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

June 2024| Vol. 4| Issue 2

SPRAYTODAY®

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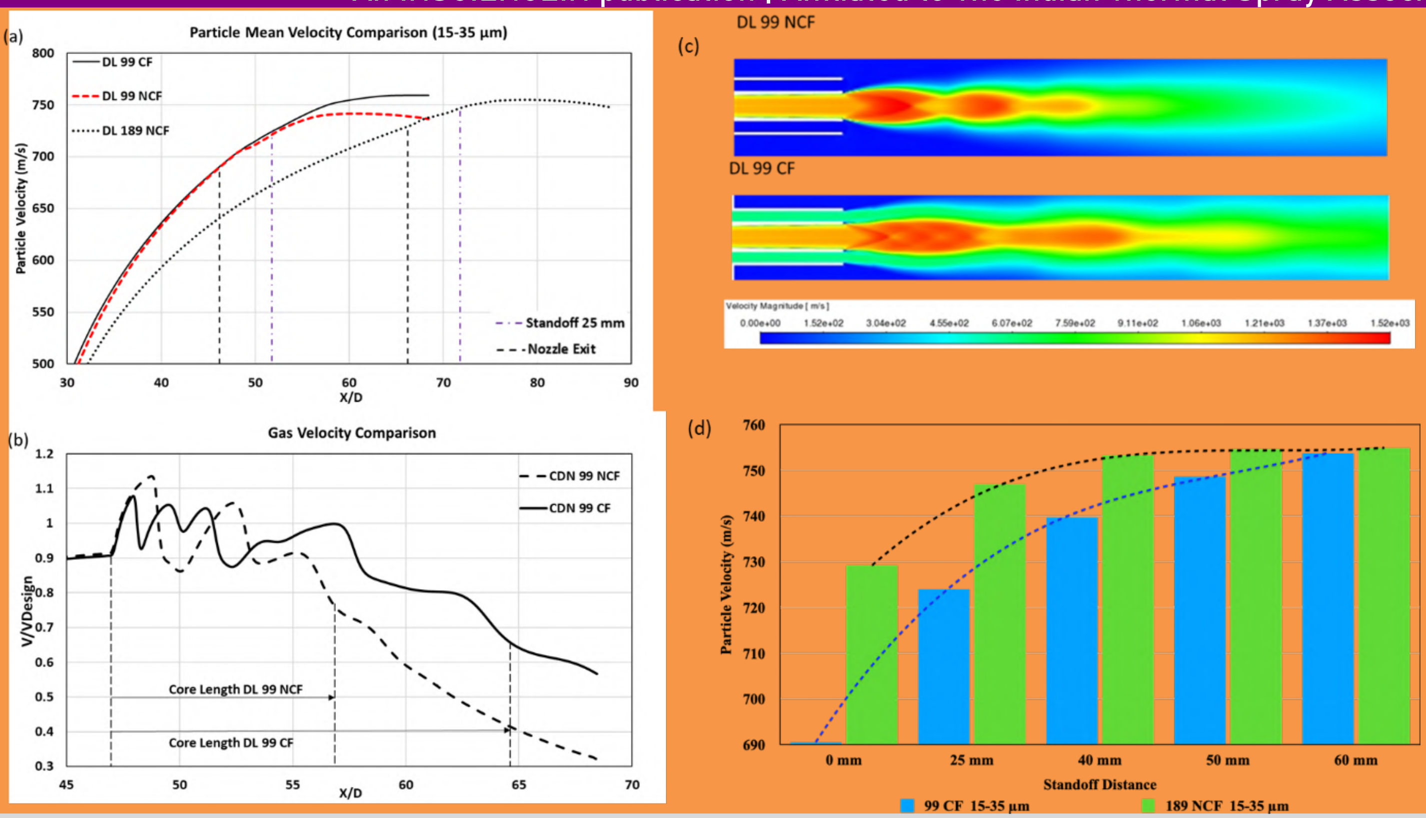

