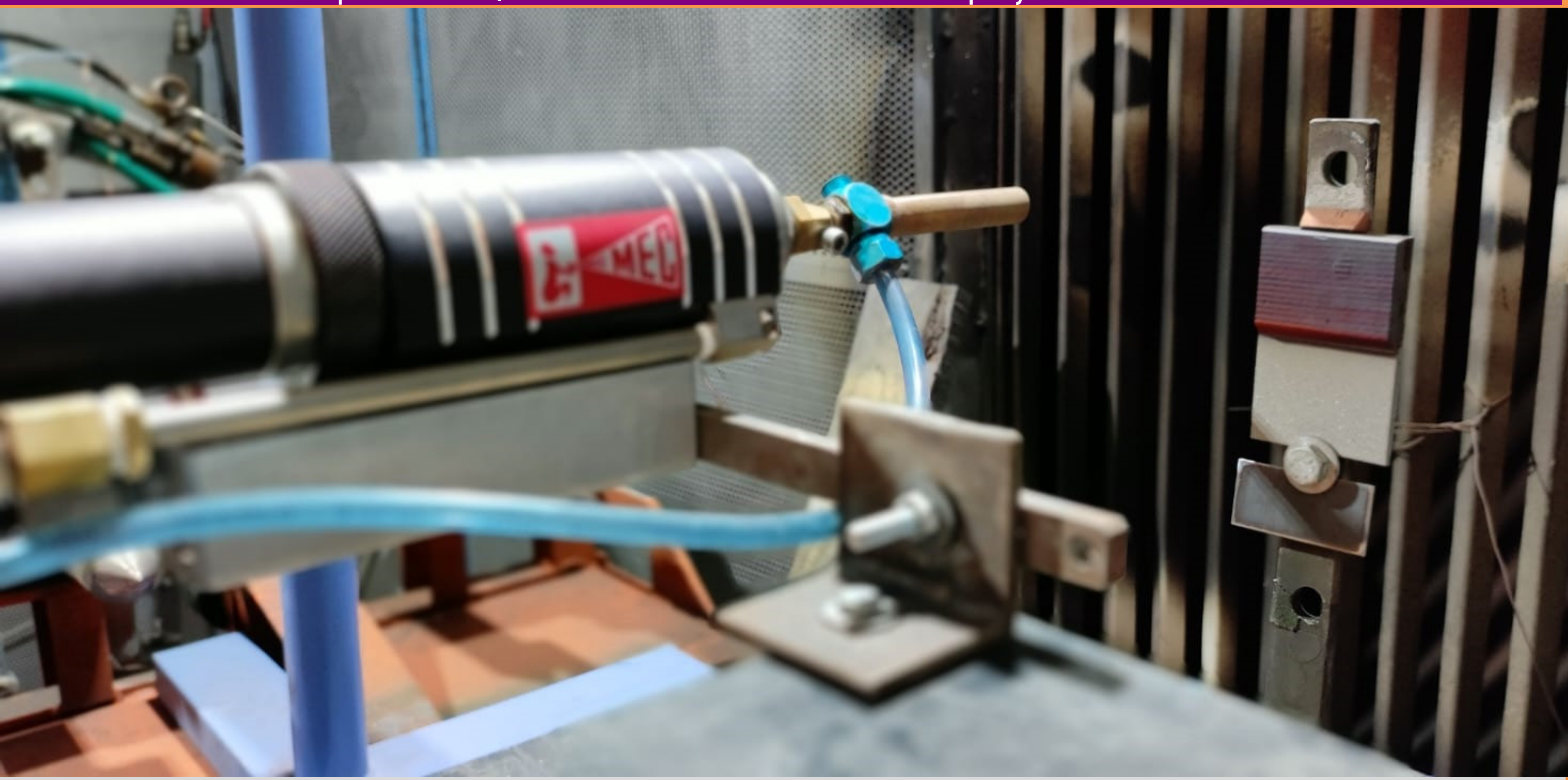
iTSA The Indian Thermal Spray Association
ITSA ASSOCIATION FOR THERMAL SPRAY TECHNOLOGY AND RESEARCH

April 2024| Vol. 4| Issue 1

SPRAYTODAY™

An INSCIENCEIN publication | Affiliated to The Indian Thermal Spray Association® as its official Newsletter



Issue Highlights

- **Featured Article**: Harnessing Low Pressure Cold Spray for Polymer-based Passive Daytime Radiative Cooling Coatings: A Report on its Tremendous Possibility
- **Academia Research**: Numerical Investigation of bonding Mechanism in Cold Spray
- **Industry Research Article**: Deposition of SS304 by Low-Pressure Cold Process "SPRAYCOLD®"

