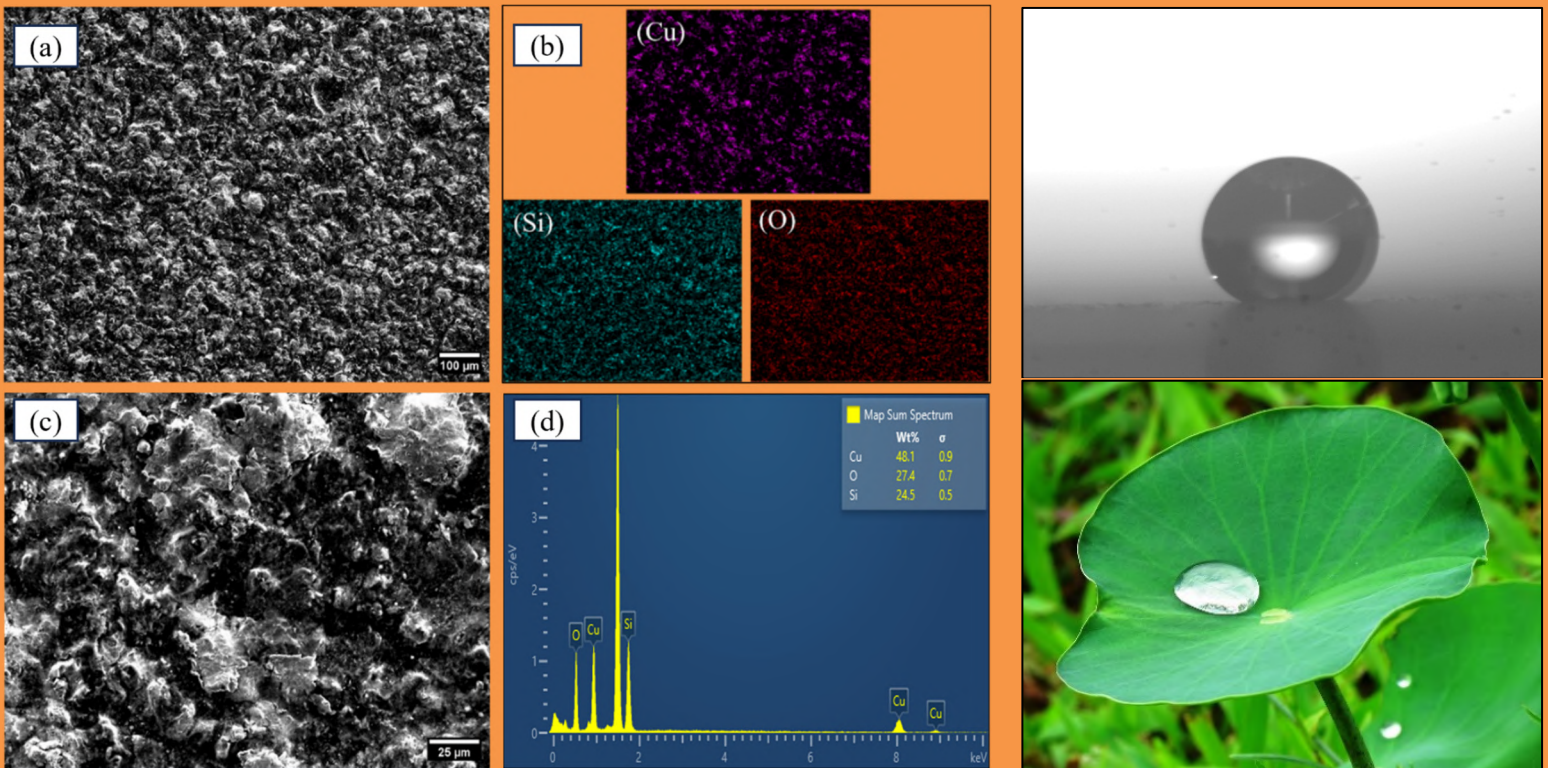


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Superhydrophobic Surfaces/Coatings by Cold Spray

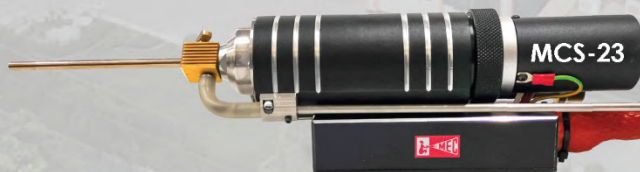
Issue Highlights

- Solid-State Fabrication of Superhydrophobic Surfaces/Coatings by Cold Spray
- Modified Cantilever Bending – A High-Throughput Technique for Interface Fracture Measurement
- Laser Cladding: Process, Characteristics and Application

