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EPSRC Centre for Doctoral Training in Innovative Metal Processing (IMPaCT)

Improving Cold Spray Additive Manufacturing with a Nozzle Designed by the Method of Characteristics

Florentina-Luiza Zavalan*, Aldo Rona
University of Leicester, Leicester, United Kingdom
*flz1@leicester.ac.uk

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Presentation outline

- Introduction to Cold Spray Process
- Statement of Problem
- Computational Methodology & Model Validation
- Results and Discussions
- Concluding Remarks
- References & Acknowledgements

Cold spray metal deposition

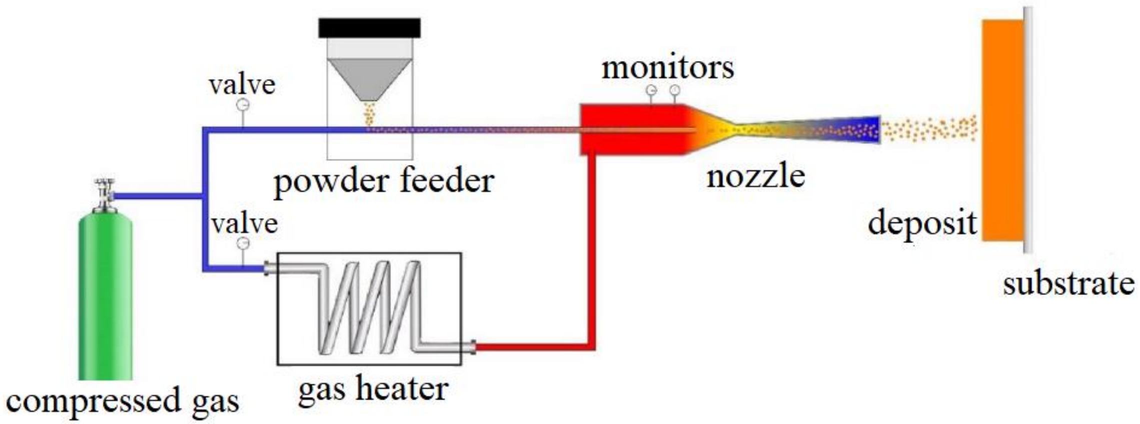

Figure 1: Operating principle of a high pressure metal powder cold spray system (S. Yin et al., 2018).

High velocities: 300 to 1200 m/s

Powder particles: 1 to 50 µm

Applications: - coating (corrosion resistance, wear resistance, composite coatings)
- repair
- additive manufacturing

Materials: Al, Cu, Ni, Ti, Cr, Co, Ag, Zn, Nb, Zr, W, Ta, Al alloys, Ni alloys, steels and stainless steels, MCrAlY, Cu-W, etc.