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MSC-500
MEC cold spray system with trolley, powder feeder and PLC controlled panel)

MCS-23
Cold spray gun with heater installed

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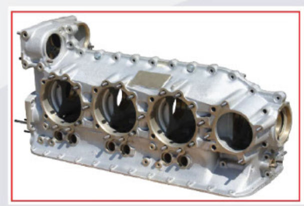

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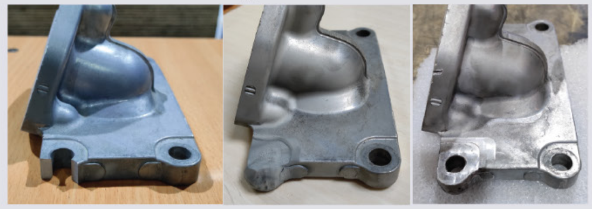
Durable, Eco-Friendly Brake Innovation

Manufacturing Inductive Cookware



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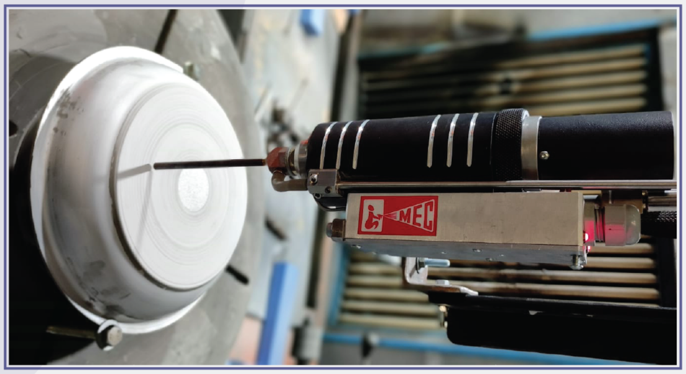

SPRAYCOLD® IN ACTION

Technical Specification of set of equipment SPRAYCOLD®

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Compressed air consumption	0.3-0.4 m /min
Compressed air purity	free of water and oil
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Compressed air operating temperature (in the input of the nozzle)	100 - 500° C
Power supply	One-phase alternate current of 50±1 Hz and 220 V (±10%)
Maximum power consumption	3.3 kW
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Total mass of the equipment	106 kg (approx)

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Mission: Our mission is to deliver the most recent thermal spray industry news and keep up to date to 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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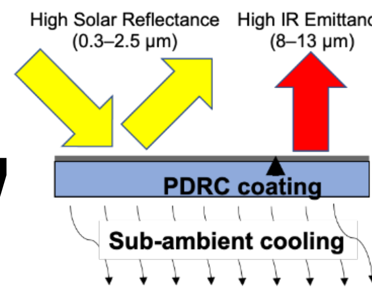

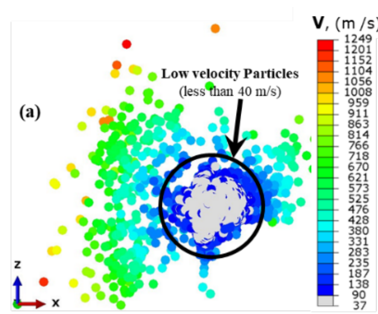

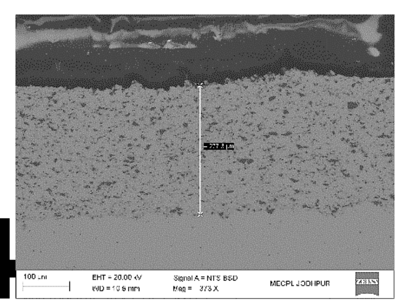

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ABOUT THE COVER

SPRAYCOLD® in action by MECPL Jodhpur

Editor's Note

Dear Readers,
In today's rapidly evolving world, innovation has become the driving force behind progress and sustainability across all industries. As we strive for a greener and more efficient future, it is crucial to embrace cutting-edge technologies that can revolutionize the way we live and work. From renewable energy solutions to advanced manufacturing techniques, innovation is paving the path toward a more sustainable planet.

One such technology that deserves attention is cold spray. This innovative process of depositing materials at high velocities without the need for melting is proving to be a game-changer in multiple sectors.

The impact of cold spray technology extends beyond specific industries. Its ability to minimize material waste and energy consumption aligns perfectly with the global push for sustainability. By adopting cold spray and similar advanced techniques, businesses can reduce their environmental footprint while also improving productivity and cost-efficiency.