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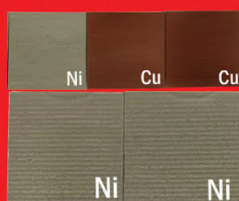
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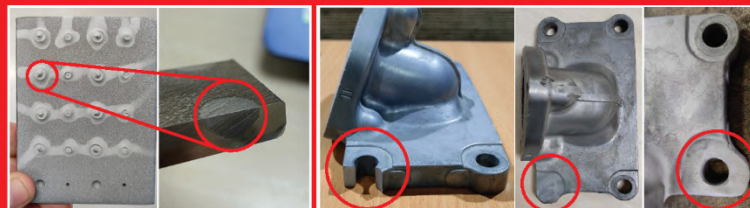
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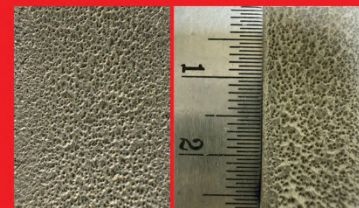
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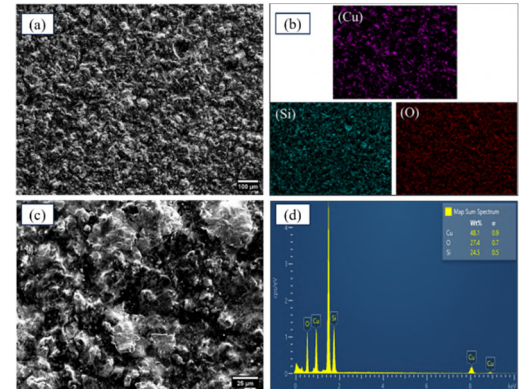
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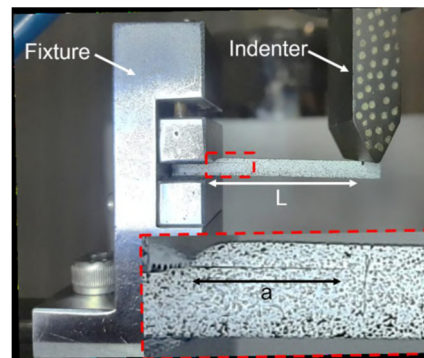
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Editor's Note



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 “Solid-State Fabrication of Superhydrophobic Surfaces/Coatings by Cold Spray”, “Modified Cantilever Bending – A High-Throughput Technique for Interface Fracture Measurement”, and Laser Cladding: Process, Characteristics”; that illustrate current research trends in thermal spray development.

We are excited to announce our upcoming event: **National Thermal Spray Conference and Expo (NTSC 2027), February 19-20, 2027, Research and Innovation Park, IIT Delhi, India.** This conference will serve as a hub of innovation and collaboration for thermal spray technology. More than 400+delegates, including leading experts, researchers, and industry professionals from around the globe will attend the NTSC2027 to discuss cutting-edge developments, share insights, and explore the future of thermal 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 thermal spray technology. Visit NTSC2027 website <https://www.indtsa.org/ntsc-2027>

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!

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A handwritten signature in blue ink that reads "Satish".

(Satish Tailor | PhD)

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Solid-State Fabrication of Super-Hydrophobic Surfaces/Coatings by Cold Spray

By **K.L.S.S. Vasu, Harpreet Singh**

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Email : harpreetsingh@iitrpr.ac.in

Abstract

Superhydrophobic surfaces have attracted considerable attention owing to their excellent water repellency, self-cleaning ability, anti-corrosion behaviour and anti-fouling performance. These multifunctional surfaces have found increasing applications in marine engineering, aerospace, transportation, electronics and energy systems. Among the various fabrication techniques available, High-Pressure Cold Spray (HPCS) has emerged as a promising solid-state deposition process capable of producing dense coatings with excellent adhesion while preserving the intrinsic properties of the feedstock materials. This article discusses the potential of High-Pressure Cold Spray for developing superhydrophobic surfaces using hydrophobic nano-silica particles, the mechanism responsible for superhydrophobic behaviour, and the prospects of this technology for advanced surface engineering.

Introduction

Nature has long inspired engineers in developing advanced functional materials. One of the most remarkable examples is the lotus leaf, whose surface exhibits exceptional water repellency due to its unique hierarchical micro/nano surface structure combined with low surface energy. Water droplets resting on the lotus leaf remain nearly spherical and easily roll off the surface, carrying dust particles and contaminants with them. This phenomenon, commonly known as the Lotus Effect, has become the foundation for designing artificial superhydrophobic surfaces.

A surface is generally classified as superhydrophobic when it exhibits a water contact angle greater than 150° and a sliding angle below 10° . Such surfaces demonstrate remarkable self-cleaning behaviour together with

excellent corrosion resistance, anti-fouling characteristics, drag reduction and anti-icing performance.



Figure 1: Lotus leaf showing water droplet beading (Natural inspiration for Superhydrophobic surfaces).

<https://pixabay.com/photos/lotus-leaf-water-drop-lotus-water-2420205/>

Conventional fabrication methods include laser surface texturing, sol-gel processing, chemical vapour deposition, anodizing, dip coating and spray coating. Although these methods can successfully produce superhydrophobic surfaces, several involve multiple processing steps, expensive chemicals or poor mechanical durability.

High-Pressure Cold Spray offers an attractive alternative because it enables the fabrication of functional coatings through solid-state particle deposition, thereby minimizing oxidation and thermal degradation while preserving the original characteristics of the feedstock material.

High-Pressure Cold Spray for Functional Coatings

High-Pressure Cold Spray is a solid-state coating process in which powder particles are accelerated to supersonic velocities using a high-pressure compressed gas through a converging-diverging (De Laval) nozzle. Unlike conventional thermal spray processes, the particles remain below their melting temperature during deposition. Upon impact with the substrate, bonding occurs through severe plastic deformation, localized adiabatic shear instability and mechanical interlocking.

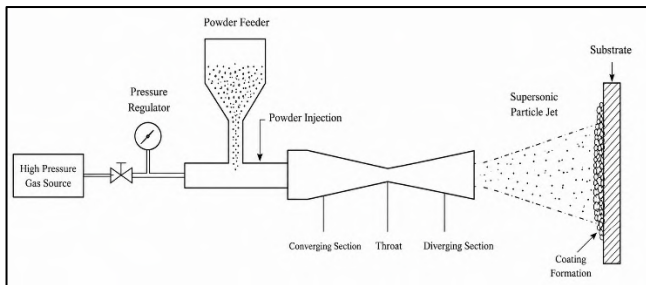


Figure 2: Schematic representation of the High-Pressure Cold Spray process.