Objective

Improve the metal particle delivery of cold spray nozzles

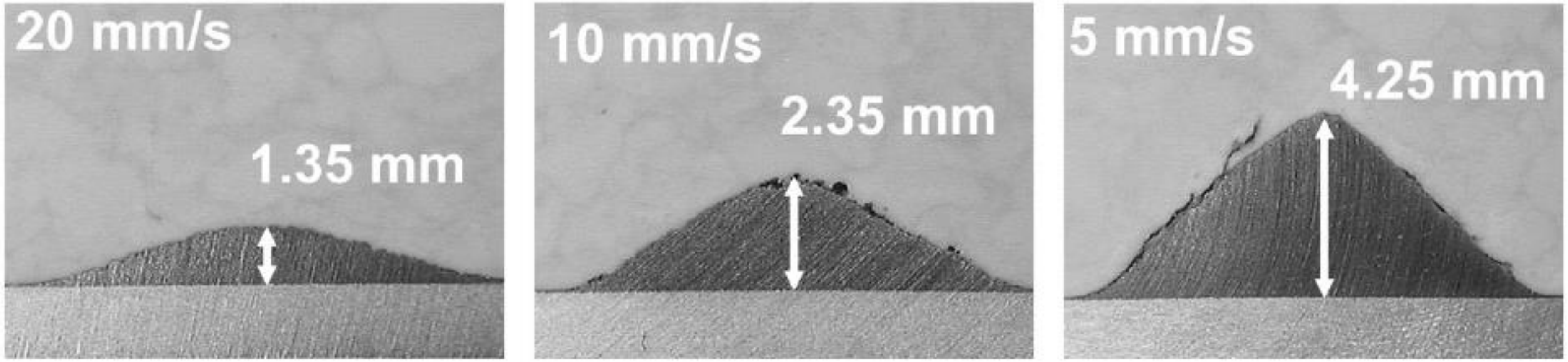

Figure 2: 316L stainless steel deposit profiles obtained at different values of nozzle traverse speed (D. Kotoban et al., 2017).

Modelling of the carrier phase

- Density-based flow solver in ANSYS FLUENT® v19.5
- Reynolds Averaged Navier-Stokes equations (RANS) – SST k-ω model
- Roe flux difference split scheme + 3rd order MUSCL interpolation

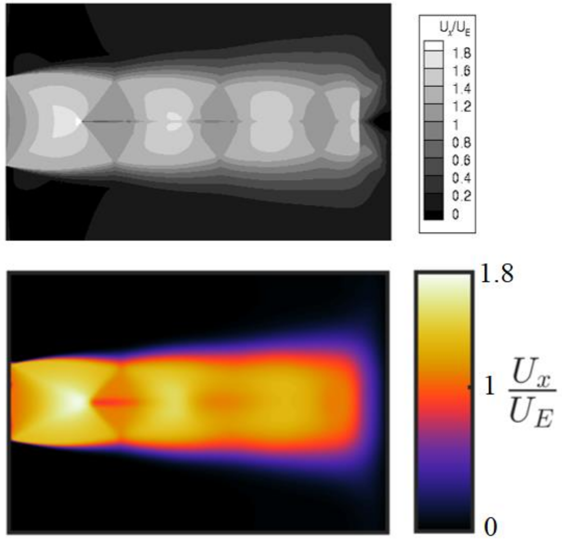

Figure 3: Greyscale levels of mean axial velocity predicted by CFD (top) and iso-colour levels of mean axial velocity from Weightman et al., 2015 (bottom).

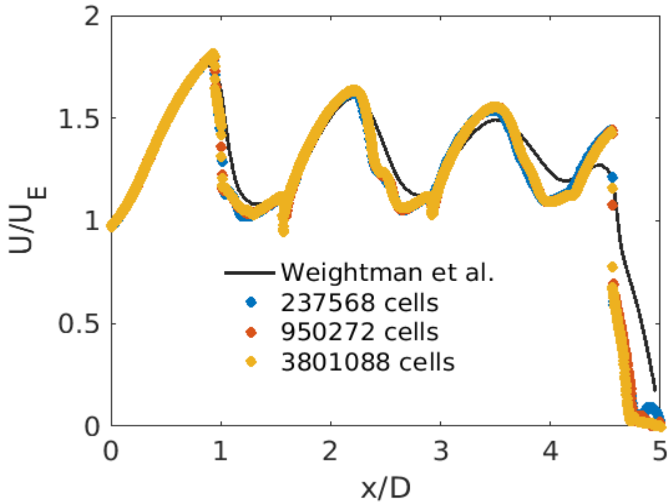

Figure 4: Axial distribution of centreline velocity from PIV (line) and CFD (symbols) for three levels of computational mesh refinement.