As we look toward the future, it is essential for policymakers, industry leaders, and innovators to collaborate and invest in technologies like cold spray. Embracing innovation is not just about staying ahead in a competitive market—it's about creating a better world for future generations. Let's seize the opportunities that innovation offers and embark on a journey toward a more sustainable and prosperous future together.

As we delve into the latest edition of our **SPRAYTODAY** Magazine, we are excited to explore the dynamic landscape of cold spray technology and its transformative impact on various industries in India. This issue encapsulates a myriad of developments, showcasing the prowess of cold spray applications and the innovative strides taken by Indian researchers, engineers, and industry leaders.

I am particularly pleased to be allowed to recommend to you the latest issue of the **SPRAYTODAY**. This issue includes invited innovative featured articles from industry and academia experts on Harnessing Low Pressure Cold Spray for Polymer-based Passive Daytime Radiative Cooling Coatings: A Report on its Tremendous Possibility; Numerical Investigation of bonding Mechanism in Cold Spray; Deposition of SS304 by Low-Pressure Cold Process "SPRAYCOLD®", that illustrate current research trends in cold spray development.

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!

Best Regards,

(Dr. Satish Tailor)

Harnessing Low-Pressure Cold Spray for Polymer-based Passive Daytime Radiative Cooling Coatings: A Report on its Tremendous Possibility

*By **Kesavan Ravi,** Assistant Professor, Department of Fuel, Minerals and Metallurgical Engineering, Indian Institute of Technology (Indian School of Mines) Dhanbad, 826004, India.*

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Abstract

In the pursuit of sustainable technologies to combat rising global temperatures, passive daytime radiative cooling (PDRC) has emerged as a promising avenue. PDRC materials when coated on surfaces reflect sunlight and emit thermal radiation into the cold expanse of outer space at the same time. PDRC coatings can effectively cool surfaces below ambient temperature passively without consuming energy. In recent years, low pressure cold spray (LPCS) technology has garnered significant attention for its potential in depositing polymeric materials with tailored properties that may be suitable for PDRC coatings. This article explores the emerging intersection of LPCS and PDRC, discussing its principles, advantages, possibilities and challenges, and future prospects.

Introduction

With the pressing need to mitigate climate change, researchers and engineers are exploring innovative approaches to reduce energy consumption and lower greenhouse gas emissions. In emerging economies like India, which has most of the regions experiencing hot and humid climates, the cooling energy demand is expected to increase 2.2 times from 59.8 Mtoe in 2017 to 118.4Mtoe in 2027 [1]. One such approach is passive daytime radiative cooling (PDRC), a passive cooling technique that leverages the principles of radiative heat exchange to cool surfaces below the ambient temperature without the need for energy input. PDRC relies on two key principles: solar reflectivity and thermal radiation emission. Firstly, materials with high solar reflectivity minimize solar absorption, preventing excessive heating of the coated surface. Secondly, these materials emit thermal radiation in the long-wave infrared range, LWIR (8-13 μm), effectively radiating heat into the relatively cool atmosphere and outer space. The combination of these principles enables PDRC coatings to achieve sub-ambient temperatures even under direct sunlight (Fig. 1) [2]. It has shown promise in reducing cooling loads for buildings, vehicles, and electronic devices.

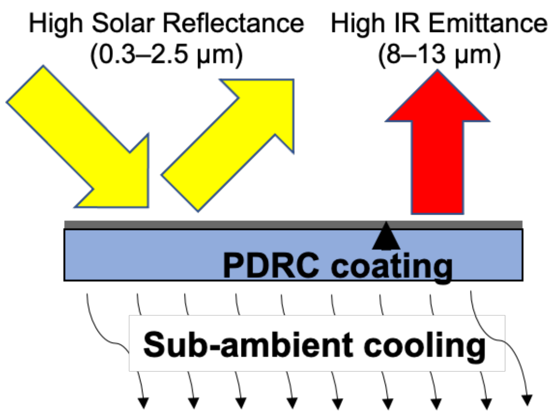

Figure 1: Schematic illustrating the sub-ambient cooling of a PDRC coating

Polymer-based Passive Daytime Radiative Coolers

There has been an emergence of several polymer based PDRC materials that have been engineered in recent times. Porous Polyvinylidene fluoride (PVDF), Polyethylene (PE), Poly(dimethylsiloxane) (PDMS) and several others have shown to exhibit high solar reflectance ranging from 90-98% and 70-97% thermal emittance in the atmospheric window exhibiting a sub-ambient cooling ranging from 5oC toi as high as 13oC [3-5].