The process offers several advantages over conventional thermal spray techniques:

- Solid-state deposition without melting
- Minimal oxidation during spraying
- Negligible phase transformation
- Low residual stresses
- Dense coatings with excellent adhesion
- Retention of feedstock chemistry
- Capability to coat heat-sensitive materials
- Environmentally friendly processing

These advantages make High-Pressure Cold Spray particularly attractive for depositing advanced multifunctional coatings.

Development of Superhydrophobic Surface

The present approach utilizes a composite feedstock consisting of a ductile metallic matrix reinforced with hydrophobic nano-silica particles. During High-Pressure Cold Spray deposition, the metallic phase undergoes significant plastic deformation, forming a dense adherent coating, while the nano-silica particles contribute to the functional characteristics of the surface.

Because deposition occurs entirely in the solid state, the intrinsic properties of the hydrophobic nano-silica particles are preserved throughout the coating process.

This allows the functional particles to remain active within the deposited coating while simultaneously benefiting from the excellent structural integrity provided by the metallic matrix.

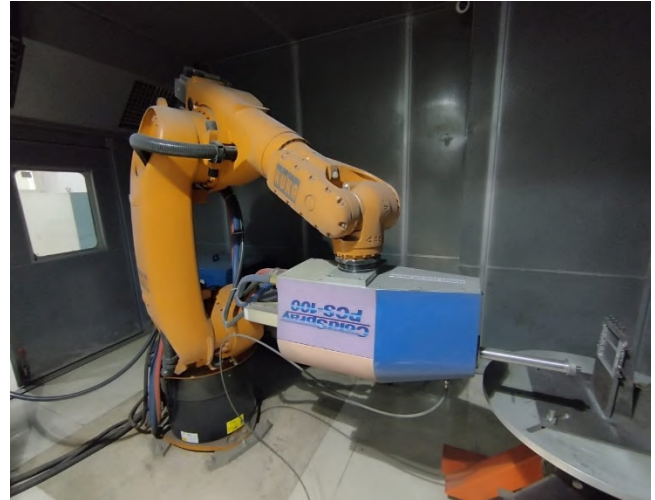


Figure 3: Experimental High-Pressure Cold Spray setup at IIT Ropar, Punjab

Feedstock Materials

The coating was developed using a composite feedstock consisting of commercially available copper powder reinforced with hydrophobic silica particles. Copper was selected as the metallic matrix because of its excellent ductility, which facilitates particle deformation and bonding during High-Pressure Cold Spray deposition. The hydrophobic nano-silica particles act as the functional phase responsible for generating the nano-scale surface features required for superhydrophobic behaviour. The composite feedstock was mechanically blended to obtain a homogeneous powder mixture suitable for cold spray deposition. Prior to spraying, the substrate surface was grit blasted to enhance surface roughness and improve mechanical interlocking between the incoming particles and the substrate.

Table 1: High-Pressure Cold Spray Parameters

Parameter	Value
Process	High-Pressure Cold Spray
Process gas	Nitrogen
Gas pressure	20 bar
Gas temperature	600°C
Powder feedstock	Copper + Hydrophobic silica
Number of spray passes	2
Stand-off distance	20 mm, 35 mm, 50 mm
Nozzle type	De Laval nozzle
Deposition mode	Solid-state

Mechanism of Superhydrophobic Behaviour

Superhydrophobicity results from the simultaneous presence of low surface energy and hierarchical surface roughness. During High-Pressure Cold Spray deposition, successive particle impacts naturally generate micron-scale splats and asperities. The incorporation of hydrophobic silica particles further introduces nano-scale surface features, creating a hierarchical micro/nano architecture. When a water droplet contacts such a

surface, air becomes trapped within the microscopic valleys, reducing the effective contact area between water and the solid surface. This wetting behaviour follows the Cassie–Baxter model, where trapped air pockets support the droplet, resulting in extremely high contact angles and very low sliding angles. Consequently, water droplets roll freely across the surface, removing dust and contaminants, thereby producing the characteristic self-cleaning effect.

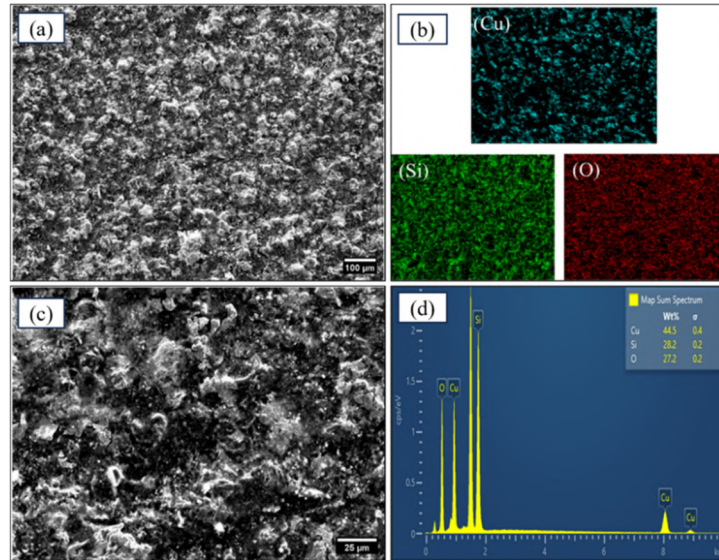


Figure 4: FESEM micrographs and EDS analysis of the cold-sprayed copper-hydrophobic nano-silica coating deposited at 20 bar, 600 °C, with a 20 mm stand-off distance and two spray passes. (a) Low-magnification FESEM image (100 μm); (b) EDS elemental mapping showing the distribution of Cu, Si and O; (c) High-magnification FESEM image (25 μm); and (d) corresponding EDS spectrum confirming the elemental composition of the coating.

