The Indian Thermal Spray Association
ITSA ASSOCIATION FOR THERMAL SPRAY TECHNOLOGY AND RESEARCH

Dec 2025| Vol. 5| Issue 4

SPRAYTODAY®

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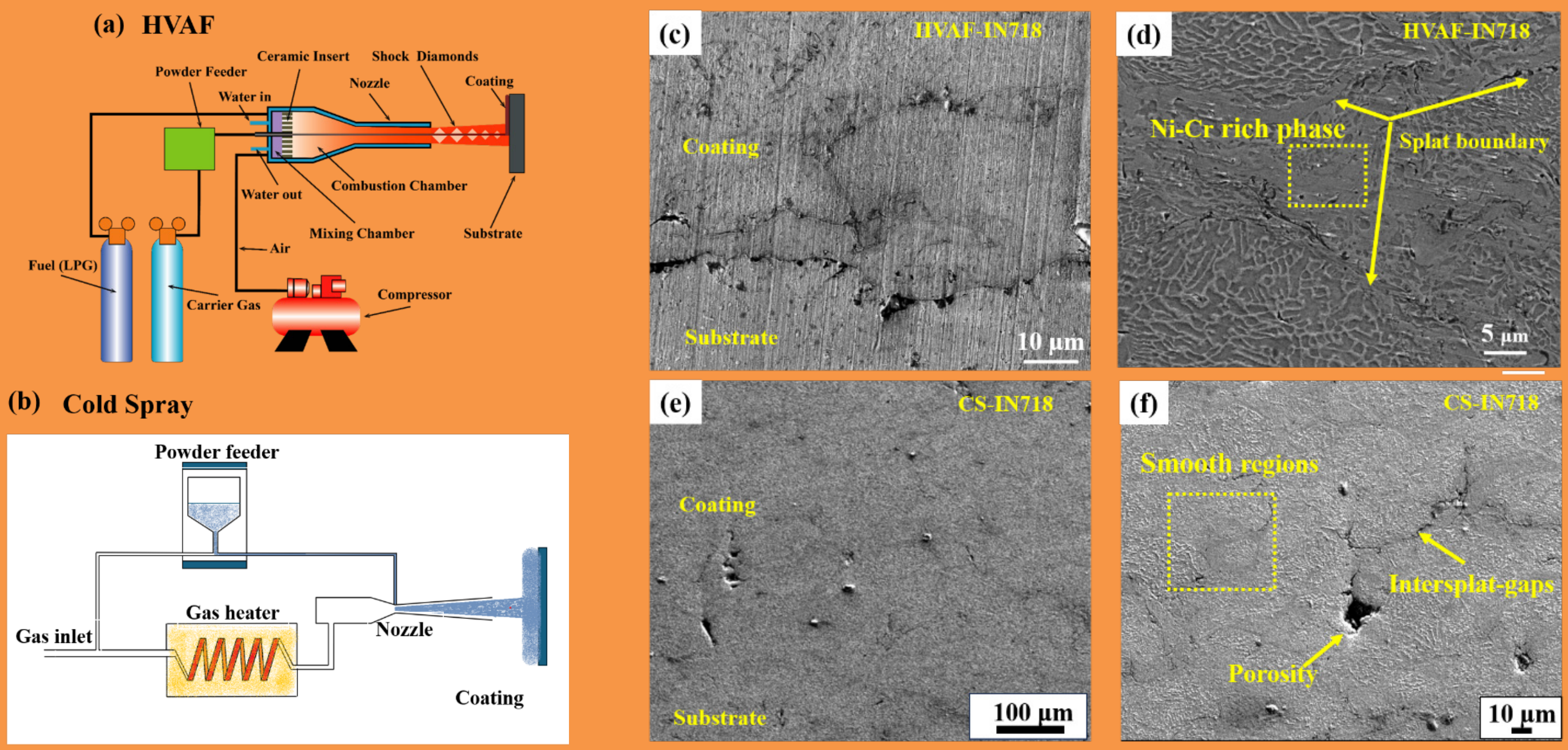

Issue Highlights

- Engineered Coatings for Reliable Semiconductor Process Chambers
- Influence of Spray Processes on IN718 Coating: Cold Spray and High Velocity Air Fuel
- A study on the Effect of Process Parameters in Low Pressure Cold Spray Deposition

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SPRAYCOLD

(COLD SPRAY SYSTEM)

Introducing a metal deposition process that requires no blast cleaning and no oxy-fuel gases. It works solely with air, providing a coating with high bond strength and density. You can apply almost any metal powder, including brass, copper, nickel, aluminum, zinc, tin, bronze, lead, stainless steel, aluminum - silicon carbide, aluminum-copper- zinc, nickel-zinc, copper-tin-lead and many more.

MCS - 23

Cold spray gun with heater installed.

MSC - 500

(MEC cold spray system with trolley, massflow controlled & pressurized powder feeder and PLC controlled panel.)

Advantages

- Green, solid-state process: No combustion flame, fumes, phase change during deposition.
- Ideal for in-situ repair, restoration & AM part correction.
- Delivers high deposition efficiency with minimal thermal impact.
- Enables coating of Al, Mg, Ti, and other reactive

Application of Cold Spray

- Repair, restore & AM part correction.
- Repair bearing seats.
- Cavitiation corrosion protection
- Hermetically seal rediators and air conditioner.
- Add electrical conductive layers to materials.
- Additive manufacturing and many more.

Special Features:

- The detachable type control screen can be removed and positioned on another stand or exterior wall of the spray chamber if user wants to spray using robot/manipulator.
- Working Gas: Air or Nitrogen
- Single Phase Electrical Supply Requirement.
- Operating pressure Temperature: 10 bar at 50 °C

Maximum power consumption:- 3.3kW

Power supply:- Single Phase 220v, 50/60Hz

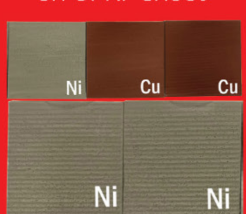
Powder consumption:- 10-20 gm/min
(compatible powder will be supplied by MEC)

Capacity of Powder Feeder:- 3350 CC (3.3 Liter)

Dimensions and Weight of the System:-
Approx. 600(W) x 500(L) x 1400(H)
Approx. 110 kg

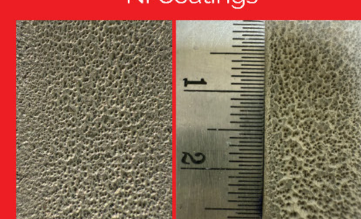
Compressed air consumption:- 0.3 - 0.4 m^3/min

Ni and Cu coatings on CFRP sheet



Repair and Restore Part

Texture Driven Cold Sprayed Ni Coatings



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Mission: Our mission is to deliver the most recent thermal spray industry news and keep up to date to the thermal spray community by providing company, event, people, product, research, and membership news of interest to industrial leaders, engineers, researchers, scholars, policymakers, and the public thermal spray community.

