meta4.0

Joint Master in Manufacturing 4.0

ÉCOLE CENTRALE LYON

Course: **High Temperature Processes**

Cold Spray

Professor: Sova Alexey

Laboratory session

on

Deposition of SS (360L) on a Cylinder (Al 3000 series)

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S/N	Name	Entity	Group	Date
1.	SIRIRO Wiseman	META 4.0	Stainless Steel	18/12/2023

TABLE OF CONTENT

1. ABSTRACT

The efficacy of particles to have the sufficient energy to adhere onto a substrate in cold spraying hinges on surpassing critical impact velocities. This laboratory session demonstrated the Cold Spray deposition of Stainless Steel (SS) 360L on an aluminium 3000series cylindrical rod, and this report aims at detailing how important the impact speed and temperature are, for a successful particle adhesion and how they were numerically obtained. This experiment employed a meticulous two-step process. Using the Conic Nozzle Software and Excel, the first process involved the analytically estimation of the optimal gas pressure, P_0 $[Mpa]$ and gas temperature, $T_o[K]$ The best deposition strategy was determined: the aluminium will be rotated against a nozzle at a predetermined angle. The second step involved testing the simulated temperature and pressure as entry parameters, and adjudging if the deposition was successful or otherwise. In this test, it was observed that the deposition efficiency was about 85% and the deposition was through local metallurgical bonding and mechanical interlocking which are caused by localized plastic deformation at the interparticle and particle-substrate interfaces.

2. INTRODUCTION

In real life applications, it is inevitable for most functional materials to be operating under degrading surroundings, such as high temperatures, high humidity, high pressures, etcetera. Such environments tend to eat away the surface of the materials or causes the materials to weaken in their functional properties. Since the environment is a constant factor that cannot be removed, ways have been devised to enable these materials to cope with such environmental factors ensuring proper functionalities and durability. These measures include:

- Alloying: For example, elements with better properties are added to iron to form stainless steel, which is not easily worn out through corrosion unlike iron.
- Coating: Substances are adhered to the surface of materials, thus shield them from directly interacting with environmental factors. Thermal spray and Cold spray are among the coating technologies used.

Thermal spray has been widely used for surface coating. Despite its success, there is a downside to this technology: the high temperature used causes modification in material properties. For instance, high temperature increases resistance in the metallic material, leading to poor conductivity, therefore, using thermal spray is not suitable for copper deposition for electrical applications. Cold spray is therefore preferred over thermal spray where there is need to retain electrical, thermal, or mechanical properties identical to the feed materials.

In cold spray, the powder material is accelerated by an inert gas at a certain speed towards the substrate, requiring coating. The high impact speed causes plastic deformation and adiabatic shearing resulting in the adherence of the particles onto the substrate, or onto previous particles. Consequently, fine grain sizes result in higher strength and fatigue properties.

Cold spray is performed in temperatures below the melting point of the particles. The maximum temperature to apply for the cold spray varies from material to material and is calculated as follows: $T_{max} = 0.5 * T_{melt}$. Higher temperatures in cold spray increase the risk of oxidation and therefore should be avoided. Besides, in case of the use of nitrogen gas, higher temperatures can result in formation of nitrides too. In addition, the gas that is mostly preferred to accelerate the feed powder particles is Helium, because it is very light and inactive. Nonetheless, Helium is expensive, and for that reason, Nitrogen is preferred. Argon is denser; therefore, it is hardly employed in this process. On the other hand, air is not used because it can cause oxidation.

The main factors affecting the adherence of the powder particles onto the substrate material include:

- Impact Temperature: Generally, up to the maximum temperature required, the higher the temperature, the better the particle deposition efficiency.
- Impact Velocity
- Particle size: Larger particles tend to retain higher temperatures during flight compared to the smaller particles. Therefore, larger particles have lower critical speed than smaller particles. Software simulations are often necessary to establish optimum conditions for the adherence of different sized particles onto the substrate. These simulations consider the critical speed, which is dependent on the powder and substrate material properties.
- Other factors include pressure, distance between the nozzle and the substrate, nozzle dimensions, etc. While conducting cold spray, safety measures should be taken. The process is conducted in a closed chamber to prevent health hazards and risks caused by dust sprays.