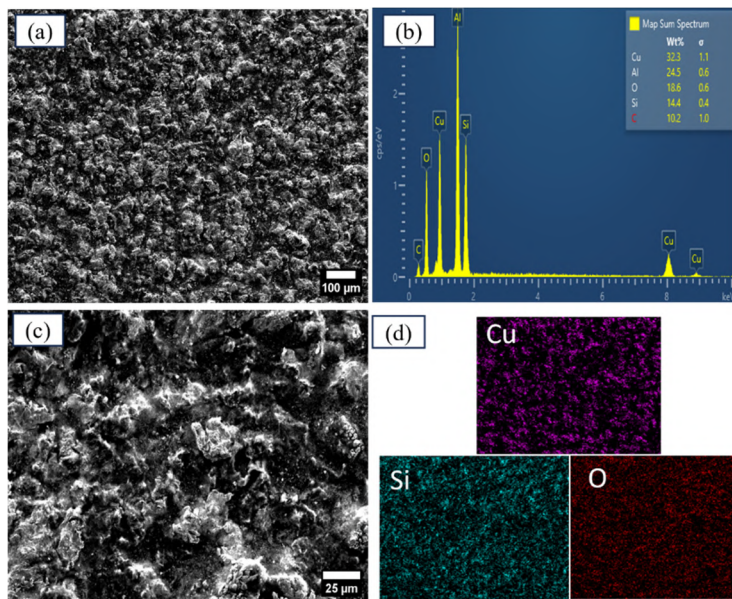


Figure 5: FESEM micrographs and EDS analysis of the cold-sprayed copper-hydrophobic nano-silica coating deposited at 20 bar, 600 °C, with a 35 mm stand-off distance and two spray passes. (a) Low-magnification FESEM image (100 μm); (b) EDS elemental mapping showing the distribution of Cu, Si and O; (c) High-magnification FESEM image (25 μm); and (d) corresponding EDS spectrum confirming the elemental composition of the coating.

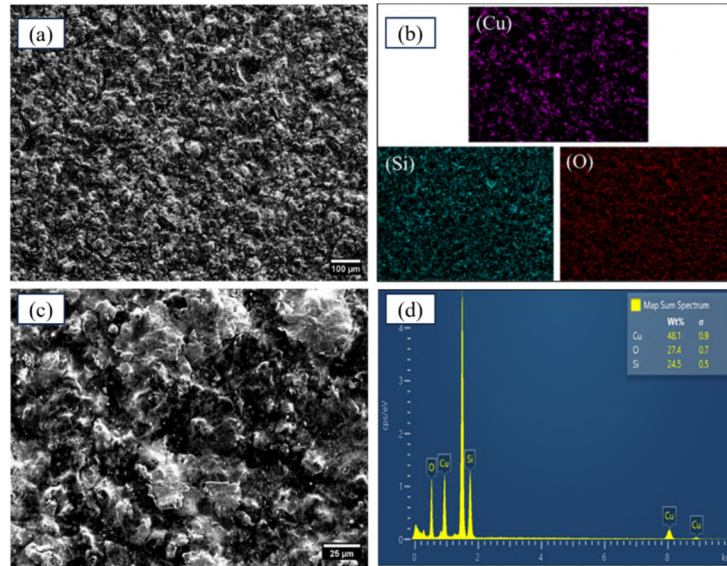
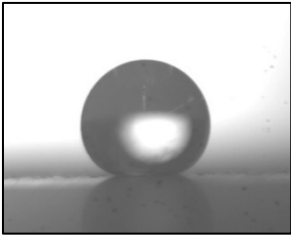
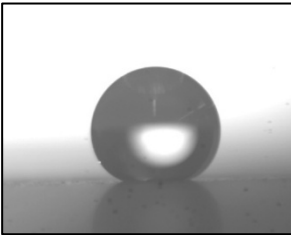
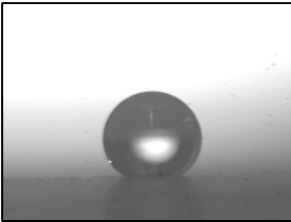


Figure 6: FESEM images (a, c) of cold-sprayed copper-silica coating at 20 bar, 600 °C, 50 mm stand-off distance with 2 passes, captured at 100 μm and 25 μm scales respectively; (b) shows EDS elemental mapping for Cu, Si, and O; (d) presents the corresponding EDS spectrum confirming elemental composition.

Contact Angle Measurement of Cold Sprayed Surfaces

Table 2: Contact angle measurements of water droplets on Cold Sprayed Copper-Hydrophobic Silica coated surfaces with varying process parameters.

S. No	Pressure-Temp-SOD-Passes	Droplet image	Contact Angle θCA (°)
1	20bar-600oC-20mm-2		154.79
2	20bar-600oC-35mm-2		155.85
3	20bar-600oC-50mm-2		144.08

Potential Industrial Applications

The combination of High-Pressure Cold Spray and hydrophobic nano-silica particles opens new opportunities for multifunctional engineering surfaces.

Potential applications include:

- Marine structures for corrosion protection and anti-fouling
- Aerospace components requiring environmental resistance
- Electronic enclosures with enhanced moisture protection
- Heat exchangers and condensers
- Transportation components with reduced contamination
- Renewable energy systems
- Self-cleaning architectural surfaces
- Industrial process equipment

The ability of High-Pressure Cold Spray to deposit coatings without thermal degradation makes it particularly attractive for repairing and functionalizing high-value engineering components.