Issue Highlights

- **Featured Article**: Sustainable Development Goals and Circularity In Thermal Spray Coating Manufacturing and Value Chain
- **Technical Note**: CFD Investigation of a Co-Flow Nozzle for Cold Spray Additive Manufacturing Applications
- **Academia Research**: Critical Role of Ablation-Resistant Thermal Barrier Coatings In Enhancing Aerospace Performance

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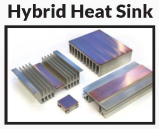
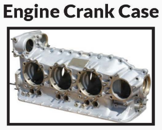
(COLD SPRAY SYSTEM)

MCS-23
with inbuilt heater

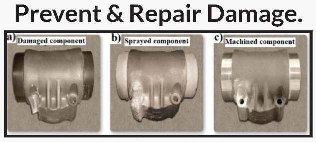
Hybrid Heat Sink



Engine Crank Case



Prevent & Repair Damage.



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

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- Repair forms & patterns for casting.
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Power supply:-	Single Phase 220v, 50/60Hz
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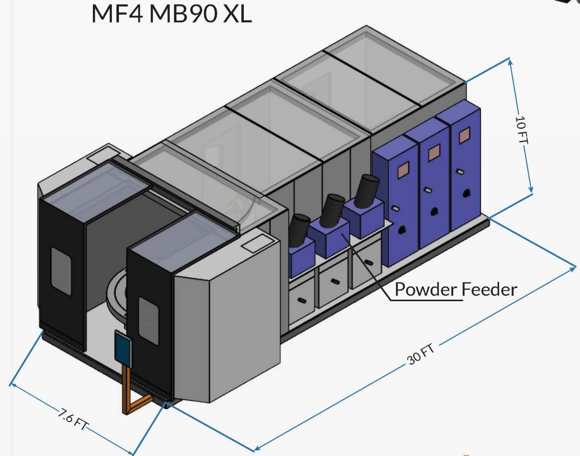

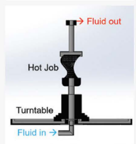

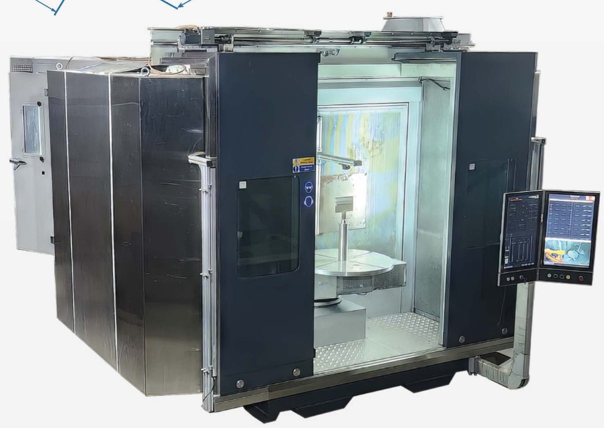

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Mission: Our mission is to deliver the most recent thermal spray industry news and keep up to date to thermal spray community by providing company, event, people, product, research, and membership news of interest to industrial leaders, engineers,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

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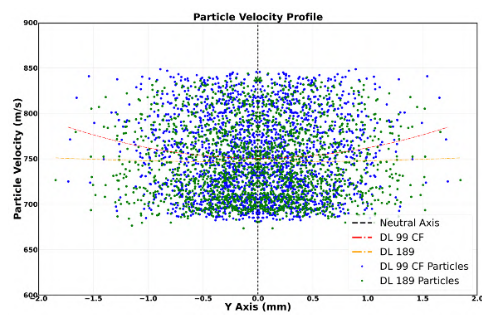

