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METAL PARTICLE ACCELERATION TO SUPERSONIC SPEED: NUMERICAL SIMULATION AND PRELIMINARY RESULTS

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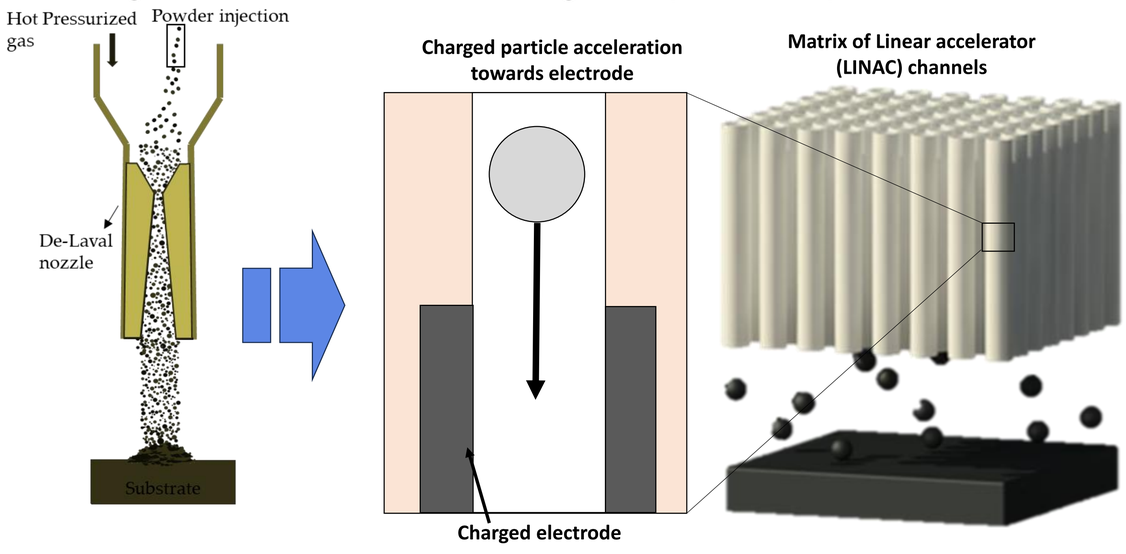
INTRODUCTION

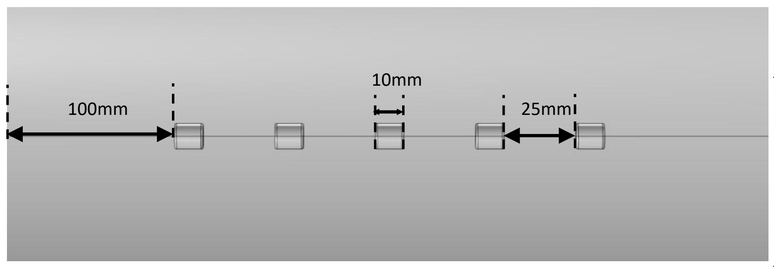
Cold spray process (CS) is a solid-state deposition process where high velocity particles undergo **severe plastic deformation upon impact to bond with the substrate**. Since CS doesn't involve typical material melting and rapid solidification, smaller heat-affected zones are formed - **preserving the original properties of the feedstock material.** Because of its ability to produce dense deposits, CS is widely used as coating and repair method in aerospace, automotive and defense industries. CS relies on **pre-heated, pressurized gas (Air, He, N_2) to propel particles through a converging-diverging nozzle** which limits feature resolution, accuracy and surface quality.

This research explores an **electric field assisted particle acceleration approach** to replace gas acceleration and improve control and efficiency. This study suggests a precise and scalable alternative broadening the capabilities of **solid-state deposition technologies for advanced manufacturing and repair techniques**.