Conclusions

High-Pressure Cold Spray represents a promising solid-state manufacturing technology for the development of durable superhydrophobic surfaces. By combining the advantages of solid-state deposition with hydrophobic nano-silica particles, it is possible to fabricate multifunctional coatings exhibiting excellent water repellency, corrosion resistance and self-cleaning behaviour without compromising the integrity of the feedstock material.

Acknowledgements

The authors gratefully acknowledge the Department of Science and Technology (DST), Government of India, for financial support through the Advanced Manufacturing Technologies - Centre of Excellence (AMT CoE) programme. The authors also sincerely thank the Department of Mechanical Engineering, Indian Institute of Technology Ropar, for providing the research facilities, laboratory infrastructure, and characterization facilities required to carry out this work. The guidance and support of Prof. Harpreet Singh throughout the course of this research are gratefully acknowledged.

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- Plasma Spray
- Cold Spray

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Modified Cantilever Bending – A High-Throughput Technique for Interface Fracture Measurement

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Introduction

Thermal spray coatings are generally used for protecting engineering components from wear, erosion, corrosion, high temperature etc. Alumina coatings are widely used for wear resistance and electrical insulation, while Yttria Stabilized Zirconia (YSZ) is used for thermal barrier coatings. In these applications, the coating not only has to survive harsh environments, but also has to remain firmly adhered to the substrate during the service.

In general, coatings can fail in two ways. It can form a crack within itself, which is the cohesive failure, or it may delaminate across the coating/substrate interface, which is referred to as adhesive or interfacial failure. In case of thermal spray coatings, the interface is a critical region because of the residual stresses, elastic mismatch, surface roughness, splat bonding and mechanical and thermal stresses.

In industries, the coating adhesion is often evaluated using the tensile adhesion tests (ASTM C633) [1]. This test is good for quality control but has some limitations as well. Arduous sample preparation, glue failure, high scatter in data and absence of well-defined interfacial crack makes it difficult to extract true interfacial fracture energy data. Indentation based techniques [2] are attractive as they are simple and localized and multiple tests can be performed on the same sample. But the stress field below an indenter is highly complex and the coating experiences a combination of compression, tension and shear loads. In brittle systems, the crack may form inside the coating before the interface is delaminated. Therefore, the results can be difficult to

directly relate to interfacial delamination. Four-point bending technique was able to measure interface fracture energy, but suffered from difficult sample preparation and asymmetrical crack growth in some cases [3,4]. Ashwini et al. [5] used modified clamped beam geometry to counter asymmetrical crack growth and crack kinking into the coating. But again, the sample preparation was tough, and FEM simulations had to be carried out to calculate interface fracture energy values.

Modified cantilever bending technique was developed by Ashwini & Abbas et al. [6] to counter these limitations. It provides a high-throughput way to calculate interface fracture energy, that is, it can measure multiple interface fracture energy data from a single sample. Its sample preparation is simple, there is no kinking of crack into the coating, and by using analytical formula, complex FEM simulations can be omitted. Abbas et al. [7] used modified clamped beam and modified cantilever geometries to compare the effect of phase angle on the interface fracture energy. It was found that modified cantilever geometry provides stable phase angle and less scatter in GC values across different phase angles

Principle of the Modified Cantilever Bending Technique

In modified cantilever bend geometry, a coated sample is fixed at one end, and the other end is loaded using an indenter. On application of load, the crack appears near the fixed end along the coating/substrate interface and grows further as the load is increased. The experimental setup is shown in Figure 1.

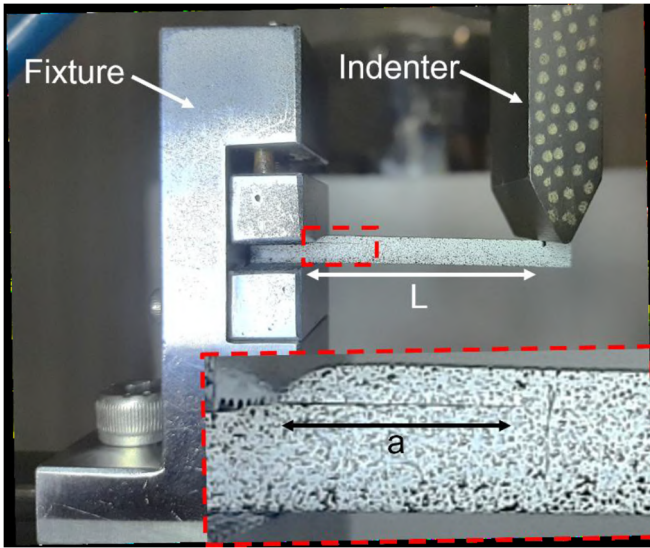


Figure 1: Experimental setup of Modified Cantilever Geometry.

For calculating the interface fracture energy, first a pre-crack is made along the interface. The sample is then unloaded and then loaded again for the first test. The critical load obtained is used to calculate the GC value, either from the FEM simulations or using the analytically derived formula. The loading and unloading can be repeated multiple times to obtain multiple GC values from the same sample as shown in Figure 2.

Digital Image Correlation is used to monitor the crack growth. This removes the subjectivity around the measurement of crack length. Moreover, the detection of crack growth can be done in real time and the test can be stopped after a controlled crack extension. This is important, since the crack length is one of the critical parameters in determining the interface fracture energy.