Emergence of Low-Pressure Cold Spray Technology in polymer deposition

Low pressure cold spray (LPCS), a low-pressure variant of cold spray technology has emerged as a promising technique for depositing thin films and coatings with tailored properties. LPCS involves accelerating fine powder particles to high speeds using a carrier gas and depositing them onto a substrate, where they form a dense coating through solid-state consolidation. Unlike traditional thermal spray methods, LPCS operates at lower temperatures, minimizing substrate thermal distortion and enabling the deposition of sensitive materials [6]. Recently research and development on LPCS that includes improvements to nozzle design [7], particle composition [8], spray parameters [9], has made it possible to coat a myriad of polymeric materials which was considered quite difficult perhaps just 10 years ago.

PDRC coatings with LPCS-Several Possibilities

Based on the available data on the improvement of PDRC properties, porosity, curved polymer-inorganic interfaces, and selective LWIR emitter inclusion plays a pertinent role in improving solar reflectance and LWIR emittance. There are several polymeric materials such as engineered surfaces of PE, Teflon, Perfluoroalkoxy alkane, PVDF, PDMS etc. with compositions including Al2O3, SiO2, BaSO4 etc that have shown excellent PDRC properties. LPCS, in recent times have established the coating possibility of PE- SiO2, PE-nano Al2O3 [10], PFA-nano Al2O3 [11]. Hence, there exists a tremendous possibility to tailor coatings of PDRC active polymers by LPCS technique. LPCS can offer several advantages for the development of PDRC coatings:

1. Scalability and Cost-effectiveness: Highly portable system (<25 kg) that can be used to spray materials with cheap compresses air as carrier gas.
2. Composition control: Being a bottom-up process, ability to tailor composition with desired selective LWIR emittors is possibile. Further possibility of functional gradience in the composition is also tremendous.
3. Porosity control: Precision of control over particle velocity and temperature, spray parameters and other deposition parameters offer an effortless deposition of uniform, thin/thick coatings with tailored porosity.

Challenges and Future Directions

Integration of LPCS with PDRCs are also presented with several challenges such as identification of LPCS compatible materials, optimization of deposition parameters, post treatment for tailoring precise optical properties. Sub-ambient performance testing, durability, possibilities of multifunctionality (such as self-cleaning, anti-corrosive properties) are to be further explored in detail.

Conclusions

The convergence of low-pressure cold spray (LPCS) technology with passive daytime radiative cooling (PDRC) holds immense promise for developing next-generation cooling solutions with minimal energy consumption and environmental impact. By leveraging LPCS's precision deposition capabilities and PDRC's radiative cooling principles, researchers can unlock new possibilities for enhancing building energy efficiency, mitigating urban heat islands, and advancing sustainable technologies. However, addressing key challenges such as material selection, optimization, and durability is essential to realizing the full potential of LPCS-deposited PDRC coatings. With continued research and innovation, LPCS-enabled PDRC coatings may soon revolutionize the way we cool our built environment and mitigate the impacts of climate change.

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Materials for Thermal Spray Coating

CUMI Plas

- Aluminum Oxide (A99)
- Titanium Oxide (T99)
- Alumina Titania (AT1, AT3, AT3, AT40)
- Mullite (Aluminum Silicate)
- Yttria Stabilized Zirconia
- Calcia Stabilized Zirconia
- Magnesia Stabilized Zirconia

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Numerical Study of The Metal-Ceramic Coating Through Cold Spray Technique