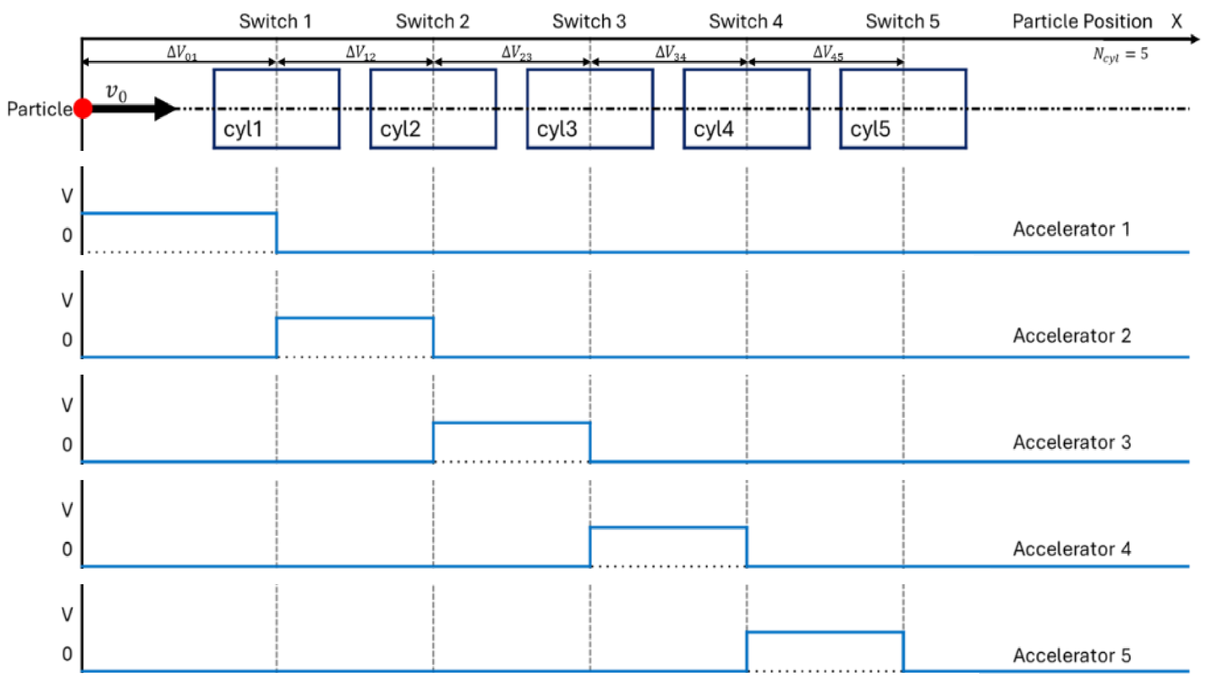
SIMULATION SETUP

Five equi-spaced cylindrical electrodes switching voltages to accelerate the particle



Cylindrical Accelerator Parameters		
Number of cylinders	5	-
Cylinder radius	3	[mm]
Cylinder length	10	[mm]
Cylinder spacing	25	[mm]

When particle enters a cylinder, the previous stage voltage is dropped to zero and applied onto the next with a **square wave voltage function** rapidly charging and discharging accelerators based on particle position



The model is implemented in **COMSOL Multiphysics** using the **Electrostatics (es)** and the **Charged Particle Tracing (CPT)** modules. The particle is assumed to be a point charge and point mass with negligible initial velocity. The final velocity is estimated using an energy balance equation.

Particle Velocity based on Energy Balance Equation

$$v_f \approx \sqrt{2 \cdot \left(\frac{q}{m}\right)_P \cdot N_{cyl} \cdot \Delta V}$$

Copper Particle Properties		
Particle diameter (d)	30	[µm]
Material density	8960	[kg/m^3]
Field Emission limit	For smooth surface: 10^{10}	[V/m]
	For rough surface: 10^9	[V/m]
Maximum charge-to-mass ratio	For smooth sphere: 1.97	[C/kg]
	For rough sphere: 0.19	[C/kg]
Particle charge-to-mass ratio	0.1, 0.5, 1	[C/kg]
Cylinder voltage	50, 100	[kV]