Modelling of the discrete phase

- Discrete Phase Model (DPM) – “two-way coupling”
- Unsteady Particle Tracking + high-Mach-number drag law
- Discrete Random Walk model

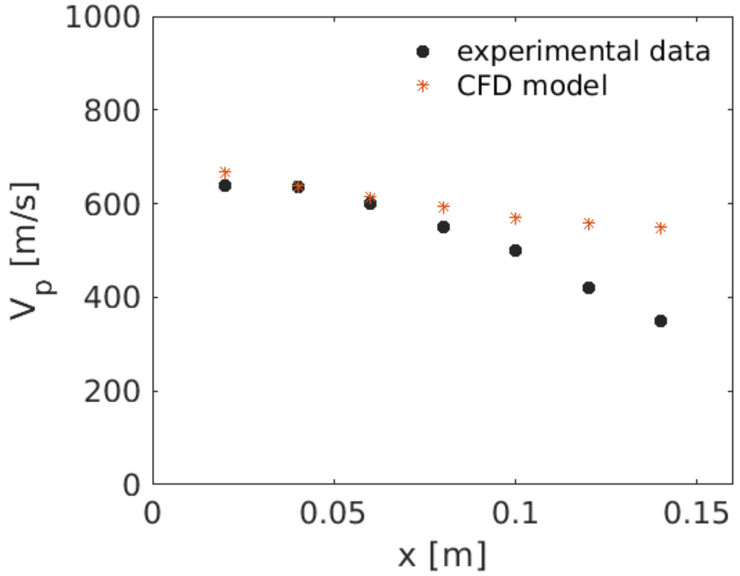

Figure 5: Comparison of titanium particle maximum axial velocity as a function of distance from the nozzle exit (Zahiri et al., 2009).

Commercial cold spray nozzle

- The commercial conical convergent-divergent cold spray nozzle (TWI)
- D_i= 12.8 mm, D_{throat}= 2.65 mm, D_e= 7.5 mm, L_{conv}= 30 mm, L_{div}= 181 mm and $L_{pre\text{-}chamber}$= 60 mm
- Structured multi-block body-fitted Cartesian mesh of about 1.6 million cells

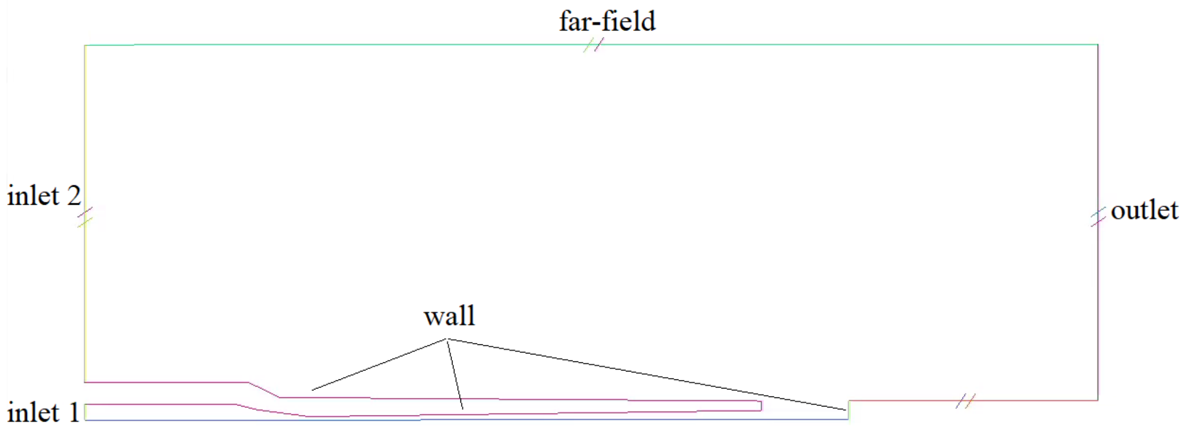

Figure 6: Sketch of the computational domain and boundaries.