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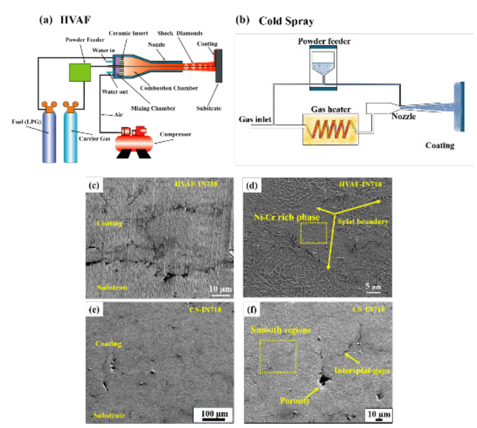

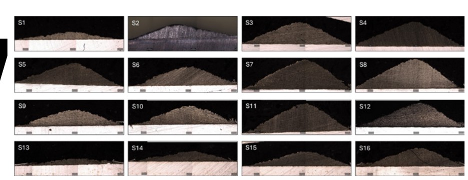

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ABOUT THE COVER

PSchematic representation of (a) HVAF spraying process and (b) cold spray process; Low and High-magnification FESEM cross-section microstructures of (c-d) HVAF-IN718, and (e-f) CS-IN718

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Editor's Note

Dear Readers,

Welcome to the latest edition of SPRAYTODAY Magazine, your premier source for all things related to thermal spray technology. We are excited to bring you this issue, which reflects the latest advancements and trends in the thermal spray field.

I am particularly pleased to be allowed to recommend to you the latest issue of SPRAYTODAY. This issue includes invited innovative featured articles on **"Engineered Coatings for Reliable Semiconductor Process Chambers; Influence of Spray Processes on IN718 Coating: Cold Spray and High Velocity Air Fuel; and A study on the Effect of Process Parameters in Low Pressure Cold Spray Deposition"**, that illustrate current research trends in thermal spray development.

We are excited to announce our upcoming event on cold spray: The international cold Spray Conference and Expo (ICSC 2026), will be held on Jan 23-25, 2026, at the IITM Research Park IIT Madras, Chennai. This conference will serve as a hub of innovation and collaboration for cold spray technology. More than 350+delegates, including leading experts, researchers, and industry professionals from around the globe will attend the ICSC2026 to discuss cutting-edge developments, share insights, and explore the future of cold spray technology in the world. With a robust lineup of keynote speeches, technical sessions, and an expansive expo will be showcasing the latest equipment, materials and recent developments. The conference significantly will contribute to learning about the latest advancements and understanding the new applications of Cold spray technology. ICSC2026 website https://www.indtsa.org/icsc-2026

As we navigate the pages of this magazine, let's collectively embrace the spirit of innovation and collaboration. The thermal spray community in India is not just witnessing change; it is driving it. We hope this edition sparks inspiration, fosters knowledge exchange, and fuels the passion for pushing the boundaries of thermal spray technology.

Thank you for being part of our journey.

Be healthy, active, and curious! Happy Spraying!

Best Regards,

(Satish Tailor | PhD)


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Great coating
every run
Thermal spray sensor
tecnar
accuraspray 4.0
The ultimate thermal spray monitoring solution
to increase productivity, streamline your processes and stay
competitive in today's research and fabrication industry.
tecnar
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Engineered Coatings for Reliable Semiconductor Process Chambers

by ***Gopi Chandran R[1], Satish Tailor[2]***

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Abstract
The semiconductor industry is expected to enter a trillion-dollar growth phase by 2030, driven by advanced semiconductor technologies and the ones enabling viz., AI, EVs, and quantum computing. As device nodes shrink below 5 nm, equipment reliability becomes critical, with chamber components exposed to extreme plasma, corrosive gases, and ion bombardment. Thermal Spray Coatings (TSC) offer robust protection by extending equipment life, reducing contamination, and lowering maintenance costs. TSC provides scalable, thick coatings for chamber walls and components, with ceramics like Y_2O_3, Al_2O_3, and ZrO_2 delivering superior plasma resistance and durability. Emerging materials including oxyfluorides, high-entropy ceramics, and hybrid coatings; promise further performance gains. With India's growing semiconductor ecosystem, expertise in advanced coatings positions the country to play a vital role in enabling sustainable, high-performance manufacturing.

Introduction
The semiconductor industry is undergoing a once-in-a-generation transformation. Valued at nearly $500 billion today, it is projected to reach $1 trillion by 2030. This growth is fueled (besides advances in semiconductors & packaging) by breakthroughs in artificial intelligence, autonomous vehicles, renewable energy, electric mobility, and quantum computing. With device nodes shrinking below 5 nm, the demand for new materials, advanced packaging, and innovative processes has never been greater.
India, through its Semiconductor Mission, is positioning itself as a serious player in this high-tech domain. The recently concluded India SEMICON 2025, in September, showcased the country's growing role, with fabs and specialized academic programs set to accelerate progress. Among the many enabling technologies, thermal spray coatings (TSC) stand out as a critical solution for semiconductor equipment reliability.

Why Coatings Matter?
Semiconductor wafer fabrication equipment (WFE) process chambers face extreme environments: erosive plasmas, corrosive gases, and ion bombardment. Components, often made of aluminium alloys, suffer erosion, contamination, and particle generation, all of which compromise wafer yield.

- Protective coatings are essential to:
- Extend equipment life cycles
- Reduce contamination risks
- Maintain dimensional stability under high temperatures
- Lower maintenance costs and downtime

Thermal spray coatings, adapted from the success in aerospace applications, now play a pivotal role in semiconductor chambers. Their ability to deliver thick, durable, and corrosion-resistant layers makes them indispensable for etch tools, deposition systems (CVD, ALD, PVD), ion implant equipment, and other high-wear chamber parts.

