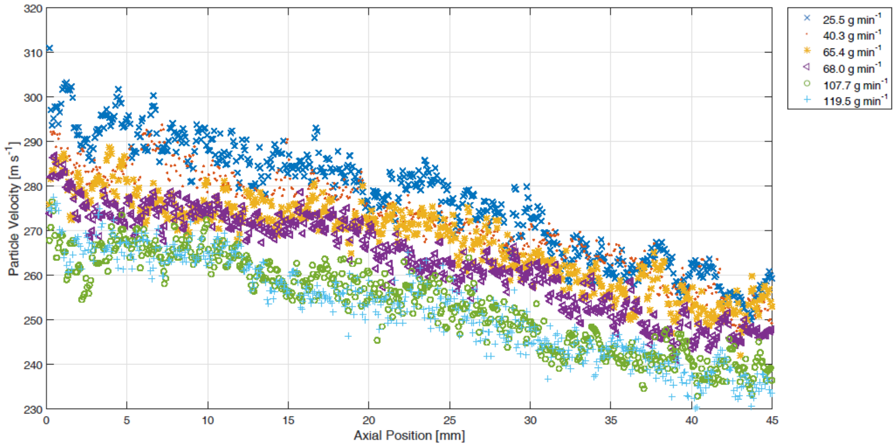

Figure 7. PIV of particle stream after the nozzle exit, Alumina.

4. CONSLUSIONS

Cold Spray in an emerging coating method that uses supersonic nozzles to accelerate powders up to high velocity. When particles strike on a surface they plastically deform and bond to it. The process is cold (low temperature) by its own nature, and free of typical thermal effects such as Heat Affected Zones and component distortion. Understanding the particle acceleration process is very important for an efficient nozzle design. This work has reported experimental measurements of particle velocity (PIV) at the nozzle exit zone, showing trends currently not possible of being captured by computer simulations (CFD). The particle mass loading in the nozzle was shown to play a critical role in the solid phase acceleration history. High loadings trigger gas-particle interactions that result in lower velocity levels at the nozzle exit. The experiments were conducted for Alumina and Stellite-6, showing similar distribution characteristics.

Acknowledgements

The authors wish to say thanks to FP-7 Marie Curie Actions (grant number 333663; Supersonic Spray Advanced Modelling – SSAM) for funding the work presented in this article, and to the technical staff in TCD for the precious advice and support.

References

[1] V. K. Champagne, ed., *The Cold Spray Materials Deposition Process*. Cambridge, UK: Woodhead Publishing Limited, 1 ed., 2007.
[2] A. Papyrin, V. Kosarev, S. Klinkov, A. Alkhimov, and F. Vasily, *Cold Spray Technology*. Oxford, UK: Elsevier, 1 ed., 2007.
[3] E. Irissou, J.-G. Legoux, A. N. Ryabinin, B. Jodoin, and C. Moreau, "Review on Cold Spray Process and Technology: Part I-Intellectual Property," *Journal of Thermal Spray Technology*, vol. 17, no. 4, pp. 495–516, 2008.
[4] R. C. Dykhuizen and M. F. Smith, "Gas Dynamic Principles of Cold Spray," *Journal of Thermal Spray Technology*, vol. 7, no. 2, pp. 205–212, 1998.
[5] D. L. Gilmore, R. C. Dykhuizen, R. A. Neiser, T. J. Roemer, and M. F. Smith, "Particle Velocity and Deposition Efficiency in the Cold Spray Process," *Journal of Thermal Spray Technology*, vol. 8, no. 4, pp. 576–582, 1999.
[6] T. H. Van Steenkiste, J. R. Smith, R. E. Teets, J. J. Moleski, D. W. Gorkiewicz, R. P. Tison, D. R. Marantz, K. A. Kowalsky, W. L. Riggs,

P. H. Zajchowski, B. Pilsner, R. C. McCune, and K. J. Barnett, “Kinetic spray coatings,” *Surface and Coatings Technology*, vol. 111, no. 1, pp. 62–71, 1999.