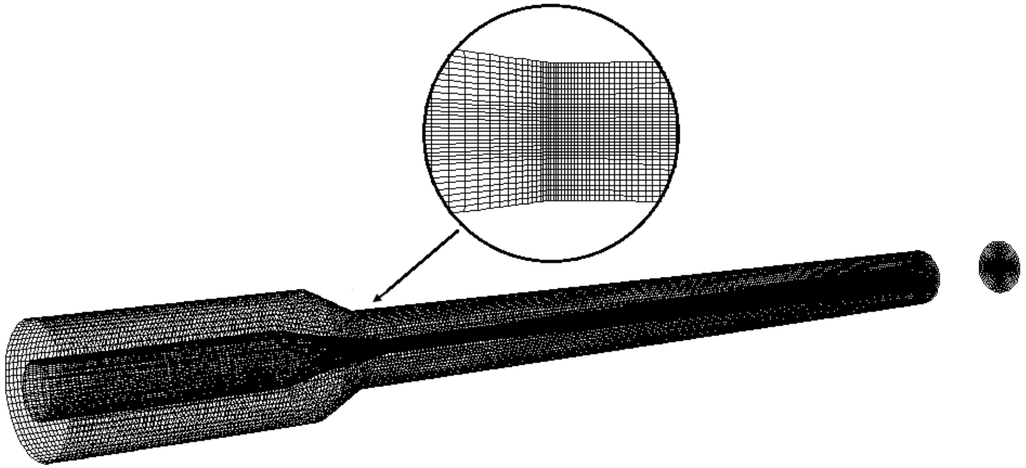

Figure 7: Computational mesh.

Nozzle redesign

- The internal wall was re-profiled using the Method of Characteristics implemented by T. Alcenius and S.P. Schneider (1994) – convergent part & the CONTUR code by J. C. Sivells (1978) – divergent part
- The throat diameter and the overall length were kept the same

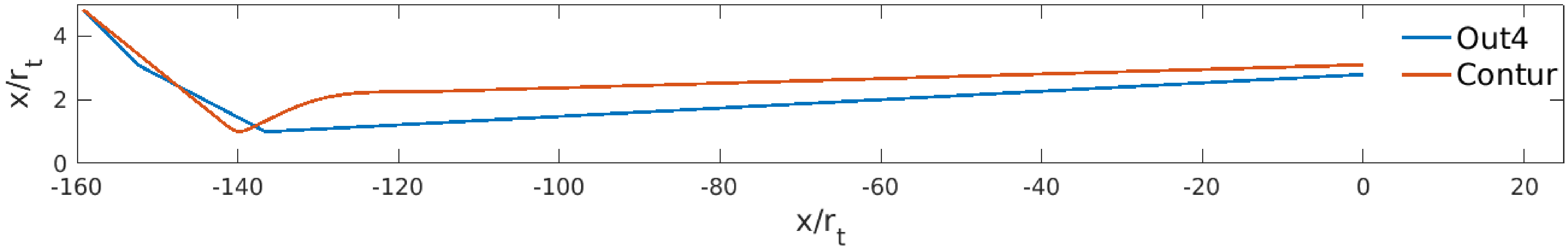

Figure 8: Sketch of the nozzle profiles.

Cold spray operating conditions

Table 1: Cold spray inlet conditions for the gas.

Boundary	Temperature	Pressure	Gas
inlet 1	1073.15 K	5e+6 Pa	N2
inlet 2	300 K	150 Pa	N2

Table 2: Properties of the simulated powder material.

Property	Description
Material	316L stainless steel
Particle shape	spherical
Particle density, kg/m^3	7765.4
Initial particle velocity, m/s	10
Initial particle temperature, K	298.15
Powder feed rate, g/min	150