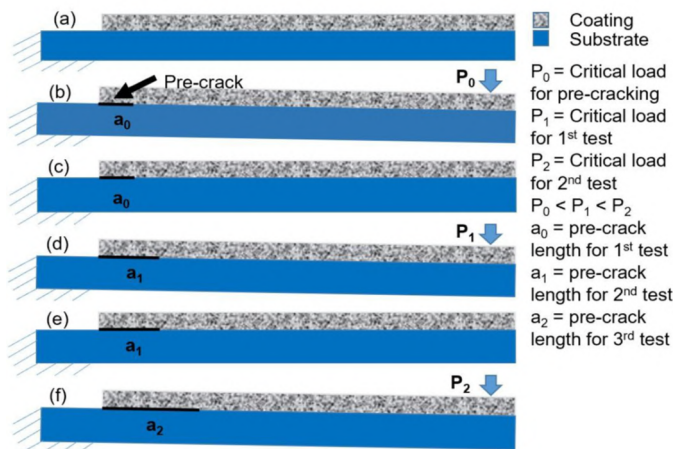


Figure 2: Schematic of the sequence of the test (a) sample before pre-crack, (b) sample after pre-crack, (c) sample before the first test, (d) sample after the first test, (e) sample before the second test, (f) sample after the second test.

Experimental demonstration done on Alumina and YSZ Coatings

The geometry was used to test plasma sprayed Alumina and YSZ coatings on steel substrates. For alumina on steel, the values of interface fracture energy were in the range of approximately 102–126 J/m². For YSZ/steel, the corresponding values were approximately 56–90 J/m². The GC values for both types of coating/substrate samples are shown in Figure 3.

These values are reasonable when compared with literature data obtained from other interface fracture techniques. More importantly, the trend between alumina/steel and YSZ/steel was consistent with earlier measurements using other bend-based methods. The measurements also showed low scatter within individual samples, and across the different samples, supporting the idea that this method can be used as a reliable high-throughput interface fracture test.

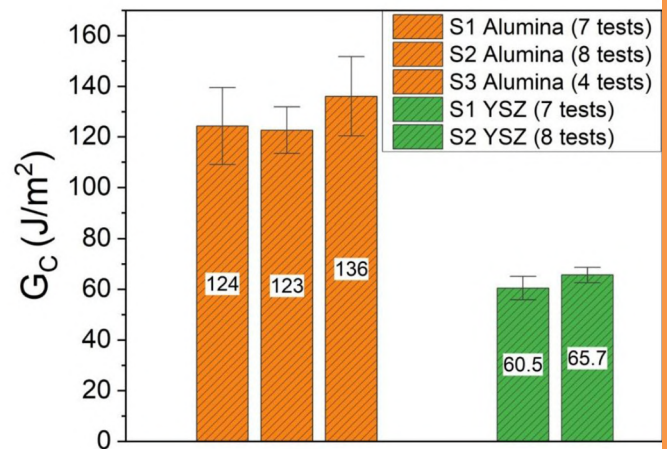


Figure 3: GC values obtained from individual samples tested multiple, showing the variability within a sample and across different samples, for Alumina and YSZ respectively.

Use and Limitations

Modified cantilever geometry has already been used to measure elaborately the effects of substrate and coating variables on the interface fracture energy of thermal spray coatings by Abbas et al. [8].

Modified cantilever geometry can be easily used for thick/thin or brittle/ductile coatings with small modifications. Even in cases where the interface fracture energy of the interface is higher than the fracture toughness of the coating itself, this geometry can be used by adding a stiffener on top of the coating. For the cases where the substrate undergoes plastic deformation before the interface fracture, the plasticity of the

substrate must be taken into account in the FEM simulations.

Conclusion

The modified cantilever bend technique is a practical and reliable route for measuring the interfacial fracture energy of thermal spray coatings in particular and coatings in general. It combines a relatively simple beam geometry with real-time crack propagation tracking using digital image correlation. The method allows stable crack growth and multiple measurements from the same specimen, making it suitable for high-throughput evaluation of coating-substrate interfaces.

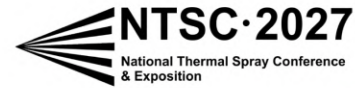
For thermal spray research and coating development, this is a valuable improvement over conventional adhesion test. It moves the discussion from simple pull-off strength toward a more meaningful fracture-mechanics-based understanding of coating reliability.

In applications where the life of the component depends on the integrity of the coating-substrate interface, such measurements are not merely academic. They provide the data needed to compare coatings, optimize processes and design more reliable coated components.

The modified cantilever bend technique therefore represents an important step toward more quantitative, repeatable and practical assessment of thermal spray coating adhesion.

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Laser Cladding: Process, Characteristics and Application

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Introduction

While spray-based technologies remain the benchmark for high-throughput, versatile surface engineering across industries, rapid expansion of laser applications and reducing system costs have accelerated the industrial adoption of laser material processing. Within this domain, laser cladding has drawn significant interest in recent years. Its capabilities extend from applying high-performance claddings and repairing high-value components to rapid prototyping and low-volume manufacturing. The process integrates laser physics, computer-aided design, robotics, sensor technology, and powder metallurgy.

During operation, a high-power diode or fiber laser beam irradiates the workpiece surface to create a localized melt pool. Feedstock material, in the form of powder or wire, is then coaxially injected into this pool. As the laser heat source traverses the substrate, the molten pool undergoes rapid solidification. This yields a dense and metallurgically bonded deposit on the underlying base material. Figure 1 depicts the schematic of a powder-based laser cladding system.