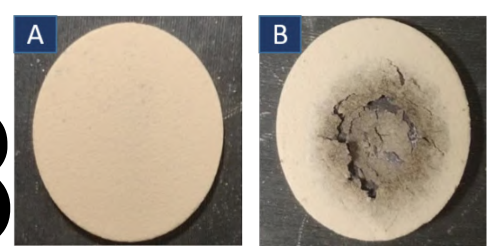

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ABOUT THE COVER

Computational domain and b) Computational grid for Co-Flow Nozzle by Amit Kumar Sharma

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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 thrilled to bring you this special issue, which not only highlights the latest advancements and trends in thermal spray field but also looks forward to one of the most significant event on the thermal spray calendar: the **2nd Indian Thermal Spray Conference and Expo (NTSC2025)** https://www.indtsa.org/ntsc-2025. Scheduled to take place from February 21-22, 2025, at the esteemed CSIR-Institute of Minerals & Materials Technology (IMMT) in Bhubaneswar, this conference promises to be a hub of innovation and collaboration. The event will gather leading experts, researchers, and industry professionals from around the globe to discuss cutting-edge developments, share insights, and explore the future of thermal spray technology. With a robust lineup of keynote speeches, technical sessions, and an expansive expo showcasing the latest equipment and materials, this conference is set to elevate our understanding and application of thermal spray techniques.

In this issue, we are also delighted to feature a series of articles that delve into the recent trends shaping the thermal spray industry. Our contributors have explored a range of topics, from advancements in coating materials and application methods to the integration of artificial intelligence and automation in thermal spray processes. These articles provide a comprehensive overview of the current state of technology and offer a glimpse into the innovations that are driving the industry forward.

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 "Sustainable Development Goals and Circularity In Thermal Spray Coating Manufacturing and Value Chain; CFD Investigation of a Co-Flow Nozzle for Cold Spray Additive Manufacturing Applications; and Critical Role of Ablation-Resistant Thermal Barrier Coatings In Enhancing Aerospace Performance", that illustrate current research trends in thermal 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)

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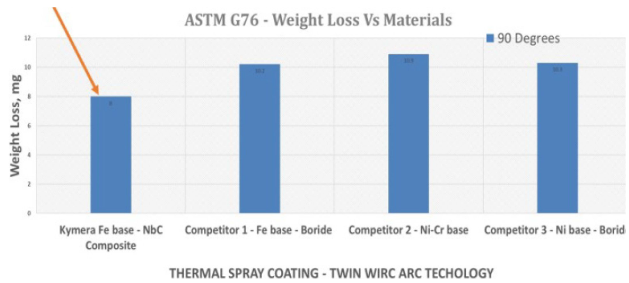

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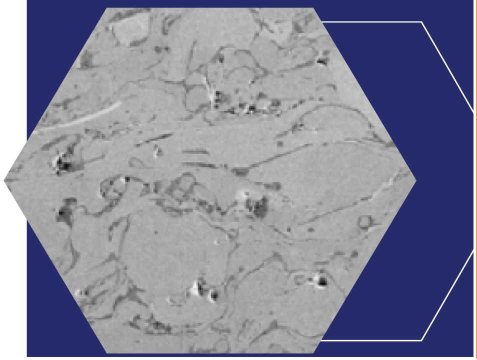

Sustainable Development Goals and Circularity In Thermal Spray Coating Manufacturing and Value Chain

By ***Nadimul Haque Faisal, Anil Prathuru***

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Summary

Thermally sprayed coating manufacturing utilizes a range of feedstock materials to develop thick layers on high-value solid and conformal structures which provide a wide range of qualities to components or parts. Due to the combination of environmental, economic, social, and regulatory factors, there is compelling need for thermal spray coating manufacturers and those associated with the value chain to embrace the United Nation's Sustainable Development Goals (UN SDGs) and circularity to stay competent in the international market. This could lead to a significant increase in the demand for sustainable and circular manufacturing practices, and potential increase in business opportunities, market size and the economy. There is a need to understand the challenges and identify opportunities for circularity in thermal spray coating manufacturing and value chain.