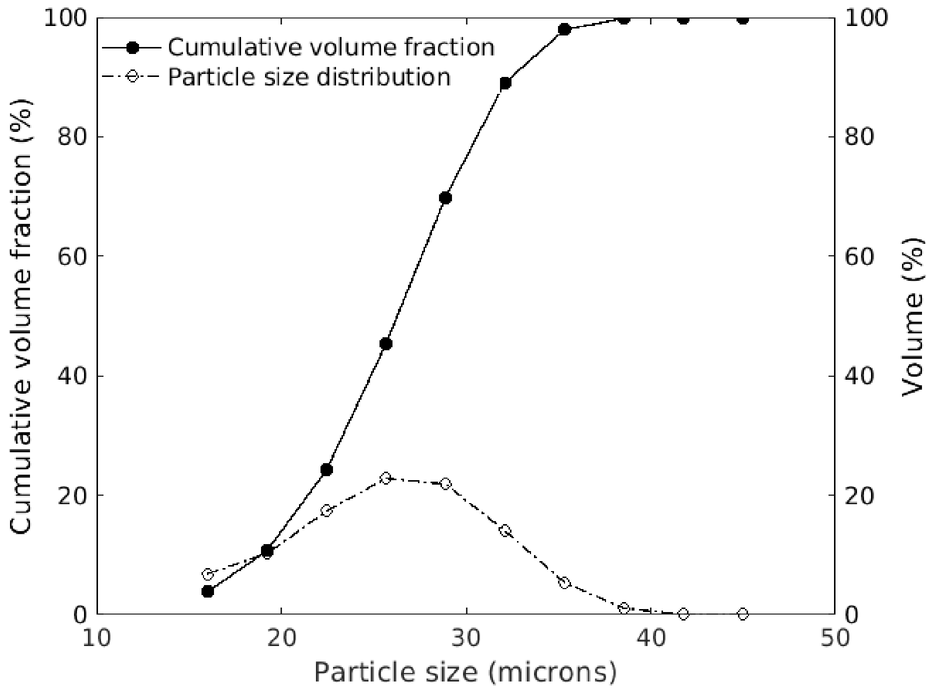

Figure 9: Particle size distribution for the 316L stainless steel powder used in the Eulerian-Lagrangian coupled CFD simulation.