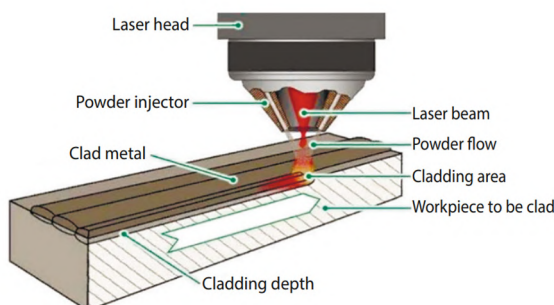


Figure 1: Schematic of powder-based laser cladding process [1]

Key Process Parameters

The properties and performance of a laser clad layer is governed by its macroscopic and microscopic structure which are result of a complex interplay of several key process parameters. These must be carefully optimized to achieve a dense, defect-free cladding with a strong metallurgical bond and a minimal dilution.

- i. **Laser power:** Laser power provides the primary thermal energy required to create the melt pool on the substrate and simultaneously melt the injected powder. Applying the optimal laser power ensures complete melting and good bonding with the substrate. If the laser power is too high, it leads to excessive heat input, causing structural deformation, cracking, and high substrate dilution. Conversely, if the laser power is too low, the energy is insufficient to fully melt the substrate and the powder, resulting in poor metallurgical bonding, local pill formation, and internal voids [2].
- ii. **Scanning speed:** The laser scanning speed dictates the interaction time between the laser beam, the powder, and the substrate. An excessively fast scanning speed reduces the amount of laser energy absorbed per unit area, resulting in insufficient melting of the materials, a narrower clad width, and a decreased depth and thickness of the deposited layer. Conversely, a slow scanning speed leads to prolonged heating and overheating of the substrate, which promotes excessive elemental diffusion between the substrate and the coating.
- iii. **Powder feed rate:** The powder feed rate and the physical properties of the powder also heavily influence the final clad. For instance, a mismatched combination of a low powder feed rate and high laser power can cause keyhole-induced porosity by creating a deep and narrow melt pool that traps gas bubbles. On the other hand, a high powder feed rate

combined with low laser power slows the liquid flow and also traps bubbles during solidification [3].

- iv. Energy density: To better predict and optimize the cladding quality, individual variables are often evaluated together as a combined mathematical parameter of energy density, E ($E = P/VD$, where P is power, V is scanning speed, and D is spot diameter) which determines the melting efficiency and depth of the cladding by defining the amount of energy transferred to the processing zone.

Why Choose Laser Cladding?

Laser cladding offers profound technical advantages over other surface modification techniques, such as thermal spraying and traditional arc welding processes [4]. Primarily, laser cladding creates a strong, metallurgical bond between the deposit and the substrate, which has higher bond strength than mechanical adhesion. Furthermore, laser cladding is characterized by a highly localized and strictly controllable heat input. The confined thermal energy restricts the melting of the underlying base material, ensuring a minimal heat-affected zone (HAZ) and a low substrate dilution rate. The HAZ refers to the area of the substrate that does not melt but undergoes microstructural changes due to thermal exposure. Since the thermal energy of the incident laser is highly confined, the HAZ in laser cladding is shallower compared to conventional fusion processes. Dilution is defined as the ratio of the melted substrate area compared to the total area of the solidified melt pool. Controlling dilution is critical, since excessive melting causes the substrate atoms to diffuse upward and mix into the deposit, compromising the chemical purity and properties of the clad. Ensuring low dilution, laser cladding prevents this elemental migration, and the claddings retain their intended chemistry, microhardness, and superior wear resistance. These distinct advantages make laser cladding an ideal solution for extending the service life of high-value industrial components that operate under extreme conditions. A prime example of this is the hardfacing of power plant control valves. The following section briefly presents highlights from a case study conducted collaboratively by Indian Institute of Technology Delhi and Industrial Processors and Metallizers Pvt. Ltd.

Application Case Study: Valve Seat Hardfacing

X22CrMoV12-1 is a heat-resistant martensitic steel commonly used in steam power plants for manufacturing control valves. The chromium-molybdenum alloy's

enhanced creep rupture strength is attributed to the presence of vanadium [5]. As shown in Figure 2, X22CrMoV12-1 exhibits exceptional high-temperature performance, making it a preferred material for steam power plant applications [6]. The control valve seat, which plays a key role in the valve's sealing mechanism, is usually exposed to high contact stresses, repeated impacts and high temperature. These harsh operating conditions result in severe wear and degradation, reducing the valve's service life and increasing downtime, leading to significant economic losses.

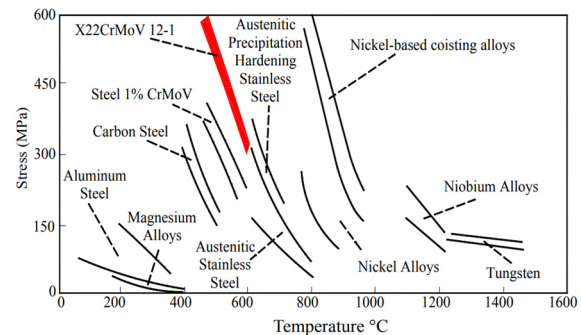


Figure 2: Ratio of stress to rupture after 100 hours with the temperature for various alloys [6].