Thermal spray coating

Thermal spray is regarded as a key surface manufacturing technique that underpins the competitiveness of critical manufacturing and engineering industries. Considering the global thermal spray market size, it is expected to grow from USD 10.91 billion in 2023 to USD 13.41 billion by 2028, at a CAGR of 4.22% (during 2023-2028) (Report Linker, April 2023). It is widely used in engineering for aerospace, industrial gas turbine, automotive, medical, printing, oil & gas, steel, pulp & paper, others as well as other new applications [1-2].

Various thermal spraying processes exist (e.g., air plasma spray, cold spray, detonation spray, flame spray, electric arc spray, high velocity oxy-fuel (Fig. 1), and more) [3] and all are used to produce thick-film coatings to combat surface degradation of engineering components or to bring in functional features, for example wear resistance, catalysis, electromagnetic wave absorption or hydroxyapatite for tissue regeneration. The materials that can be deposited through thermal spray include pure metals, metallic alloys, ceramics, and a mix of ductile and brittle materials. During spraying, several variables and process parameters have a direct impact on coating properties, which can be quantified. The process of such coating deposition involves complex phenomena occurring with overlapping timelines. The temporal evolution of overall coating formation constitutes splat formation, cooling, and subsequent layer deposition followed by cooling to room temperature post-deposition (Fig. 2). Such coatings are vital to improve the performance of components and industrial products to maximise their life cycle.

Value chain in thermal spray sector can be split into the following fields: materials and processes pre-spraying (materials mining, feedstock processing and their manufacturing), during spraying (consumables, coating manufacturing, equipment's), post-spraying (coated part finishing and handling), during use or in-service operations (coating degradation), and then the end-of-life and circularity of coated parts. The materials and manufacturing vision as well as the entire value chain should be guided by sustainable development goals (SDGs) and circularity imperatives. Due to barriers within this sector, such as lack of understanding, skills, experience, as well as training, resources, strategy, regulations, and environmental awareness on the part of suppliers, clients, or end users, the circularity within the thermal spray value chain is currently at a nascent stage.

Sustainable Development Goals (SDGs) and thermal spray sector

To bring prosperity, peace, and partnership to all people on the planet by 2030, the United Nations enacted a set of 17 goals in 2015, called Sustainable Development Goals (SDGs), which have economic, social, and ecological