In order to prevent chamber interiors from extreme plasma environments (etch, deposition, ion implant), corrosive chemistries arising from CFx, halogens, radicals & ions contribute to the formation of particles which lead to erosion damage to process chamber and component parts. To avoid damage, reduce defects, maintain wafer yield, reduce downtime in the wafer processing; there is a need for protective coatings to avoid corrosion/erosion and subsequent creation of defects or particles during fab operations. TSC is required to enhance the performance characteristics and durability of process chamber and component parts. The versatility of thermal spray technologies (Air Plasma Spray, Vacuum based and High Velocity Oxy Fuel, Cold Spray) provide immense benefits to this industry. Thermal spray due to its proven track record of providing thick coatings at scale acts as a protective barrier for Equipment Protection. A CombiCoat® thermal spray system is shown in Figure 1. CombiCoat® Spray System is an advanced surface coating technology that combines multiple thermal spray processes—such as Air Plasma Spray, Vacuum based and High Velocity Oxy Fuel, Cold Spray, Arc Spray & flame spray—to apply protective coatings on metal and non-metal substrates. This hybrid approach enhances corrosion resistance, wear protection, and surface restoration across various industries, including aerospace, automotive, semiconductor and energy.

	PLASMA	HVOLF	HVOF	LVOF WIRE	LVOF POWDER	ARC
Main Control Module	✓	✓	✓	✓	✓	✓
Gas Module	✓	✓	✓	✓	✓	✗
Power Source	✓	✗	✗	✗	✗	✓
Jam Box	✓	✓	✓	✗	✗	✗
Powder Feeder	✓	✓	✓	✗	✓	✗

Figure 1: CombiCoat® thermal spray system (Make MEC Jodhpur)

Process Matters

In thermal spray coating, feedstock particles are accelerated, heated, and expelled from the nozzle in a softened or molten state. On impact, they rapidly solidify to form dense, thick, and durable coatings. By carefully optimizing process parameters (including post processing), coating can be tailored to meet the stringent requirements of semiconductor chamber components, imparting resistance to corrosion, erosion, and aggressive chemistries encountered during fab operations.

Maintaining low porosity is critical, as excessive porosity can lead to particle generation and contamination. Special attention is also required when working with ceramics, the preferred choice, since their brittleness makes them prone to cracking under stress. Achieving reliable, consistent outputs at scale demands both process expertise and state-of-the-art capabilities, as the semiconductor industry has very tight tolerances on the coatings specifications.

Beyond thermal spray, other advanced deposition technologies such as Chemical Vapor Deposition (CVD) and Atomic Layer Deposition (ALD) leverage chemical precursors and sophisticated tools to deliver conformal, high-performance coatings for specialized applications. Comparison of these techniques with TSC is given in Table 1.

Table 1: Comparison of different coating techniques with TSC

Technique	Thickness	Conformality	Plasma Resistance	Particle risk	Typical Use
Thermal Spray	50–500 µm	low	High (e.g Y2O3)	moderate	Chamber walls, shields
CVD	1–50 µm	medium	High	low	SiC-coated parts
ALD	10–500 nm	excellent	Moderate-high	Very low	Nanoscale features, precision parts

Materials that Make Difference

Ceramic coatings are the backbone of semiconductor chamber protection:

- Y_2O_3: Exceptional plasma resistance, especially against fluorine chemistries; widely used in etch chambers.
- Al_2O_3: High hardness and wear resistance; suitable for general wear parts.
- ZrO_2: Superior thermal shock resistance; ideal for high-temperature components.
- Cold Spray Metals: Provide toughness and repair options, though limited for ceramics.

Cost of Yttrium Oxide is high and sometime composite of Y & Al oxides are also considered to protect parts under plasma. The composites or the garnet phase (Y3Al5O12) helps to keep the cost lower. Designing newer materials with better corrosion & erosion properties might be needed in future as the advanced nodes are getting miniaturized. For this to become a reality cationic and anionic substitutions in parent Y2O3 may provide vital clues. One of the choices is the partial replacement of O2- anion with F- due to its common nature with F in plasma. Oxyfluorides of Y are already reported for the same application (see for e.g. Materialstoday Comm., 2025, 42, 111403; Coatings 2024, 14, 1091).

Table 1: Materials and key properties

Coating Material	Key Property	Typical Application	Limitations
Y2O3	High Plasma resistance and low contamination	Etch Chambers	Expensive, Brittle
Al2O3	Hardness, wear resistance	General wear parts	Moderate plasma resistance
ZrO2	Thermal shock resistance	High temperature components	Less chemical resistance
Cold Spray Metals	Toughness, no melting	Structural repair, hybrid coatings	Limited success with ceramics

Emerging Trends in Materials & Process

Figure 2: Emerging Trends in Materials & Process

Evolving classes of materials to be considered are Refractory Oxyfluorides, Multicomponent systems designed for better performance (e.g. high entropy ceramics counterparts/replacement for Y2O3 or bulk metallic glasses designed for better plasma, corrosion & erosion resistance), materials with higher covalency that can further enhance the strength of material and provide greater protection. Hybrid coatings comprising of metals & ceramics can be considered for better toughness. Cold Spray (CS) where solid particles are accelerated at supersonic velocities under high pressure & temperature (below melting point) is gaining importance, especially in metals, as it helps avoid oxidation. However, CS has limited success with ceramics. Nanostructured Thermal Spray (NTS) helps reduce porosity with improved purity. Conventional TSC combined with NTS or ALD for few nm top layers may help reduce porosity and improve surface roughness.

The Road Ahead

Thermal spray coatings continue to dominate bulk coating applications due to scalability, versatility, and proven reliability. As semiconductor manufacturing becomes more complex, coatings will remain central to sustaining productivity, minimizing downtime, and ensuring wafer yield.

India's expertise in thermal spray research, combined with the establishment of clean-room spray facilities and up-skilling manpower, can position the country as a global coating's hub for semiconductor industry.

Influence of Spray Processes on IN718 Coating: Cold Spray and High Velocity Air Fuel

by ***Malar Vadani GT[1], Sudha Kumari[1], Chandan Mondal[2], Nitya Nand Gosvami[1], Ayan Bhowmik[†]***

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Email: abhowmik@iitd.ac.in

Abstract
This study investigates the influence of cold spray (CS) and high velocity air fuel (HVAF) processes on the microstructural, mechanical, and tribological properties of Inconel 718 (IN718) coatings. IN718 powders were deposited onto IN718 substrates via CS and HVAF under controlled conditions, and the resulting coatings were characterised using X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM), microhardness, and wear testing. A predominance of only th γ-Ni phase was noted in all coatings, with CS coatings exhibiting broader peaks indicative of higher dislocation density and microstrain. Microstructural analysis revealed that HVAF coatings are denser (~1.5% porosity) with well-bonded lamellae and uniform interfacial cohesion, while CS coatings show heterogeneous splat deformation with retained dendritic cores and refined splat boundaries. Mechanically, CS coatings exhibit higher hardness (~500–550 HV) due to strain hardening, whereas HVAF coatings demonstrate superior interfacial strength and lower wear volume (~10% reduction). The findings highlight that CS promotes hardness and oxidation resistance through solid-state particle deformation, whereas HVAF enhances interfacial bonding and wear stability via thermal-assisted deformation. Overall, the study provides insight into how spray mechanisms govern coating integrity, guiding optimal process selection for high-performance IN718 surface protection.