[7] T. Stoltenhoff, H. Kreye, and H. J. Richter, “An Analysis of the Cold Spray Process and Its Coatings,” *Journal of Thermal Spray Technology*, vol. 11, no. 4, pp. 542–550, 2002.

[8] X. Meng, J. Zhang, J. Zhao, Y. Liang, and Y. Zhang, “Influence of Gas Temperature on Microstructure and Properties of Cold Spray 304SS Coating,” *Journal of Materials Science & Technology*, vol. 27, no. 9, pp. 809–815, 2011.

[9] T. Schmidt, H. Assadi, F. Gärtner, H. Richter, T. Stoltenhoff, H. Kreye, and T. Klassen, “From Particle Acceleration to Impact and Bonding in Cold Spraying,” *Journal of Thermal Spray Technology*, vol. 18, pp. 794–808, Aug. 2009.

[10] A. Alkhimov, V. Kosarev, and S. Klinkov, “The Features of Cold Spray Nozzle Design,” *Journal of Thermal Spray Technology*, vol. 10, no. 2, pp. 375–381, 2001.

[11] M. Grujicic, C. Tong, W. S. De Rosset, and D. J. Helfritch, “Flow analysis and nozzle-shape optimization for the cold-gas dynamic-spray process,” in *Proceedings of the Institution of Mechanical Engineers, PartB: Journal of Engineering Manufacture*, vol. 217, pp. 1603–1613, Jan. 2003.

[12] J. A. Pattison, *Cold Gas Dynamic Manufacturing*. PhD thesis, University of Cambridge, 2006.

[13] T. Schmidt, F. Gaertner, and H. Kreye, “New Developments in Cold Spray Based on Higher Gas and Particle Temperatures,” *Journal of Thermal Spray Technology*, vol. 15, pp. 488–494, Dec. 2006.

[14] H. Tabbara, S. Gu, D. G. McCartney, T. S. Price, and P. H. Shipway, “Study on Process Optimization of Cold Gas Spraying,” *Journal of Thermal Spray Technology*, vol. 20, pp. 608–620, Oct. 2011.

[15] T. Stoltenhoff, *Kaltgasspritzen von Kupfer*. Aachen: Shaker Verlag, 1 ed., 2003.

[16] W.-Y. Li and C.-J. Li, “Optimal Design of a Novel Cold Spray Gun Nozzle at a Limited Space,” *Journal of Thermal Spray Technology*, vol. 14, pp. 391–396, Sept. 2005.

[17] W.-Y. Li, H. Liao, G. Douchy, and C. Coddet, “Optimal design of a cold spray nozzle by numerical analysis of particle velocity and experimental validation with 316L stainless steel powder,” *Materials & Design*, vol. 28, no. 7, pp. 2129–2137, 2007.

[18] H. B. Jung, J. I. Park, S. H. Park, H.-J. Kim, C. H. Lee, and J. W. Han, “Effect of the expansion ratio and length ratio on a gas-particle flow in a converging-diverging cold spray nozzle,” *Metals and Materials International*, vol. 15, no. 6, pp. 967–970, 2009.

[19] S. Klinkov, V. Kosarev, and V. N. Zaikovskii, “Influence of Flow Swirling and Exit Shape of Barrel Nozzle on Cold Spraying,” *Journal of Thermal Spray Technology*, vol. 20, pp. 837–844, Feb. 2011.
[20] R. Lupoi, “Current design and performance of cold spray nozzles: experimental and numerical observations on deposition efficiency and particle velocity,” *Surface Engineering*, vol. 30, pp. 316–322, June 2014.
[21] M. Raffel, C. E. Willert, S. T. Wereley, and J. Kompenhans, *Particle Image Velocimetry*. Berlin Heidelberg: Springer-Verlag, 2 ed., 2007.