3. METHODOLOGY

3.1 EXPERIMENTAL PROCEDURE

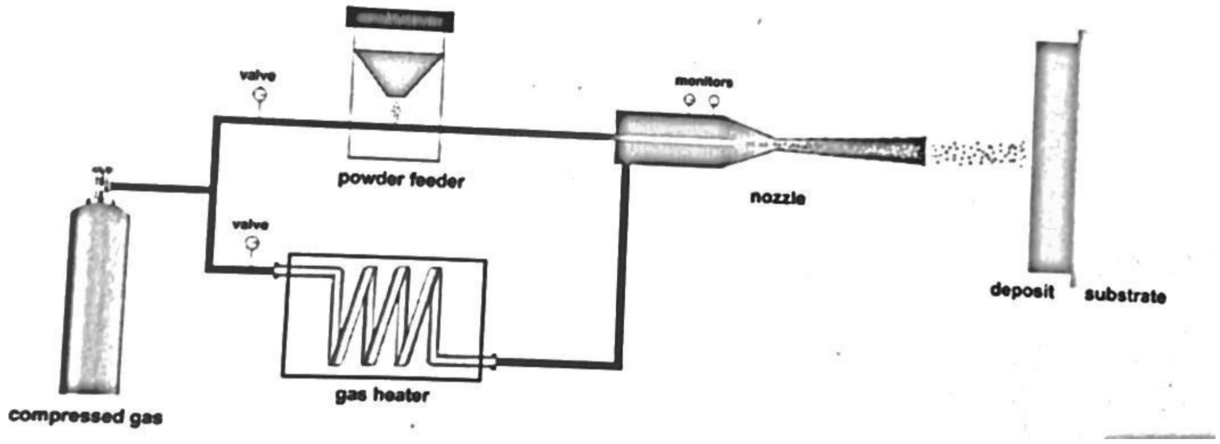


Figure 1 Schematic Diagram of Cold Spray

Figure 1 provides a detailed schematic of a high-pressure cold spray system, showcasing the essential components and the flow of gas and powder particles that enable the deposition of a dense and adherent coating onto a substrate.

Key Components

a. Powder Feeder: The powder feeder delivers a controlled flow of feedstock material, typically in the form of fine particles, into the cold spray system. The specific powder material is selected based on the desired properties of the coating.

b. Compressed Gas Supply: The compressed gas supply provides the driving force for accelerating the powder particles to supersonic velocities. The gas typically consists of air, nitrogen, argon, or a mixture of these gases. Gas Heater: The gas heater raises the temperature of the propulsive gas to a high level, typically 1,000°C. The elevated temperature increases the kinetic energy of the gas molecules, imparting a significant momentum to the powder particles as they pass through the gas stream.

c. Carrier Gas: The carrier gas, typically at a lower pressure than the propulsive gas, carries the powder particles from the feeder to the de Laval nozzle. The carrier gas also serves to stabilize the powder particles during their journey through the nozzle, preventing them from breaking up or deviating from their intended trajectory.

d. De Laval Nozzle: The de Laval nozzle is a specialized nozzle that expands the gas to supersonic speeds, generating a high-pressure shockwave that further accelerates the powder particles. The supersonic velocity of the particles is crucial for achieving a dense and strong coating.
e. Nozzle Exit: The nozzle exit is the point where the supersonic gas and powder stream emerges from the nozzle. The high-velocity particles impact the substrate at a temperature well below their melting point, resulting in plastic deformation and fusion, forming a strong metallurgical bond between the coating and the substrate.

Detailed Process

Powder Feeding: The powder feeder delivers a controlled flow of powder particles into the cold spray system.
Gas Splitting: The compressed gas entering the system is split into two streams: the carrier gas and the propulsive gas.
Gas Heating: The propulsive gas passes through the gas heater, where it is heated to a high temperature.
Gas Mixing: The carrier gas, carrying the powder particles, is mixed with the heated propulsive gas before entering the de Laval nozzle.
Supersonic Expansion: The mixed gas stream enters the de Laval nozzle, where it expands and undergoes a sudden decrease in pressure. This expansion generates a high-pressure shockwave that further accelerates the powder particles to supersonic velocities.
Particle Impact and Bonding: The highly accelerated powder particles impact the substrate at a temperature well below their melting point. The high impact energy causes the particles to plastically deform and fuse together, forming a dense and adherent coating.
Coating Formation: The continuous deposition of powder particles results in the formation of a continuous and uniform coating on the substrate. The thickness of the coating can be controlled by adjusting the process parameters, such as gas pressure, nozzle geometry, and coating speed.