By ***Ajay Kumar Behera*[1]*, Sisir Mantry*[2]*, Sudesna Roy*[1]*, Soobhankar Pati*[3]**
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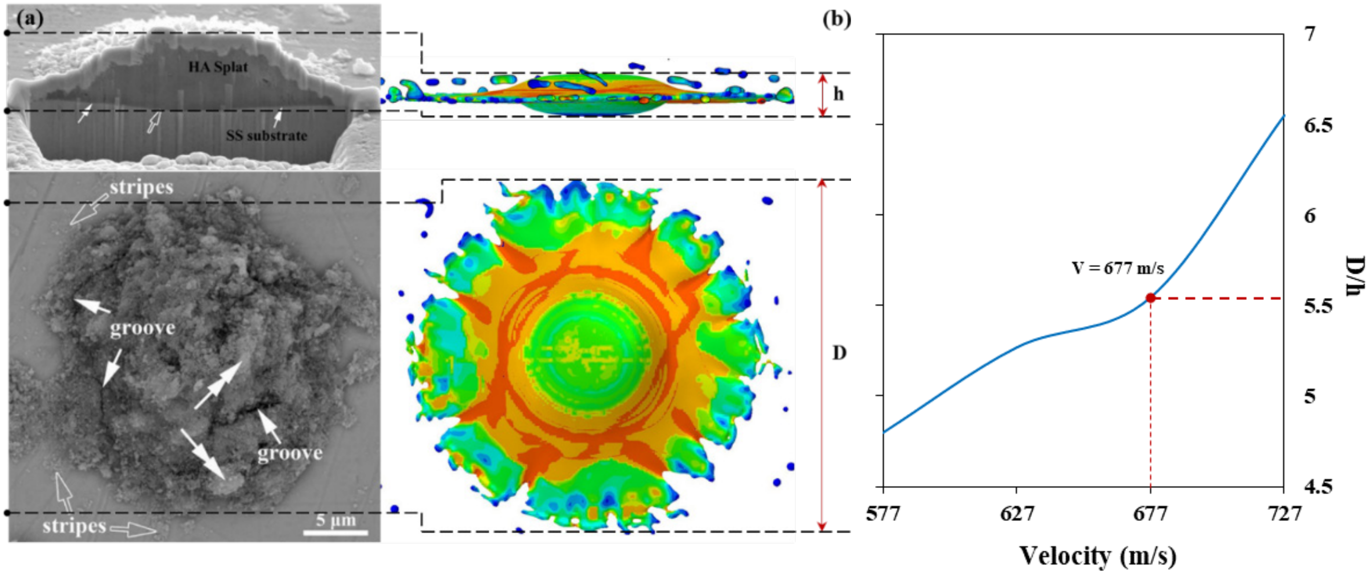
Introduction
Ceramic coating on metals through the cold spray technique has traditionally been avoided due to its inherent brittleness. This is primarily attributed to the lack of plastic deformation at the particle-substrate interface, a characteristic not typically found in ceramics. However, recent studies conducted by Viswanath et al. [1], found that ceramic material like Hydroxyapatite (HA) crystal exhibits plastic deformation under nanoindentation test. Zamiri et al.[2] used computational approach to extract elastic-plastic properties of HA from nanoindentation data and found that the predicted stress-strain curve shows a lower rate of work hardening exponent along the [1010] direction, which confirms the ductility of HA single crystals. Jami et al.[3] in their studies found that HA particles undergo ultrafast deformation under high strain rate within few picoseconds due to the elastoplastic behavior of HA under high impact or shock loading. Such behaviors of individual HA particles were also observed by Nakano et al. [4]. Building on this insight, few researchers could able coat HA on metals, like Vilardell et al. [5] and Chen et al. [6], successfully deposited pure HA on Ti and 316L-SS, respectively. Nonetheless, these works have been unable to provide a comprehensive explanation for the bonding mechanism. Additionally, it is rather difficult to precisely infer the bonding mechanism from the experimental results only because the particle-substrate interaction in a cold spray process is highly transient, nonlinear, and dynamic. It occurs in a period of 10 – 100 ns and thus may be difficult to experimentally analyze the mechanism of coating adhesion. The numerical study may provide further insight because the time frame can be scaled down to a few nanoseconds. Therefore, in this study, the numerical investigation was done considering the HA particle to be ductile and brittle, separately. CEL (Coupled Eulerian Lagrangian) and SPH (Smoothed Particle Hydrodynamics) numerical approach was used when HA particles were considered ductile, and brittle respectively. Finally, the simulation results were compared with the experimental results reported by Chen et al. [6], to understand the possible bonding mechanism.

Numerical Model
In this simulation, the particles were impacted onto the substrate with impact velocities obtained from the CFD simulation using commercially available ABAQUS/EXPLICIT software. The impact analysis was done through the CEL approach while considering the elastoplastic behavior of the particle and substrate. A separate set of simulations using SPH and ALE (Arbitrary Lagrangian Eulerian) numerical approach was performed considering the brittle nature of HA particles. Particle impact velocity obtained from the above CFD analysis with other additional velocities was set for initial conditions.