Velocity distribution

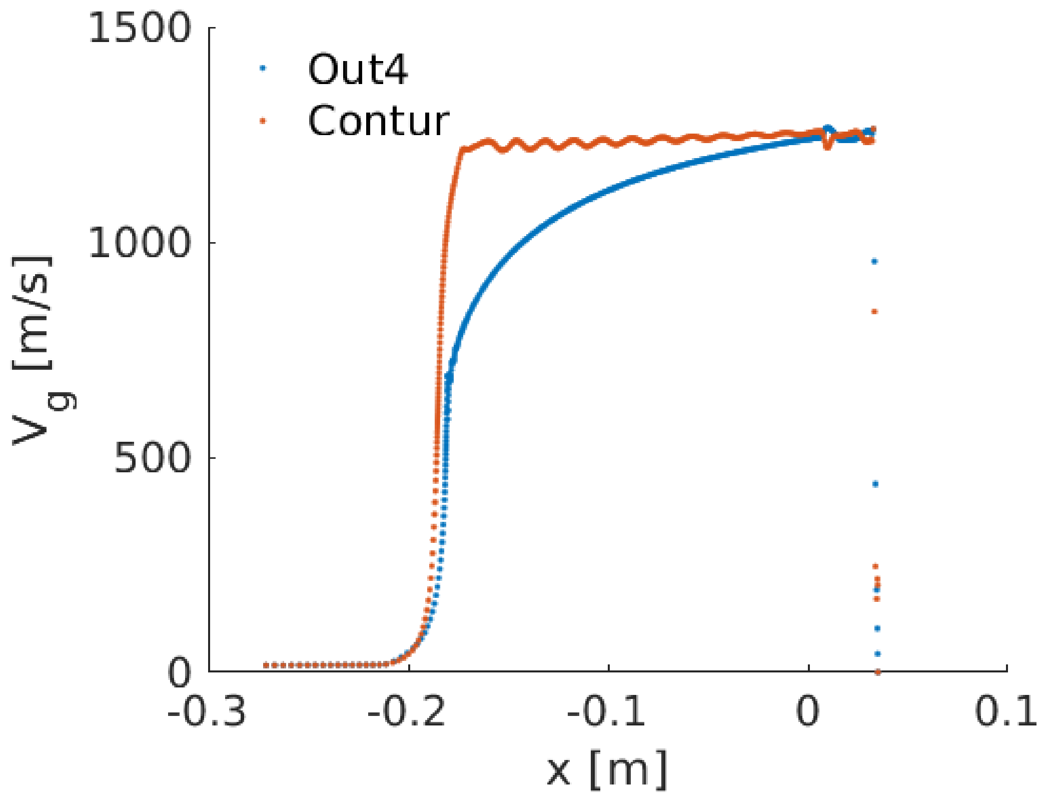

Figure 10: Velocity magnitude of the carrier gas phase along the axis of the nozzle.

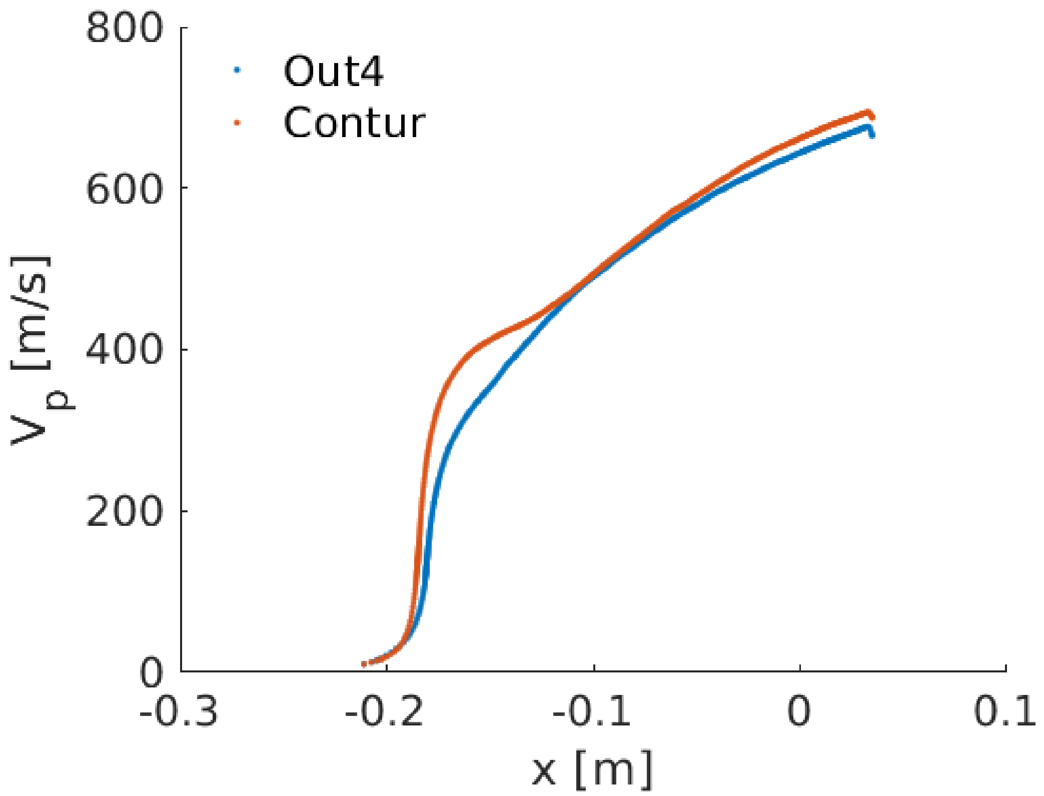

Figure 11: Velocity magnitude of a 316L stainless steel particle with a reference diameter of 19 µm.