Stellite-6, a cobalt-based hardfacing alloy, is well-known for its excellent wear and impact resistance, as well as hardness retention at high temperatures, making it particularly suited for hardfacing valve seats. The alloy consists of complex carbides embedded in a CoCr matrix. Chromium imparts corrosion resistance, while refractory elements such as molybdenum and tungsten enhance the alloy's creep resistance. PTA welding has traditionally been employed as the conventional hardfacing technique for depositing Stellite-6 onto power plant control valve seats. Switching to laser cladding for the application is advantageous due to the inherent benefits of the process. Figure 3 demonstrates the laser cladding of Stellite-6, a Co-based alloy on X22CrMoV12-1 steel substrate. The process utilizes a highly focused, low-energy input laser beam which minimizes substrate dilution and promotes rapid cooling rate. The rapid heating and cooling cycles prevent coarse dendritic grain growth, instead yielding a fine microstructure as shown in Figure 4. This structural refinement translates to superior mechanical properties and wear resistance. Laser-cladded Stellite-6 layers achieve microhardness higher than PTA-cladded counterparts (Figure 5).

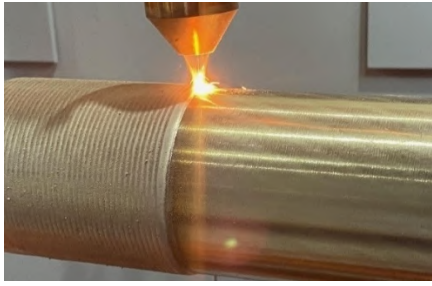


Figure 3: Laser cladding of Stellite-6, a Co-based alloy on X22CrMoV12-1 Steel Substrate at Center of Robotic Laser Processing, Industrial Processors & Metallizers Pvt. Ltd.

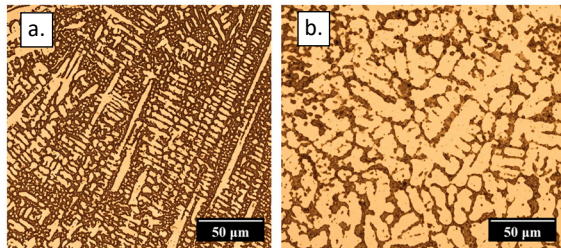


Figure 4: Typical microstructure of the Stellite-6 cladded layers deposited via (a) Laser cladding (b) PTA showing much finer dendrites in Laser cladding.

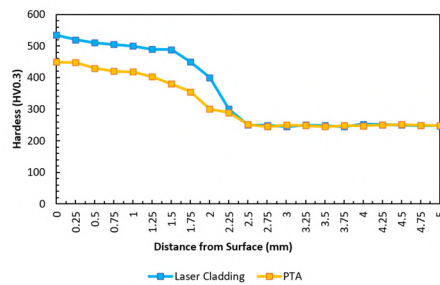


Figure 5: Microhardness profile of Stellite-6 cladded layers via Laser cladding and PTA

Conclusions

We have presented the unique metallurgical and thermal characteristics of laser cladding that position it as a technology of choice across a diverse array of demanding industries, including steel, oil and gas, aerospace, mining, biomedical, and others. Utilizing in-situ optical, thermal, and acoustic sensors to monitor the melt pool, intelligent systems can autonomously predict structural defects and potentially adjust processing parameters on the fly, guaranteeing better quality and reproducibility. With ongoing advancements, reducing equipment costs and increasing processing ease, laser cladding has emerged as a highly promising technology.

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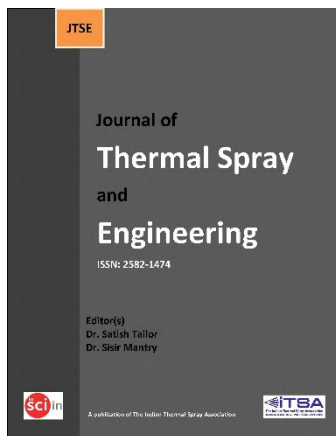
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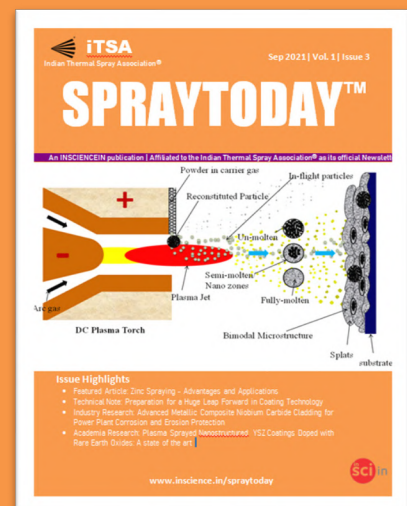
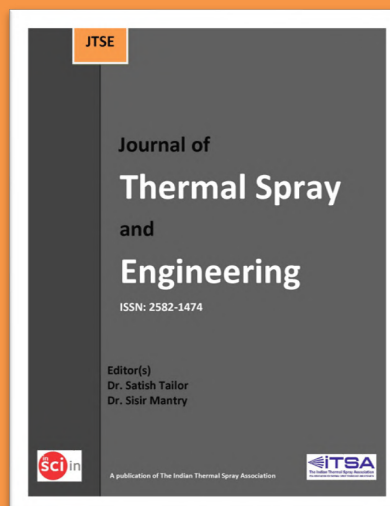
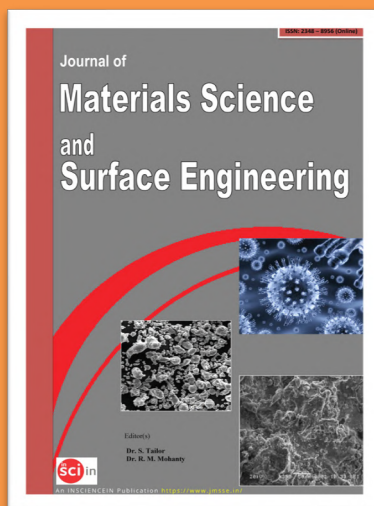
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