Introduction
Nickel-base superalloys such as Inconel 718 (IN718) serve critical roles in aerospace, energy, and chemical engineering because they maintain strength, oxidation resistance, and phase stability at high temperatures [1,2]. Yet, even with their excellent bulk properties, IN718 parts undergo surface degradation in service, such as wear, erosion, and high-temperature oxidation, which degrade the performance of components. Applying repair coatings offers a pathway to enhance surface durability and longevity of components while preserving the structural integrity of the underlying substrate.
Thermal spray techniques are widely used to deposit such protective layers on metallic substrates. These methods accelerate fine particles toward a surface, where impact induces bonding. Among the spray methods, cold spray (CS) and high velocity air fuel (HVAF) have shown promise for nickel-based systems because they offer potential to reduce thermal damage while achieving strong adhesion [3,4].

In cold spray, particles remain in a solid-state during flight. A high-pressure gas jet propels them to supersonic velocities, and on impact, they bond through severe plastic deformation and mechanical interlocking [4]. Because the material does not melt, cold spray largely preserves the feedstock microstructure and limits oxidation or phase changes [5-7]. However, cold spraying

IN718 presents challenges: its limited ductility hinders adequate deformation, thereby reducing deposition efficiency or bonding integrity unless process parameters are pushed high [8,9]. HVAF introduces controlled thermal energy along with high kinetic energy. The combustion of fuel in air produces a high-velocity jet at about 1900–2100°C, heating the particle surface close to its melting point but not fully melting it, so the core remains solid or semi-solid. This controlled heating improves ductility, with minimal oxidation and limited thermal degradation,and encourages metallurgical bonding, often producing denser, more cohesive coatings relative to cold spray [10-13]. Because temperature is kept below extreme levels, oxidation and phase decomposition remain limited compared to higher-temperature processes. Yet, the added heat raises the risk of minor oxidation or residual stress [11,14].

Despite the advantages, direct comparative studies on IN718 coatings deposited by CS and HVAF under similar conditions are limited. Many works focus on individual processes [8,12,15], which makes it difficult to isolate how the balance of thermal and kinetic energy drives coating microstructure, porosity, phase constitution, and mechanical performance. The aim of this work is to evaluate the influence of the spray process on IN718 coating properties by comparing cold-sprayed and HVAF-sprayed coatings on IN718 substrates. Key metrics include coating density, interfacial bonding, phase composition (via XRD), hardness, and wear behaviour. Through this comparative analysis, we seek to elucidate how deposition mechanisms govern coating integrity and thereby guide the selection of optimal spray routes for nickel-based alloy surfaces.

Experimental Procedure

The gas-atomized powder exhibited a spherical morphology and a particle size range of approximately 15–45 µm, ensuring good flowability and low oxide content. The coatings were deposited on IN718 substrates using both cold spray (CS) and high velocity air fuel (HVAF) processes. HVAF spraying was performed at 6 bar air pressure with a gas temperature of about 1100 °C. The HVAF process was employed via HVAF spray gun (Kermetico, USA) with a standoff distance of 250 mm, fuel pressure of 98.5 psi, hydrogen pressure of 70 psi, air pressure of 93.1 psi, and a robot traverse speed of 600 mm/s. The powder feed rate was maintained at 10 rpm, while cooling air was supplied at 90 psi. The resulting coatings exhibited a uniform thickness of about 300 µm with low porosity. The substrates utilised in this work were IN718 plates that had been annealed and cold rolled. The plates had dimensions of 50 mm by 30 mm by 3.2 mm. The cold spray deposition process was carried out using a high-pressure cold spray equipment manufactured by Plasma Giken PCS-1000. Nitrogen gas (N2) was used as the propellant at a temperature of 950 °C and a pressure of 5 MPa. The distance between the exit of the spraying nozzle and the surface of the substrate was 30 mm, and the spray gun was positioned perpendicular to the substrate surface. The scanning speed of the nozzle was 500 mm/s, while the feed rate of IN718 powder was about 46 g/min.

The coated samples were sectioned, polished, and etched using a solution of HCl (15 mL), glycerol (10 mL), and HNO_3 (5 mL) for 20–25 minutes. Surface and cross-sectional microstructures were examined using field emission scanning electron microscopy (FESEM, JEOL JSM-7100F). Phase identification was carried out through X-ray diffraction (Bruker, USA) using Cu-Kα radiation to study phase stability and crystallinity.

Vickers microhardness was measured using a Shimadzu HMV-2 tester at a 5 N load for 10 s. Tribological behavior was evaluated using a pin-on-disc setup (ASTM G99) against a Si_3N_4 ball under a 30 N load, 10 Hz frequency, and 2 mm stroke length for 20 minutes. The coefficient of friction was recorded in real time, while wear scars were analyzed using 3D optical profilometer. Wear volume loss was determined using OmniSurf3D analysis software.

Results and Discussion

Phase constitution in coatings

X-ray diffraction (XRD) was used to examine the phase stability and structural modifications in HVAF IN718 coatings and CS IN718 coatings Figure 1 show the γ-Ni phase remained predominant in all conditions, as evident from the (111), (200), and (220) diffraction peaks, confirming the coatings' retained austenitic nickel structure. The XRD patterns investigation indicated the existence of a supersaturated γ-phase matrix containing small fragments of elements. The as-sprayed deposits exhibit wider peaks compared to the IN718 powder and the HVAF sample, indicating the presence of microstrain resulting from severe plastic deformation and an increased dislocation density due to high-velocity impact. XRD patterns of the as-sprayed HVAF coatings confirm the preservation of the γ-Ni solid solution phase, with minor peak broadening and a slight shift toward higher 2θ values compared to the feedstock powder. These changes indicate the introduction of compressive residual stresses and marginal lattice distortion, which result from rapid particle impact and cooling. The presence of compressive stress is beneficial as it enhances the coating's resistance to fatigue and wear under service conditions.