3.2 FINDING CRITICAL VELOCITY, V_{cr}, & TEMPERATURE.

The critical velocity, $V_{cr,}$ was calculated using the formula given below:

$$v_{cr} = \sqrt{\frac{F_1 \cdot 4 \cdot \sigma_{TS} \cdot \left(1 - \frac{T_i - T_R}{T_m - T_R}\right)}{\rho} + F_2 \cdot c_p \cdot (T_m - T_i)} \quad (1)$$

Where, F_1 and F_2 are constants and equal to 1.2 and 0.3 respectively. σ_{TS} is the tensile strength of Stainless Steel 316l which is equal to 5.15×10^8 MPa. T_m is the melting temperature for stainless steel is equal to 1673 K. T_R is the room temperature with the value 293K. ρ is the density of SS 316l and is equal to 7890 Kg/m^3. Lastly, c_p, the specific heat capacity of SS 316l is equal to 490 J/Kg·K. The value of the critical velocity was calculated from the values of temperature, T_i in the range of room temperature, T_R (300 K), to 0.5*(Melting Temperature of Stainless Steel 316l, T_m). Optimal Velocity, V_i, is approximately 1.5 times critical velocity, V_{cr}.

Table 1. Result of temperature and corresponding critical and impact velocity

Temperature (K)	Critical Velocity, V_{cr} (cm/s)	Impact Velocity, V_i (cm/s)
300	716.62	1074.94
350	703.45	1055.18
400	690.03	1035.05
450	676.35	1014.52
500	662.38	993.56
550	648.11	972.16
600	633.51	950.27
650	618.58	927.87
700	603.27	904.91
750	587.57	881.35
800	571.43	857.15
850	554.82	832.24

The above values of critical and optimal velocity are plotted on a graph below.

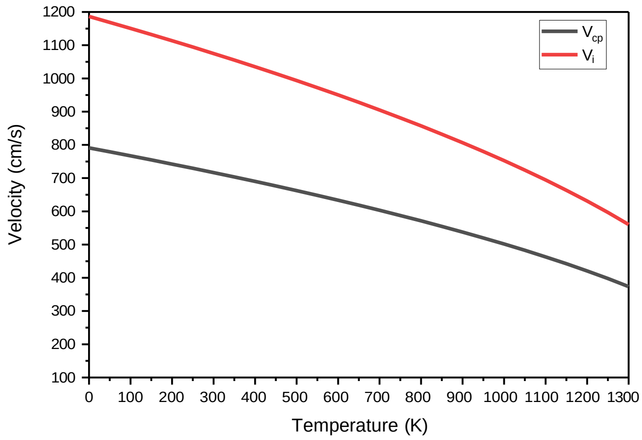


Figure 2: graph depicting the trend for critical velocity V_{cp} and ideal velocity, V_i.

3.2 SIMULATING VELOCITY & TEMPERATURE AS A FUNCTION OF GAS T_o, P_o, NOZZLE GEOMETRY.

To find the optimum parameters the “Conic Nozzle” software was used to calculate the exit velocity and temperature as a function of gas pre-heating temperature, gas pressure and particle size. Nozzle geometry was predetermined. The boundary conditions for the gas pressure were set to be 2.6 – 3.6 MPa.