Results and Discussion
Particle elastoplastic behaviors on impact

This section explains the impact behavior of hydroxyapatite (HA) particles on a substrate across various velocities considering its elastoplastic properties. At all velocities, a cap-shaped morphology is consistently observed, shown in Fig-1 (a). Notably, at velocities of 577 m/s and 627 m/s, high-stress rings form around the hump of the particle splat. These regions experience the highest stress and strain, generating a spring-back force at the center, potentially leading to splat separation, and



(a) (b)

Figure 1: Comparison of (a) Cap-shaped morphologies with a hump at the center [6] with numerical simulation results and (b) D/h ratio with particle velocity.

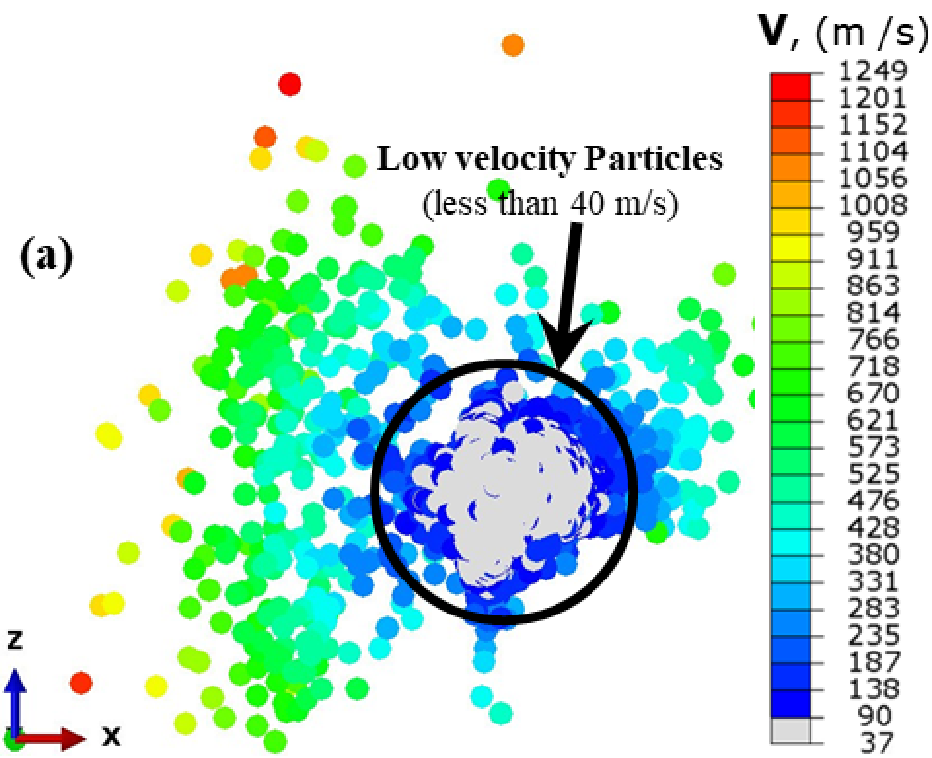


Figure 2: Low velocity (less than 40 m/s) simulated pseudo-particles deposition morphology.

leaving a ring-like residue on the substrate. Although numerical simulations lack a damage model, the stress-strain difference between the ring and central area aligns with conditions for the spring-back force. The critical particle velocity for this phenomenon is approximately 577 m/s. Additionally, with increasing impact velocity, the volume of the central part decreases, leading to an increased spread-out rim. This observation is supported by the impact velocity versus (D/h) ratio graph, where a sudden peak in the ratio occurs at 677 m/s due to a rapid decrease in hump height compared to increasing splat diameter, shown in Fig-1 (b). This peak may correlate with central part detachment, leaving particles in the ring regions.

Particle fracture and damage behaviors on impact

This section explains the impact behavior of hydroxyapatite (HA) particles on a substrate across various velocities considering its damaging properties. The investigation considers fracture and damage properties of the particles to understand bonding mechanisms. Using Smoothed Particle Hydrodynamics (SPH) simulations, cloud-like patterns of pseudo particles are observed upon impact, with radial spreading and size augmentation as velocities increase, shown in Fig-2. The criterion for bonding is based on the presence of low-velocity pseudo particles near the central region of the splat. A consistent low velocity of 40 m/s is maintained for uniform analysis. Results indicate that particle retention in the central region persists until a critical velocity of 577 m/s is reached, beyond which retention decreases, possibly due to spring back force detachment. Conversely, the radial region retains particles due to mechanical interlocking facilitated by substrate thermal softening. These findings align with experimental observations and provide insights into particle-substrate interactions at varying impact velocities.