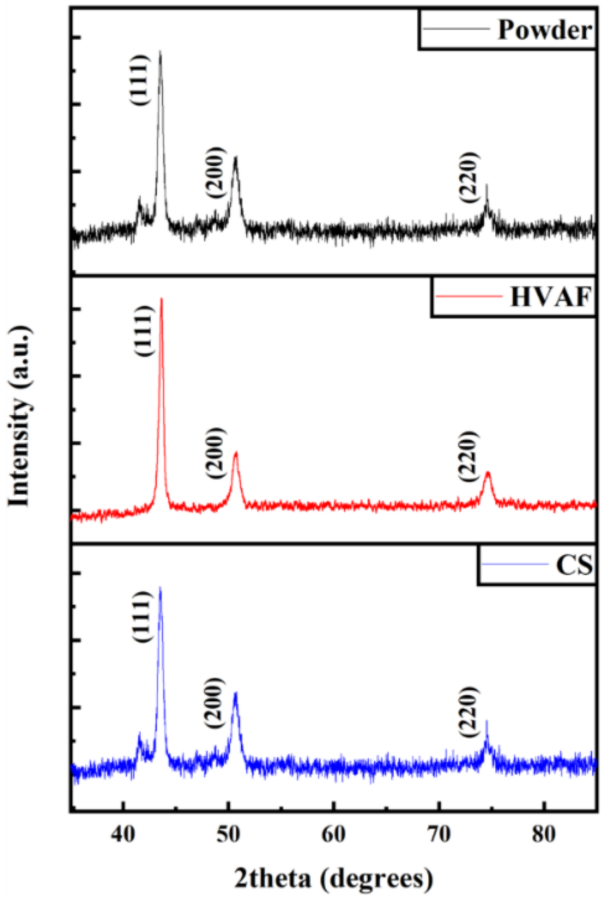

Figure 1: XRD spectra of IN718 coatings via HVAF-sprayed, and cold sprayed (CS) deposition process

Microstructural Evolution of HVAF and CS coatings

Figures 2(a) and 2(b) show schematic representations of the HVAF and Cold Spray processes used for depositing IN718 coatings. In the HVAF process, IN718 powder particles are injected into a high-velocity air-fuel jet produced by the combustion of LPG and air. The particles experience partial heating and softening and some may undergo surface melting while traveling under the hot air stream. The particle surfaces reach a semi-molten state, but the cores remain solid before striking the substrate at supersonic speeds, which promotes strong bonding through a combination of mechanical interlocking and limited thermal softening, resulting in dense coatings with minimal oxidation. In contrast, during the cold spray process, IN718 particles accelerated in a compressed gas stream at high velocity but remain in a solid state throughout flight. Bonding occurs primarily through severe plastic deformation and mechanical interlocking at the interface. The two processes thus differ in their dominant bonding mechanisms as thermal-assisted deformation in HVAF and purely kinetic deformation by adiabatic shear instability in cold spray, which directly influences coating density and microstructure.

The microstructural characteristics of the IN718 coatings produced by the HVAF process were examined to evaluate coating integrity and deposition quality. Figure 2 (c–d) presents low- and high-magnification cross-sectional FESEM images of the HVAF-sprayed IN718 coating. The coating exhibits a dense structure with very few isolated pores, indicating effective particle consolidation during deposition. Quantitative analysis of porosity from image-based evaluation shows a porosity level below 1.5 %, reflecting the efficiency of the HVAF process in achieving near fully dense coatings. In Figure 1(c), the splat morphology becomes evident, displaying well-flattened and tightly bonded lamellae. The microstructure lacks distinct oxide stringers or unmelted particles, which are common in high-temperature thermal spray processes. This indicates that the relatively lower flame temperature and higher particle velocity in HVAF facilitate solid-state particle deformation and metallurgical bonding while minimising oxidation. The high magnification FESEM image (Figure 2d) shows elongated grain structures and localised shear bands formed due to the severe plastic deformation of IN718 particles upon impact. The absence of microcracks and minimal porosity within these regions suggests high inter-splat cohesion and uniform deformation behavior. Such features directly contribute to the mechanical integrity and improved load-bearing capacity of the coating.

Figure 2(e-f) shows the cross-sectional images of CS coatings at low and high magnification respectively. Figure 2(e), the low-magnification image reveals a dense coating layer with minimal visible porosity (~3%), indicating effective particle cohesion during high-velocity impact. While the overall porosity is slightly higher than in HVAF coatings, the coating remains largely dense and continuous. At higher magnification in Figure 2(f), the splat morphology becomes apparent. The CS process produces distinct splats formed by the supersonic impact of solid-state IN718 particles. Within individual splats, plastic deformation is highly heterogeneous: the interiors retain traces of the original dendritic microstructure, while the peripheral regions, particularly near splat–splat boundaries, undergo severe plastic deformation. This extreme localised deformation results in the