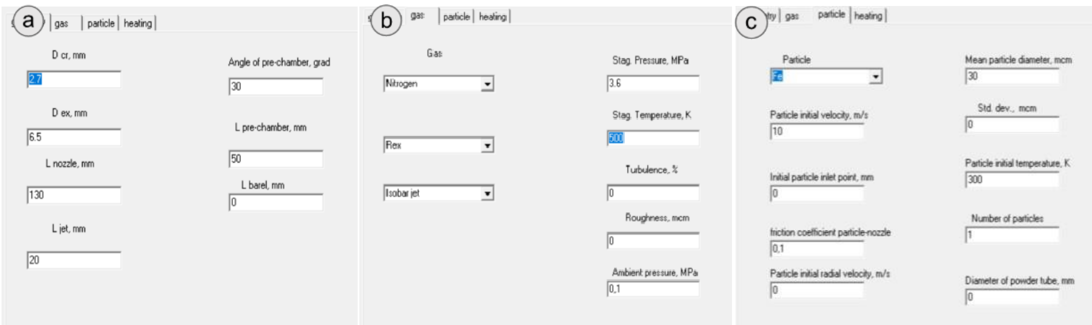
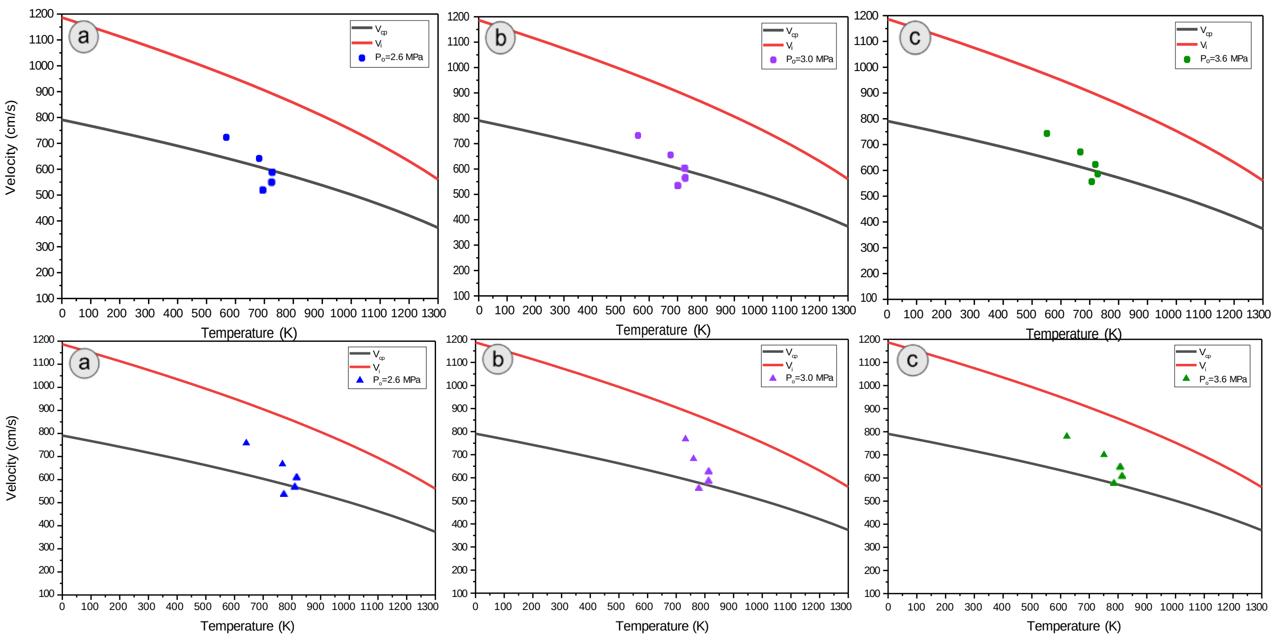


Figure 3: Input parameters for simulation software.

From figure 2, It was observed that the values obtained through the simulation software for optimum velocity that for the larger particle size 30, 40 and 50 microns was below the critical velocity required for particle adhesion at the substrate at Po = 2.6 MPa and To = 840 K. Increasing the pressure to 3.0 MPa and 3.6 MPa had a very minimal effect on the optimal velocity obtained.



Therefore, we then increased the gas temperature parameter to 940 K. And obtained the results as shown below in figure 3. We can see that when the T_o = 940 K and P_o = 3.6 MPa, all particle sizes have an optimum velocity above the critical velocity line.

3.3 CALCULATING NOZZLE SPEED

Thickness of coating, T: 0.1cm

Radius of the rod, r. 2.9cm

Coating Length, L: 12.5cm

Deposition efficiency of Stainless Steel 316l, D.E: 75%

Deposition flow rate, f: 0.3 cm^3/s

Calculations

Volume of the Cylindrical rod, Vr = $\pi \cdot r^2 \cdot h = \pi \cdot (2.9)^2 \cdot (12.5)$ = 327.99 cm3.