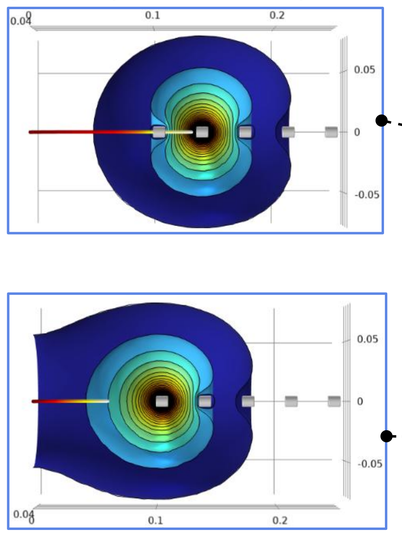
RESULTS

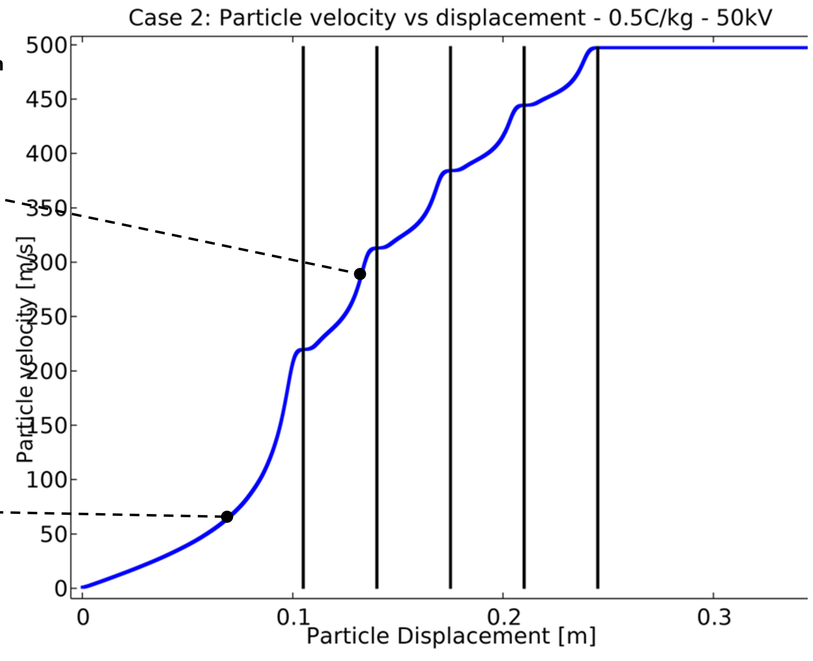
Initially, the particle starts far from the first accelerator, where the electric field is negligible, leading to a longer time to gain speed. The electric field strength increases sharply as the particle approaches each cylinder, resulting in higher acceleration.

Comparing theoretical and simulated velocities after each acceleration stage reveals that the first-stage velocity is slightly lower than expected due to non-zero potential at charged particle entry. However, in subsequent stages, almost all electric energy is successfully converted into kinetic energy, closely matching theoretical predictions.

Three cases are analyzed with **charge-to-mass ratio** and **accelerator voltage** of **0.1C/kg - 50kV, 0.5C/kg – 50kV and 1C/kg – 100kV**. The resulting velocities were approximately **222, 497 and 994m/s**, respectively, with case 2 and case 3 **achieving sufficient velocity for copper particle deposition**.

Equi-potential surfaces and potential gradient dependent on boundary condition





Case 2: Particle with charge-to-mass ratio of 0.5C/kg and 50kV on electrodes

Particle Position	Expected Velocity [m/s]	Total Applied Energy [keV]	Simulated Velocity [m/s]	Energy gained [keV]	Total Energy [keV]
Cylinder 1	223.6	50	219.69	48.26	48.26
Cylinder 2	316.23	100	312.98	49.7	97.96
Cylinder 3	387.3	150	384.52	49.9	147.86
Cylinder 4	447.21	200	444.42	49.65	197.51
Cylinder 5	500	250	497.47	49.97	247.48

Case 3: Particle with charge-to-mass ratio of 1C/kg and 100kV on electrodes

Particle Position	Expected Velocity [m/s]	Total Applied Energy [keV]	Simulated Velocity [m/s]	Energy gained [keV]	Total Energy [keV]
Cylinder 1	447.2	100	439.28	96.48	96.48
Cylinder 2	632.46	200	625.96	99.43	195.91
Cylinder 3	774.6	300	768.9	99.69	295.6
Cylinder 4	894.42	400	888.66	99.25	394.85
Cylinder 5	1000	500	994.51	99.7	494.55

CONCLUSION

The **velocity equation correctly predicts the final velocity of the particle** attained using multistage accelerators. The first acceleration stage is the most time-consuming phase. So, **adjusting voltage gradient at each stage can optimize process time and energy consumption**. The **voltage difference across each stage, number of accelerators and charge-to-mass ratio determine final velocity** of the particle. Optimizing these parameters can reduce operational costs for hard materials that require higher impact velocity.

This study presents a potential **new method for solid-state deposition of metal powders through electrostatic charging and acceleration, offering several advantages over existing thermal spray processes**. The simulation results closely match with theoretical predictions demonstrating process feasibility and with a well-designed equipment process efficiency can be improved. Further numerical and experimental work is required to refine the approach and develop an optimized prototype for practical implementation.

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