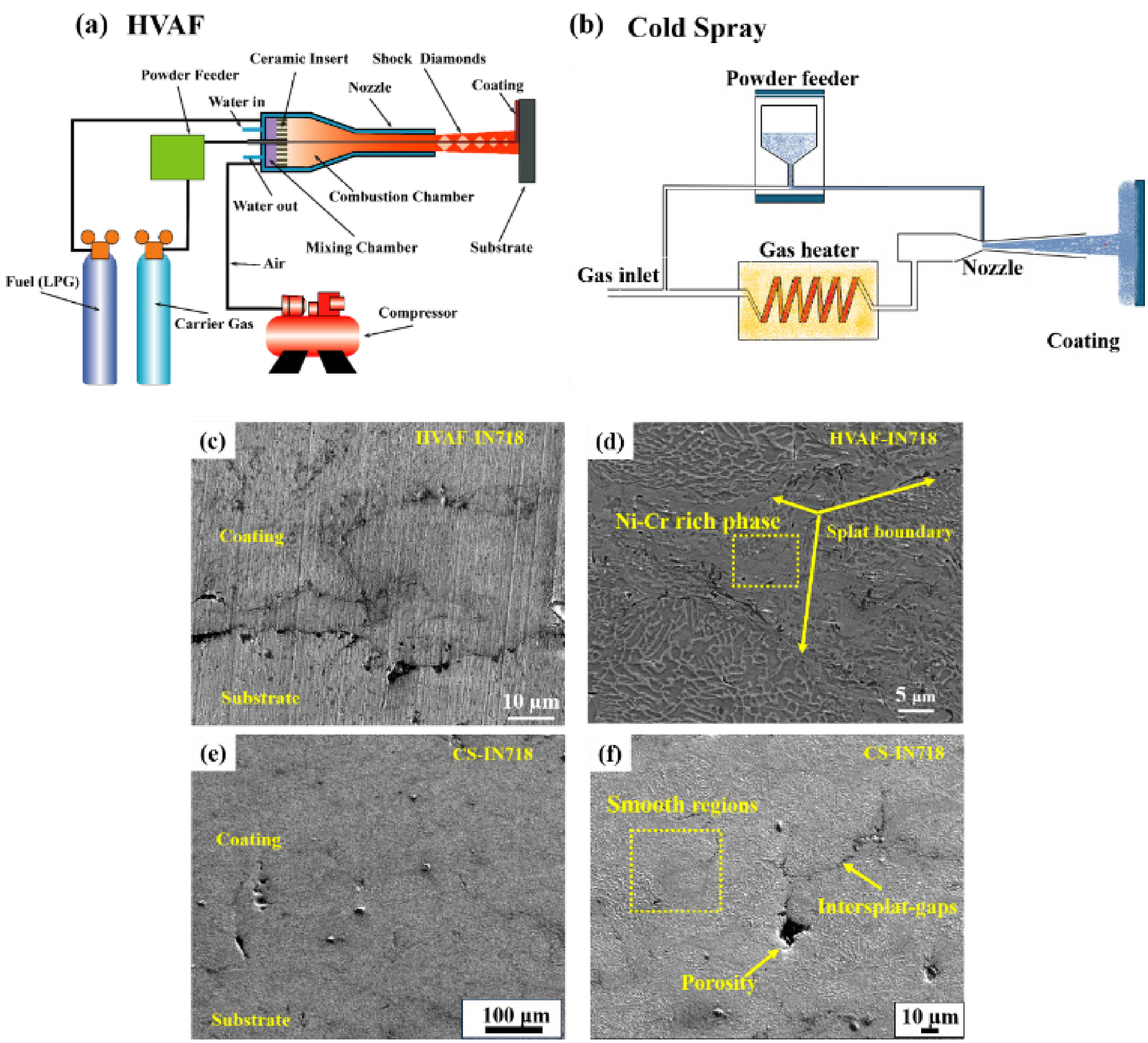

Figure 2: Schematic representation of (a) HVAF spraying process and (b) cold spray process; Low and High-magnification FESEM cross-section microstructures of (c-d) HVAF-IN718, and (e-f) CS-IN718

formation of smooth patches along the splat boundaries, while the splat interiors maintain partially undeformed parent structures. The microstructural gradient from dendritic cores to smooth splat peripheries reflects the non-uniform distribution of strain during high-velocity particle impact. Unlike high-temperature thermal spray processes, oxidation is negligible due to the solid-state nature of the deposition, preserving the chemical integrity of the IN718 powder. The combination of retained dendritic cores and severely deformed splat boundary zones enhances strain hardening, contributing to higher hardness within the coating. Moreover, the absence of significant microcracks or large voids suggests good inter-splat cohesion, although micro-voids can form in regions of incomplete bonding, particularly near the substrate interface.

Mechanical and Tribological Behaviour

Figure 3(a–d) shows the variation in microhardness across the coating–substrate interface, the wear volume comparison, and the 3D wear track morphology for IN718 coatings deposited by cold spray (CS) and high velocity air fuel (HVAF) processes. Both coatings adhered well to the IN718 substrate, but their interfacial hardness and wear responses differed noticeably. As shown in Figure 3(a), the cold sprayed IN718 coating exhibits a higher overall hardness within the coating region compared to the HVAF coating. The CS coating attains around 500–550

HV near the top surface, while the HVAF coating records about 400–450 HV. However, a sharp drop in hardness occurs at the interface of the cold sprayed coating, where the value falls below both the coating and substrate hardness. In contrast, the HVAF coating shows a local hardness increase at the interface compared with both the substrate and the CS interface region. Overall, CS coating shows ~10% higher hardness compared to HVAF coating. This difference originates from the distinct particle-substrate interaction mechanisms in the two processes. During cold spray deposition, the particles impact the substrate at very high velocity, leading to severe plastic deformation and localized strain hardening in the coating. However, this high strain rate can also create a narrow zone of residual tensile stress and microvoids near the interface, reducing the effective hardness when measured in that region. In addition, incomplete bonding or inter-splat gaps can form a mechanically weak layer, which explains the sudden hardness drop at the CS interface. The HVAF process, in contrast, involves particles at moderately lower velocity but at higher temperature. These conditions promote partial softening of the particles before impact and enable better metallurgical bonding upon deposition. The local heat input and plastic flow can refine the grain structure and improve interfacial cohesion, leading to a compact diffusion-affected layer with enhanced hardness. This strengthening at the interface provides improved load transfer during sliding and minimizes the tendency for delamination. Despite the slightly lower overall hardness, the HVAF-IN718 coating demonstrates superior wear resistance, as evident in Figure 3(b). The HVAF coating exhibits roughly ~7% lower wear volume compared to the cold sprayed coating. The narrower wear scar (1.478 mm vs. 1.6 mm for CS) and smoother 3D wear track profile, Figure 3(c–d) indicate reduced material removal and a more stable contact during wear. The shallow and uniform wear track of the HVAF coating suggests the formation of a protective oxide or tribofilm layer that resists adhesive wear. The cold sprayed coating, although harder, shows deeper and wider wear tracks due to localized crack formation and particle pull-out from weakly bonded inter-splat regions. These defects accelerate material removal and increase the effective wear coefficient, offsetting the advantage of higher hardness.

Overall, the results confirm that wear resistance in sprayed IN718 coatings depends not only on hardness but also on interfacial integrity and coating density. The HVAF process produces a denser, well-bonded microstructure with improved interfacial strength, leading to enhanced wear performance. The cold sprayed coating, while harder, contains residual stresses and microvoids that promote interface weakening and higher wear.