Volume of the rod + coating, Vr+c = $\pi \cdot (r+T)^2 \cdot h = \pi \cdot (2.9+0.1)^2 \cdot (12.5)$ = 351 cm3.

Coating volume, Vc = Vr+c – Vr = 351 – 327.99 = 23.01 cm3.

Time required for coating, t = Vc/(f × D.E) = 23.01/(0.3·0.75) = 102.27 s

Nozzle velocity, v = l/t = 12.5/102.27 = 0.12 cm/s.

The calculated nozzle velocity is 1.2 mm/s but experimentally we rounded off to the closest unit and used 1 mm/s.

4. RESULT AND DISCUSIONS

In the cold spray demonstration, a series of experiments were meticulously conducted to investigate the coating process of stainless steel 316L onto 360cm^3 aluminium cylinder substrates. The experimental methodology involved the utilization of cold spray techniques, where particles were propelled at high velocities through a supersonic gas stream, enabling their deposition onto the aluminium substrate. This innovative process is renowned for its efficiency in material buildup while concurrently minimizing thermal impact, thereby preserving the intrinsic properties of the substrate.

The goal of these experiments was to deposit a 3mm coating with a powder rate of 0.3cm^3, utilizing a nozzle speed designed to produce 1mm per layer. Despite the deviation in parameters, the deposition efficiency for stainless steel 316L onto 360cm^3 aluminium cylinder substrates was observed at an encouraging 85% after two passes instead of the initial 3 passes.

After numerous analytical simulations, the graph shows that at To = 940 K and Po = 3.6 MPa, all particle sizes have an optimum velocity above the critical velocity line. The calculated nozzle velocity is 1.2 mm/s but experimentally we rounded off to the closest unit and used 1 mm. The Conic Nozzle Software was used in simulating parameters related to geometry, gas, particle, and heating, providing crucial data for the experiments.

Furthermore, a noteworthy observation arose as the velocity emerged as a pivotal factor influencing the pressure necessary to propel the powder through the nozzle onto the aluminium 6000 series substrate. This unanticipated deviation from the planned parameters underscores the intricate interplay of variables inherent in cold spray coating processes. It emphasizes the importance of meticulous control and a comprehensive understanding of the factors influencing deposition outcomes, reinforcing the need for continued research and refinement in this innovative field.

5. CONCLUSION

Cold Spray is a solid-state material deposition process, and in contrast to conventional high-temperature deposition processes, the particle adhesion depends on the particle kinetic energy before impact rather than thermal energy. The particles are not melted in the converging-diverging chamber, but they are only preheated below their melting temperature and then accelerated to supersonic speed by the propulsive gas which induces deformation at impact. This report has successfully demonstrated that the adhesion of particles in cold spraying hinges on surpassing critical impact velocities, necessitating an optimal interplay of impact speed and temperature, optimizing the deposition strategy, the optimal nozzle speed, material type and particle size. This case-study elucidates that the ability to achieve the aforementioned lies on the detailed analytical estimation of the gas pressure and gas temperature by considering the tensile strength, the heating capacity and ensuring that the melting temperature of the particle is stringently controlled. Like examined, this was strictly controlled during the analytical estimation stage by considering that the maximum gas temperature is limited to halfway of the stainless steel’s melting temperature. These parameters are crucial for particle adhesion, leveraging the acceleration and preheating of particles within the nozzle's gas flow, and ensuring that particle is not splatted within the preheat chamber but at the point of impact. Rigorous estimations of Nitrogen's gas properties and temperatures at the entry stage profoundly influenced the meticulous design of an optimal deposition strategy. This approach ingeniously incorporated cylinder rotation as an integral deposition tactic, synergized with precise nozzle speed calculations.

Our experimental investigation prioritized the meticulous calibration of input parameters for depositing Stainless Steel (360L) onto a 327cm^3 Aluminium Cylinder. This meticulous calibration culminated in the achievement of successful Stainless Steel (360L) adhesion under specific conditions—where an impact temperature of 940K and a pressure of 3.6MPa proved pivotal. Notably, our meticulous experimental exploration surpassed initial expectations by showcasing a deposition efficiency that marginally outstripped the anticipated 75%. This overachievement yielded a tangible result—a robust 3mm layer thickness meticulously achieved after executing just two spraying passes.