Radial spread of particles

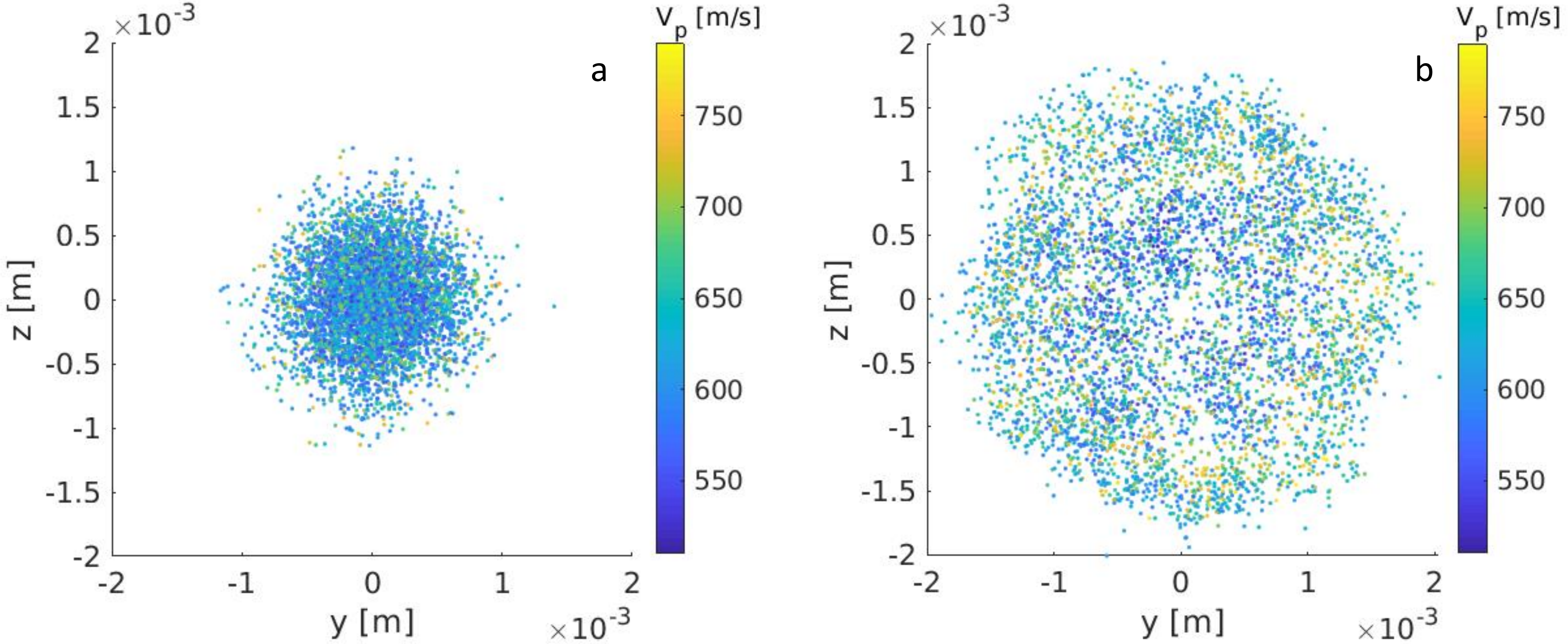

Figure 12: Radial spread of the 316L stainless steel particles on impact with the substrate located at 35 mm from the nozzle exit (a) Out4 nozzle and (b) Contur nozzle.