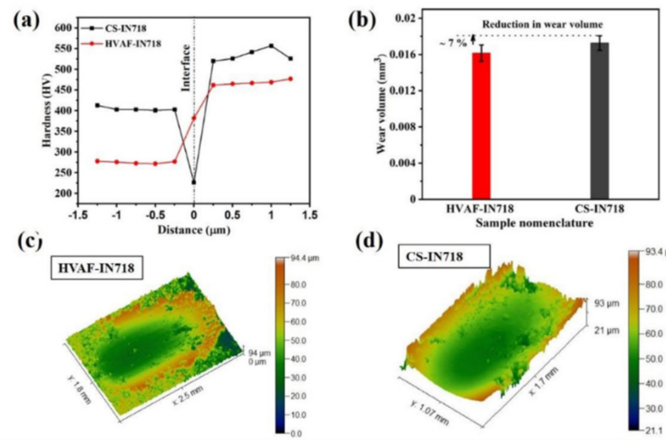

Figure 3: (a) Microhardness profile across the coating–substrate interface, (b) comparison of wear volume loss for HVAF-IN718 and CS-IN718 coatings, and 3D wear track surface profile of (c) HVAF-IN718 and (d) CS-IN718 coatings

Conclusion

This study compares the microstructural, mechanical, and tribological characteristics of IN718 coatings deposited by cold spray (CS) and high velocity air fuel (HVAF) processes. Both techniques successfully produced dense and well-adhered coatings with minimal porosity and strong bonding to the substrate. The HVAF process facilitated metallurgical bonding through partial particle softening and localized diffusion, resulting in a uniform coating with good interfacial integrity and low porosity. In contrast, the CS process, characterized by solid-state particle impact and severe plastic deformation, produced a refined microstructure with mechanical interlocking of the splats – individual splats then consisting of nanocrystalline grains near splat boundaries and retained dendritic regions within splat interiors. This microstructural gradient, along with minimal oxidation, enhanced inter-splat cohesion and strain hardening.

The predominance of the γ-Ni solid-solution phase in both coatings were observed without any additional peaks from other phases, with the CS coating exhibiting broader peaks indicative of higher dislocation density and microstrain than HVAF counterpart. The superior strain-hardened microstructure of the CS coating contributed to higher microhardness and improved wear resistance compared to the HVAF coating. The HVAF coating, though slightly softer, demonstrated good ductility and interface stability, attributed to its diffusion-assisted bonding and compact lamellar structure.

Overall, the results highlight that while both methods are effective for producing high-quality IN718 coatings, the cold spray process offers a more favourable combination of hardness, wear resistance, and oxidation control, making it particularly suitable for high-performance and repair applications in aerospace and energy components.

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A study on the Effect of Process Parameters in Low Pressure Cold Spray Deposition

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Abstract
Cold Spray Additive Manufacturing (CSAM) is gaining huge popularity recently due to its solid-state deposition capabilities. Specifically, in repair and manufacturing applications, where CS can restore the worn out/damaged components without degrading/affecting the base materials composition. However, cold spray is a complex deposition process that involves multiple number of process parameters, which need to be controlled precisely to achieve high quality deposition. Also, this technology is at early stage of maturity though it has significant potential. Hence, an in-depth understanding on the role of process parameters on underlying deposition mechanism is needed of the hour. In this regard present work deposited Al/Al2O3 composite powders on mild steel substrates via., Low Pressure Cold Spray Technique; and studied the input parameter's effect on the output deposition. For that 16 single tacks were deposited following L16 Taguchi array (mixed design) and studied the deposition characteristics with respect to the input process parameters variation. The results show that higher the powder feed rates are resulting in increased deposition efficiency and deposit area. Pressure and Temperature effect was shown to be minimal on the output, which is mainly due to the input variation is highly localized. Further to add, increasing the Alumina percentage in feed stock initially increasing the deposition efficiency and achieved maximum at 15 %. However, deposition efficiency started declining once the Alumina percentage was beyond 15 %. Further, Grey relation analysis was performed to optimize the process parameters set for the give set of material combination. The optimization studies help the CSAM process planning to improve geometric accuracy and achieve close dimensional tolerances.

Introduction
The repair and remanufacturing demand techniques that restore geometry without degrading the base materials properties. Cold Spray (CS) meets this need as a solid-state deposition process. In CS, micro-sized particles are accelerated supersonically onto a substrate. The impact induces severe plastic deformation, which breaks down surface oxides and creates a metallurgical bond without melting1. By eliminating the liquid phase and associated heat-affected zones, CS preserves the microstructure of both the feedstock and the substrate, making it an ideal candidate for high-integrity repair applications. CS processes are broadly categorized into high-pressure cold spray (HPCS) and low-pressure cold spray (LPCS). HPCS propels particles at high velocities (600 – 1200 m/s), generating extreme strain rates (~106–107 s-1) that induce dislocation accumulation, localized adiabatic heating, and dynamic recrystallization. This leads to dense coating with excellent bond strength2. However, HPCS reliance on costly helium as a process gas, and sophisticated equipment limit its economic viability for large-scale repairs. Conversely, LPCS operates with affordable nitrogen or air and simple hardware, offering an economical alternative. However, lower particle velocities (300–600 m/s) of LPCS, results in inadequate deformation, low deposition efficiency, high porosity, and consequently a weak interfacial bonding. This trade-off between cost and performance currently limits LPCS from becoming a universal repair solution.
In this regard a few attempts have been made in the past to optimize the LPCS and attain high quality deposition

and higher efficiency. Adding peening particles to the feedstock is one way to improve the deposition characteristics3-5. The added peening particle in the feed stock have had a peening effect on the already deposited particles and reduces the porosity, improves bonding. Another way of improving process efficiency is process parameters optimization, to ensure the particle velocities are well above the critical velocity and less than erosion velocities6-8. The present work combined these two techniques to optimize the LPCS process. Single and multi-track of Al/Al_2O_3 of length of 30 mm were deposited on MS substrates. The samples as deposited were sectioned in the transverse direction, and the cross section of the coatings were observed in microscope. Coating height, arear of deposition were measured along with microstructure studies.

Table 1: Experimental conditions based on input parameter variation (L16 Taguchi array), and the measure output responses measured

SN o	Input Variables				Output Parameters		
	(Wt.) % Alumina	Powder Feed rate	Pressure	Temper-ature	Height	Width	Deposition
	Wt %	g/min	bar	°C	mm	mm	efficiency
1	10	22.0	7	500	0.443	5.777	19.3
2	10	24.1	7	600	0.749	5.948	25.2
3	10	26.0	8	600	1.256	6.257	17.1
4	10	22.8	8	500	1.422	6.432	19.0
5	15	22.0	7	600	1.252	6.276	20.3
6	15	24.1	7	500	1.073	5.903	24.0
7	15	26.0	8	500	1.694	6.132	23.0
8	15	22.8	8	600	1.699	6.441	26.6
9	20	22.0	8	600	0.922	6.161	13.4
10	20	24.1	8	500	1.075	6.197	14.5
11	20	26.0	7	500	1.647	6.285	23.9
12	20	22.8	7	600	1.413	6.081	24.8
13	25	22.0	8	500	0.343	5.959	6.1
14	25	24.1	8	600	0.622	5.721	9.2
15	25	26.0	7	600	0.838	5.918	17.6
16	25	22.8	7	500	1.063	5.967	19.6