Conclusion

In this study, a numerical investigation was conducted on the initial layer deposition behavior of hydroxyapatite (HA) particles on a substrate, considering elastoplastic and damage properties using the CEL and SPH models, respectively. Both experimental and simulation results show similar particle behavior upon impact. The CEL approach reveals a cap-shaped morphology of the HA particle at all impact velocities. However, beyond 577 m/s, a high-stress region around the splat's cap begins to form, resembling a ring shape, becoming more pronounced after 677 m/s. The stress-strain difference between the cap and the ring increases with velocity, suggesting detachment of the central splat portion due to spring-back force after 677 m/s, leaving leftover particles around the substrate's crater. A sudden increase in the D/h ratio after 677 m/s velocity further indicates central splat detachment. SPH simulations support this observation, showing decreased particle retention at the crater center after 577 m/s and significantly less retention after 677 m/s, indicating central splat detachment. However, particles in the ring region bond with the substrate through mechanical interlocking rather than adhesive strength improvement (ASI) due to insufficient substrate heating. These findings offer insights into first-layer ceramic deposition during cold spray, suggesting potential coating enhancement by adjusting particle velocity. Nonetheless, our study focuses solely on the initial deposition stage and warrants further investigation into subsequent layers and beyond.

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Deposition of SS304L by Low-Pressure Cold Process "SPRAYCOLD®"

By ***Satish Tailor, Ankur Modi***

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Traditional thermal spray methods work at elevated temperatures, leading to significant residual stresses caused by the rapid solidification and shrinkage of molten powder particles upon impact with the substrate. Consequently, cold spray technology offers an appealing alternative for certain materials. It allows the production of dense and firmly adherent coatings at temperatures below the material's melting point. Moreover, because of the lower process temperature, the oxide content in deposited materials remains minimal.

The characteristics of cold-sprayed coatings are established through the adhesion and cohesion of splats, which are influenced by the energy of the particles (generated by high velocity) upon impact with the substrate. Furthermore, only particles reaching a critical velocity are capable of being deposited.

Stainless steel coatings are commonly employed for protective purposes, offering a cost-effective solution for safeguarding against wear and corrosion. Utilizing low-carbon stainless steel variants like AISI 304L or 316L helps mitigate issues associated with chromium carbide precipitation, especially when the cooling rate after annealing isn't rapid enough.

Several studies have investigated the deposition of SS304L and 316L using the high-pressure cold spray process, but there is no literature available on SS deposition using the low-pressure cold spray process. This study aims to deposit SS304L using the low-pressure cold spray process (**SPRAYCOLD®** MSC-500), which differs from high-pressure cold spray methods by using ultra-pure air as the process gas instead of N_2 or He. SS304L coating deposited on a low carbon steel plate.

High purity (> 99.7%) SS304L powder with average particle size 5-45 µm, was used for coating deposition. SS304L powder is mixed with Alumina particles. The mixing ratio was 1:1. Before applying the coating, substrate was grit blasted with alumina grit and cleaned with ethanol. Surface roughness after blasting was 6±2 µm.