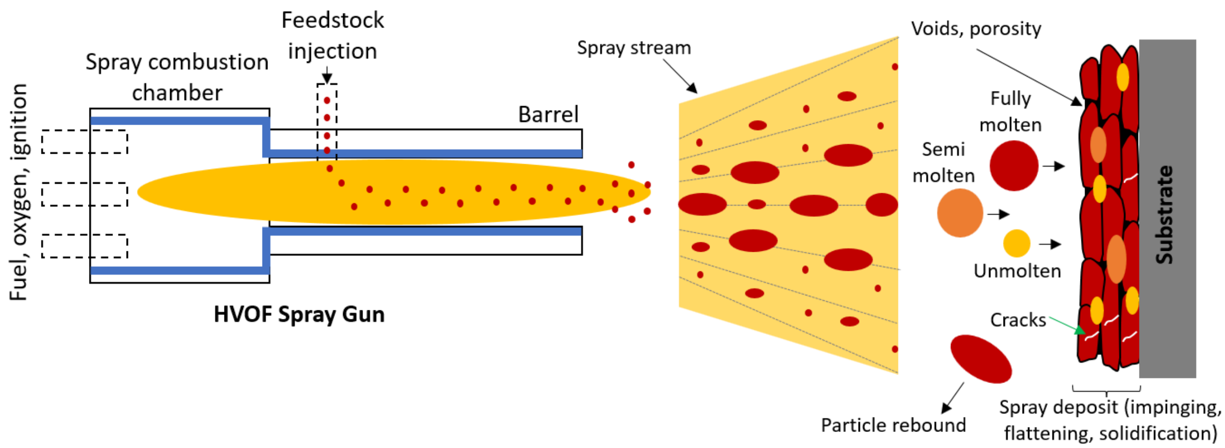

Figure 1: Various stages of thermal spraying

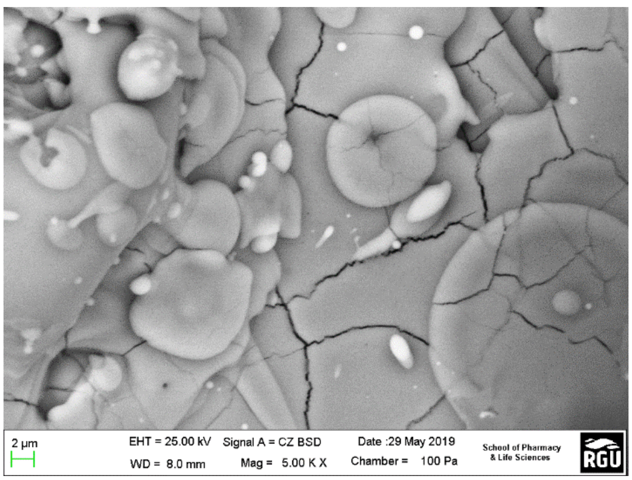

Figure 2: Air plasma sprayed TiO2 coatings on mild steel, showing splats and microcracks

dimensions. Given the size of the thermal spray value chain and market, it has an important role to play in reaching relevant SDGs. Relevant SDGs could be SDG7 (affordable and clean energy), SDG8 (decent work and economic growth), SDG9 (industry, innovation, and infrastructure), SDG12 (responsible consumption and production), SDG13 (climate action), and SDG17 (partnership for the goals) (Fig. 3).

Like other manufacturing sectors, the thermal spray sector could create a sustainable framework for the industry which could help meet its social responsibility goals. There is very limited data, however, in certain practices associated to thermal spray value chain, there is overexploitation of resources, including creation of huge material waste. There is a need to provide incentives of the SDGs to thermal spray value chain stakeholders, including encouragement to transition to circular economies (reuse, recycle, remanufacture, and recover), and support various framework directives related to waste (e.g., EU's Waste Framework Directive, 2023 [4]). Overall, such directives require the stakeholders and businesses to protect human health and the environment, by reducing waste and its adverse effects through efficient management.

Figure 3: Relevant SDGs appropriation for thermal spray value chain

Circularity opportunity

Competitiveness in thermal spray manufacturing is highly dependent on the ability of such manufacturing sector to provide high-quality, innovative products through enhancing circularity, and facilitating decarbonization [5]. This would mean a range of modern tools need to be employed to achieve the systemic circularity of the thermal spray sector. The transition to circular manufacturing requires a new mindset, resources, and expertise in the sector. All the technological improvements of the manufacturing process should always support the human aspect to uptake these improvements through upskilling and reskilling of the manufacturing workforce. Currently, there is a skill gap within professionals with knowledge of circular manufacturing processes. The workforce should be engaged in the realization of circular approaches.

Considering the future requirements of thermal spray coating manufacturing, there is need to forecast the environmental impact, quantify state of products after their use, develop simulation and modelling software or build on existing solutions fostering new circular manufacturing capabilities with a view to be more efficient and more sustainable product design. There is a need to enable the manufacturers to implement the Digital Product Passport initiatives [6], and focus on gathering relevant data, material and product tracking and tracing, certification protocols for secure re-used materials and components among sectors.