Experimental

Aluminium (avg. size 50 µm) and Alumina (avg. size 30 µm) powders were used as feed stock. LPCS setu0p DYMET 423 was used for deposition. A total of four input parameters, i.e., i). pressure (P), ii). Temperature (T), iii). powder feed rate ($\dot{m}$), and iv). Alumina weight percentage was considered in this study. Pressure and temperature were varied at two levels, whereas powder feed rate and Alumina weight percentage were varied at four levels, allowing for a comprehensive assessment of both primary and interaction effects. The experimental design was developed using the L16 Taguchi orthogonal array given in Table 1. Coating thickness and deposition efficiency (Eq. 1) were considered as the output responses to characterize deposition quality and process performance; the measured responses were given in Table 1. Gun scan speed (v) - 10 mm/s, standoff distance - 10 mm, and nozzle exit diameter 5.5 mm are kept constant throughout the experimentation. Microstructure observations were done on these samples using an optical microscope (Leica) and Scanning Electron Microscope (Zeiss - Germany make, SIGMA 300), attached with EDX. Coating thickness measurements were done on the Optical Microscope images using ImageJ software.

$$\text{Deposition Efficiency} = \frac{\text{Amount of Powder Deposited}}{\text{Amount of Powder Supplied}} \times 100\,\% \quad (1)$$

Results and Discussion

Single layer and multi-layer Al + Al_2O_3 coatings were successfully deposited on low carbon steel substrates, via. LPCS technique. The input parameters window was carefully selected after so many screening experiments; all samples had resulted in continuous track with defect-free deposition such as no layer delamination and surface cracks. Deposited samples were sectioned in transverse direction, and observed in Optical Microscope, shown in Fig. 1. The cryosection images show no visible voids, cracks either at the interface or in the coatings. Further, coatings height was measured using ImageJ software.

Statistical analysis was done on the results obtained, to determine the significance of each parameter and quantify their contributions to the output responses. Analysis of Variance (ANOVA) was conducted, and Grey Relational Analysis (GRA) was employed to perform multi-response optimization. An integrated understanding of parameter effects on overall process behavior, was drawn along with input output correlation. The results showed that, powder feed rate and Alumina weight percentage are significantly influencing the deposition characteristics. Whereas the role of pressure and temperature seems highly local and less significant, shown in Fig. 2. Further, it is evidenced from the plot (Fig. 2.) that increasing the Alumina percentage initially has positive effect on the output, however once it is above 15 % it starts negatively affecting the DE and coating thickness. This can be attributed to the fact that increased alumina content is eroding/removing the already deposited soft Al particles by pitting action. Analysis of variance is performed to identify the significant parameters, shown in Table 2. The parameters

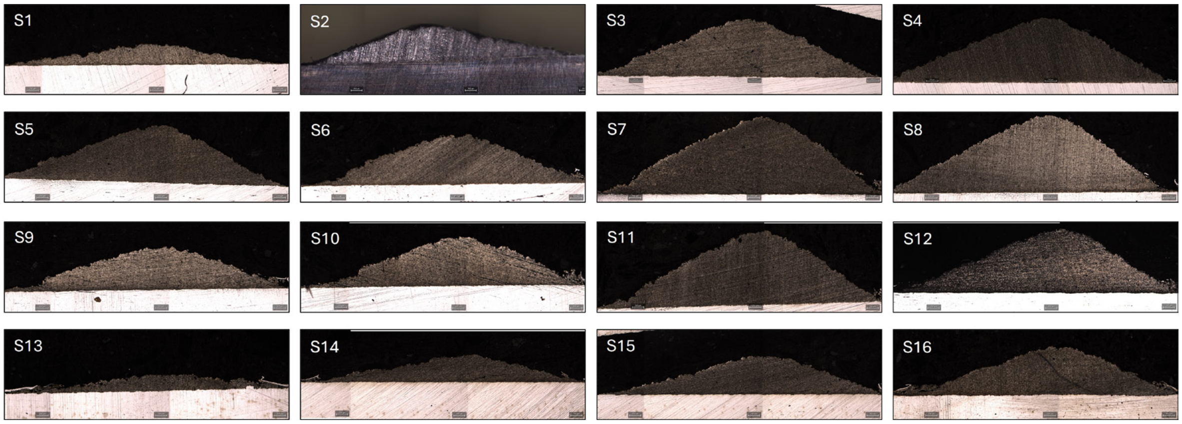

Figure 1: Cross-section images (micrographs) of single tracks captured in Optical Microscope

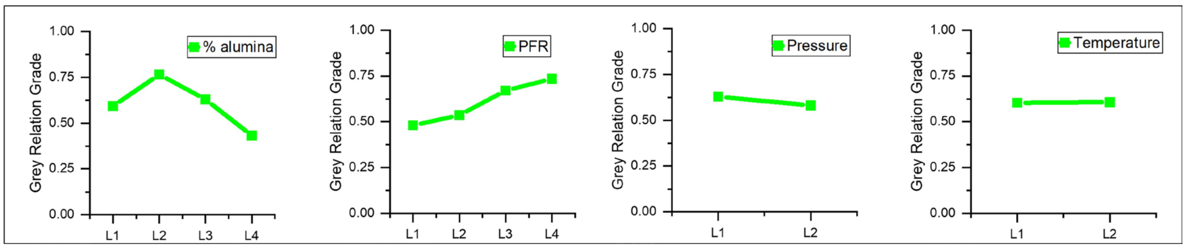

Figure 2: Grey relation grade vs input parameter

Table 2: Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
% Alumina	3	0.225656	0.075219	7.31	0.015
PFR	3	0.166005	0.055335	5.38	0.031
Pressure	1	0.009266	0.009266	0.90	0.374
Temperature	1	0.000045	0.000045	0.00	0.949
Error	7	0.072018	0.010288		
Total	15	0.472990			

alumina percentage and powder feed rate have had a significant effect on the output deposition. Though pressure and temperature play crucial role in the CS deposition, the present investigation showed insignificant effect, this is attributed to the fact that variation range is too small to cause a significant change in the output.

Conclusions

Al/Al203 composite powder was successfully deposited on MS substrates without any major defects via, LPCS. Which indicates that a proper parameters window was chosen for this study. Statistical analysis has shown that the Alumina content in the feed stock is one of the significant parameters. Increasing the alumina content in the feedstock positively influences the coating properties up to a critical value of 15%; beyond this threshold, a detrimental effect is observed. Furthermore, the powder feed rate exhibits a positive correlation with the coating performance, highlighting its important role in controlling deposition behavior. Overall, these findings emphasize that a systematic investigation and optimization of cold spray process parameters is a prerequisite, given the complexity of the process and its current stage of technological maturity.

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