Figure 1: SPRAYCOLD® Model MSC-500

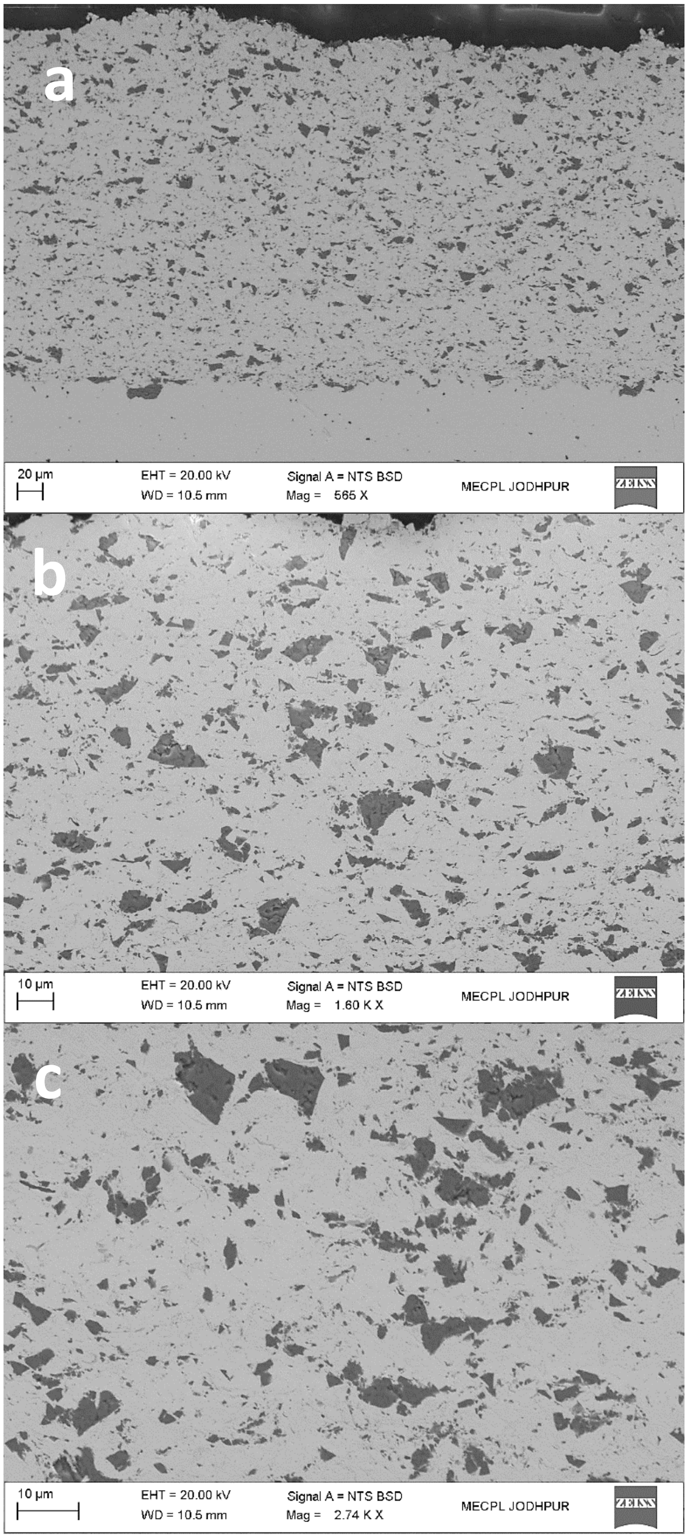

Figure 2: Micrographs of the as-sprayed SS304L coating

SPRAYCOLD® is a newly developed patented mass-flow controlled low-pressure cold spray system from Metallizing Equipment Company in Jodhpur, India as shown in Fig. 1. It enables the deposition of high-temperature materials like stainless steel (SS), including SS304L, 316L, 420, and 403. The **SPRAYCOLD®** Model MSC-500 operates within a pressure range of up to 10 Bar and a temperature range of 100-500°C, with a maximum power consumption of 3.3 kW and compressed air consumption of 0.3-0.4 m3/min.

Micrographs of the as-sprayed SS304L coating are shown in Fig. 2, revealing a relatively dense structure. Fig. 2b and c show particle deformation resulting from high-speed impact, with continuous interparticle boundaries evident. Additionally, there is clear evidence of good bonding between SS304 and alumina particles, as seen in their close association during deposition. The coating's thickness was measured at 270 microns, and its porosity was found to be less than 1%. Remarkably, the coating displayed good hardness, measuring 643±7 HV0.3, attributed to the presence of hard alumina particles within the coating.

Ductility and strength were evaluated for the coating as well. In its as-sprayed state, the Ultimate Tensile Strength (UTS) is notably high, yet brittle fractures were consistently observed. This brittleness can be attributed to the extensive plastic deformation of the particles, which contributes to the material's high mechanical resistance. However, at this stage, the inter-particle bonding seems inadequate, leading to brittle fractures. Similar outcomes have been noted in prior studies conducted using high-pressure cold spray techniques. Post-heat treatment could potentially increase the hardness, ductility, strength, and reduce porosity in the coating.

Conclusions

A uniform coating of SS304L was successfully deposited using a low-pressure cold spray process, resulting in a fairly dense structure. The porosity and hardness were measured at less than 1% and 643 ± 7 HV (at 0.3 kg) respectively. However, the coating exhibited poor ductility, and in its as-sprayed state, inadequate inter-particle bonding led to brittle fractures. This is a characteristic of as-sprayed cold sprayed coatings at high load.

Post-heat treatment presents an opportunity to potentially enhance the coating's hardness, ductility, strength, and reduce porosity. Utilizing a low-pressure cold spray method offers an economical advantage as it utilizes air instead of more costly gases like N2 or He.

Further research is necessary to develop methods for depositing pure SS material without incorporating alumina particles. Nonetheless, it's worth noting that alumina particles contribute to increasing the hardness of the coating.

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