Efforts are necessary to consider recycling and reuse in the thermal spray sector and to continue drawing the advantage of thermal spraying being a relatively green technique. To achieve a circularity or circular economy of thermal spray coated products after use (i.e., end-of-life), there is a need to start looking at value retention processes [7]. This includes practices such as choosing repair and overhaul (where possible) over buying new or purchasing remanufactured equipment as opposed to new. It is not new, but thermal spray industries have been using the practice of rebuilding and remanufacturing for reuse or recycling (either through removing damaged materials via machining or rebuilding the surface of coated components through mix of thermal spray techniques, through using heat, depending upon the metallurgical properties of the coating and structural part material). The key advantage of such remanufacturing are its cost-effectiveness and a process that can be done multiple times [8], and importantly it is an accepted practice as the sector has been able to achieve original equipment manufacturers (OEMs) specification through remanufacturing [9]. However, some aspects of reuse and recycling are currently not possible in thermal spray industry (e.g., reusing coating materials which are removed from the coated parts). As an example, thermally sprayed thermal barrier coatings (TBC's) could be removed using techniques such as grit blasting, chemical stripping (autoclaving, aqueous stripping), water jet (abrasive, non-abrasive), and laser ablation. With varied degree of removal efficiencies, all these coating processes are useful only to remove the coatings, but these does not help in recovering the removed materials. It would be quiet a cumbersome and costly process (with very low yield) to recover the useful part of the removed coatings, as the removed mass would have contaminants, rusts, stains, and high toxicity, which can be a less attractive offer for many businesses.

Thermal spray processing generally requires feedstock in the form of fine powders. These powders are made using methods such as atomisation, spray drying, and solid-state reduction. All these processing methods require some level of energy to either melt the raw material or to enable a chemical reaction process. Efforts should be put in place to achieve carbon neutrality in such feedstock manufacturing processes to reduce the overall carbon footprint. To understand the circularity of thermal spray process and its overall carbon footprint, it is important that the background processes be accounted for too. One possible way to implement the concept of circularity is to evaluate how waste or by product material from other industries can be used in thermal spray. For example, copper waste from the electronics and electrical (WEE) industries could be a possible source of copper feedstock for electrically conductive coatings. In addition, low melting point metals such as zinc and aluminium can be recycled for reuse with minimal heat input. However, in such cases, particle oxidation in the spray plume is a potential hurdle.

Overspray is seen extensively in most thermal spray shops. The general operational philosophy of such facilities is the collection of the overspray dust to be either sent to a landfill or selling to a waste buyer who separates the individual powder materials and reprocesses them to be resold. Understanding the cost benefit of recycling instead of discarding into a possible landfill provides the basis for formulating the business case of introducing circularity in thermal spray manufacturing value chain. Classifying the materials according to the ease of recycling is one way of understanding and creating a circularity framework. For instance, being able to collect the overspray dust in separate bins according to the material type makes it easier for the buyer to recycle the waste material at a later stage. This could also increase the sale value of the dust and could present a cost recovery opportunity to the thermal spray manufacturer. Creating an implementation plan around the product life cycle, not just of the coated product but also the feedstock could be an effective way of reducing waste while increasing the overall cost return.

One excellent demonstrator of the reuse of thermally sprayed feedstock overspray dust is the LIFE ReTSW-SINT project [10] funded by the European Commission (EC). The objective of the project was to establish the processing methods to use thermal spray waste in other industries. The project was able to successfully demonstrate the reuse of nickel metal powders in creating sintered products using the spark plasma sintering (SPS) method. In addition, the project also established the process of incorporating YSZ waste powder into ceramic frits and tiles. This project also demonstrated the critical aspect of environmental safety consideration while developing a recycling process. Given that most of the materials of commercial interest used in thermal spray are hazardous, it is critical that the reuse process isolates these materials and reduces their interaction with the environment. Most ceramics exhibit leaching behaviour where the constituent metals are slowly released into the environment creating environmental contamination.