Area density of particles

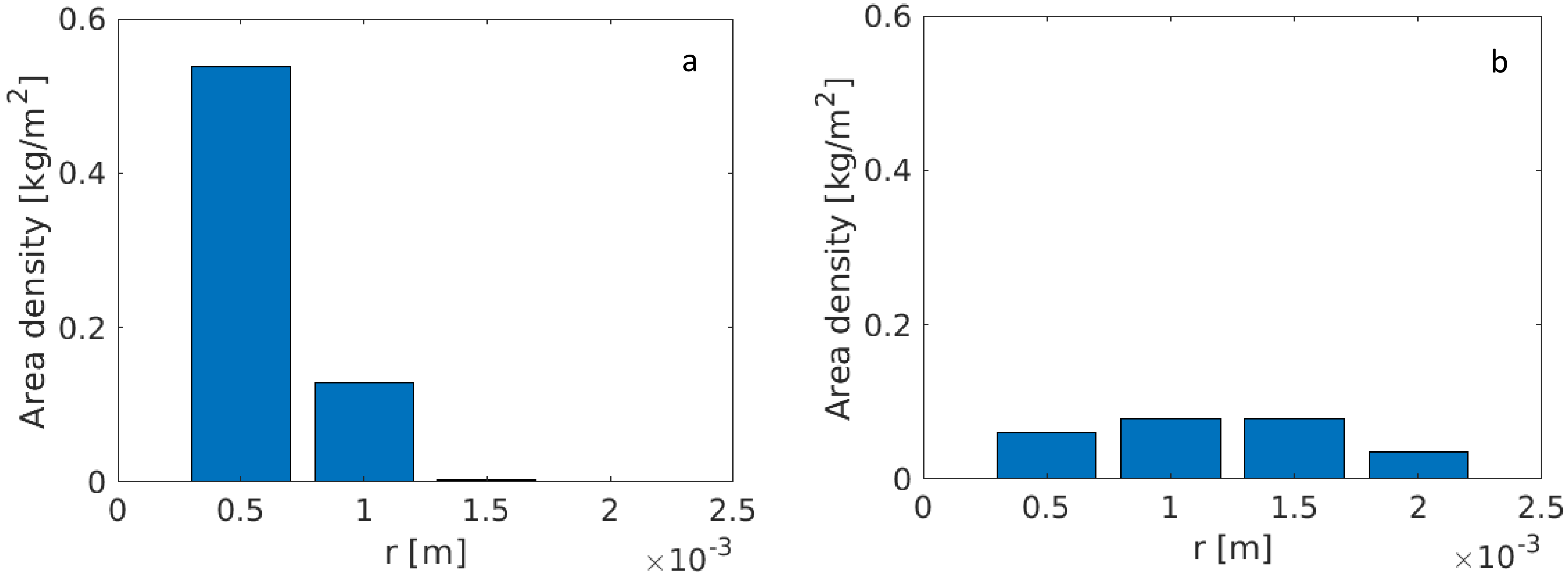

Figure 13: Area density of the 316L stainless steel particles on impact with the substrate located at 35 mm from the nozzle exit (a) Out4 nozzle and (b) Contur nozzle.

Penalty function

Table 3: Bulk performance of the baseline and redesigned cold spray nozzles based on the ensemble of particles impacting the substrate located 35 mm downstream of the nozzle exit plane.

	TWI	**Contur**
$Z_1 = \bar{V_p}/\max(V_g)$	0.4603	0.4759
$Z_2 = \sigma(V_p)/\bar{V_p}$	0.0598	0.0724
$Z_3 = COV$	0.7610	0.6077
$\Phi = 0.25(1 - Z_1) + 0.25Z_2 + 0.5Z_3$	0.5304	0.4530

Z_1 - ratio of the mass-weighted particle speed evaluated just off the substrate (target) to the maximum gas velocity
Z_2 - mass-weighted standard deviation of the particle speed normalized by the mass-weighted mean particle speed
Z_3 - coefficient of variation, which is a point-to-point measure of the uniformity in the spread of the particles over the substrate face

Conclusions

- CFD simulations of a supersonic nitrogen jet lightly laden with 316L stainless steel particles were performed.
- The flow dynamics and the particle behavior reproduced the experimental data pattern reported in the literature.
- The CFD results indicate that tangible benefits are achievable by redesigning the cold spray nozzle by the Method of Characteristics.
- Future work aims to use computer based optimization of the nozzle inner wall to further improve the deposition performance.

References

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Acknowledgements

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