Concluding remarks

Since the invention of the thermal spray process by Dr. Max Ulrick Schoop of Zurich in 1911, a lot has changed in the sector. Thermal spray market is experiencing significant growth as the sector is seeking advanced coating solutions to enhance the performance and longevity of coated parts, including emergence of new ways to deposit coatings and applications. Quality and affordable thermal spray products will be the future growth opportunities in coming decades. There is a need to drive low-carbon processes in thermal spray coating manufacturing and value chain through efficient resource utilisation, enhanced performance, and waste minimisation, strategically address critical (social, economic, environmental) needs sustainably, develop global centre of excellence and achieve high quality, multidisciplinary research, engage (co-create/co-deliver) with partners, and create opportunities for staff and end user skill development, and embed equality, diversity, and inclusion (EDI) within the sector through specific action plans. There is a need of new entrants (entrepreneurs) in thermal spray value chain who can focus on the deployment of next generation technology solutions at scale to meet short and medium-term targets, including meeting sustainable development goals and transition to circular economies. Such strategies could also help improve loyalty of the buyer and influence the brand.

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CFD Investigation of a Co-Flow Nozzle for Cold Spray Additive Manufacturing Applications

By ***Amit Kumar Sharma[1,2], Ashish Vashishtha[1,2], Dean Callaghan[1,2], Srinivasan Rao Bakshi[3], M. Kamaraj[3] and Ramesh Raghavendra[4]***

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Abstract
This current work evaluates the efficacy of a co-flow nozzle for cold spray applications with the aim of mitigating nozzle clogging issues, which can occur during long-duration operations, by replacing the solid wall of a divergent nozzle section with an annular co-flow fluid boundary. Simulations were conducted on high-pressure nitrogen flowing through convergent-divergent (C-D) axisymmetric nozzles, with a stagnation pressure of 6 MPa and a stagnation temperature of 1273 K. In these simulations, Inconel 718 particles of varying sizes (15 µm to 35 µm) were modelled using a 2-way Lagrangian technique, and the model's accuracy was confirmed through validation against experimental results. An annular co-flow nozzle with a circular cross-section and straight passage covering the primary C-D nozzle has been designed and modelled for cold spray application. Co-flow was introduced to the reduced nozzle length to compensate for particle velocity loss at higher operating conditions. It was found that co-flow facilitates momentum preservation for primary flow by providing an annular gas boundary, resulting in increased particle speed for a longer axial distance beyond the nozzle exit of the reduced divergent length nozzle. The particle acceleration performance of the reduced divergent section nozzle, when combined with co-flow, is comparable to the original length nozzle.

Introduction
Cold gas dynamic spray (cold spray) has emerged to be the most attractive non-thermal metal deposition process that has garnered significant interest from researchers and industry due to its potential in the coating, repair, and additive manufacturing fields [1]. The performance of a cold spray system can be assessed by deposition quality & efficiency and metal powder acceleration. The three main parameters, that affect the performance are; input power (gas stagnation pressure and temperature at nozzle upstream), powder & substrate material properties, and nozzle efficiency. However, in cold spray, a significant challenge is nozzle clogging, where particles bond to the nozzle's inner surface, hampering deposition efficiency and quality. Nozzle clogging usually occurs in two sections of a converging-diverging (CD) nozzle, first at the nozzle throat and secondly downstream of divergent length as depicted in Fig. 1. The primary factors that contribute to nozzle clogging are the high temperature of the nozzle wall and particle dispersion as highlighted by Wang et al. [2] which is consistent with the findings by Ozdemir [3]. In general, dense, and low melting point powder materials are known for their propensity to clog which include aluminum, copper, nickel, stainless steel, Inconel, and titanium [4-8].

Nozzles, typically made from robust materials such as tool steel or metal carbides, are costly to replace. Although cleaning clogged nozzles is an option, it disrupts operations and adds to costs. One innovative solution involves modifying the convergent-divergent (CD) nozzle design. To address this, a coaxial co-flow nozzle design introduces a high-speed fluid around the primary flow, maintaining particle velocity and reducing clogging. Experimental studies and computational fluid dynamics (CFD) simulations have demonstrated that the co-flow design extends the supersonic core length and preserves momentum, enhancing particle acceleration after the nozzle exit. Additionally, the co-flow design aids in

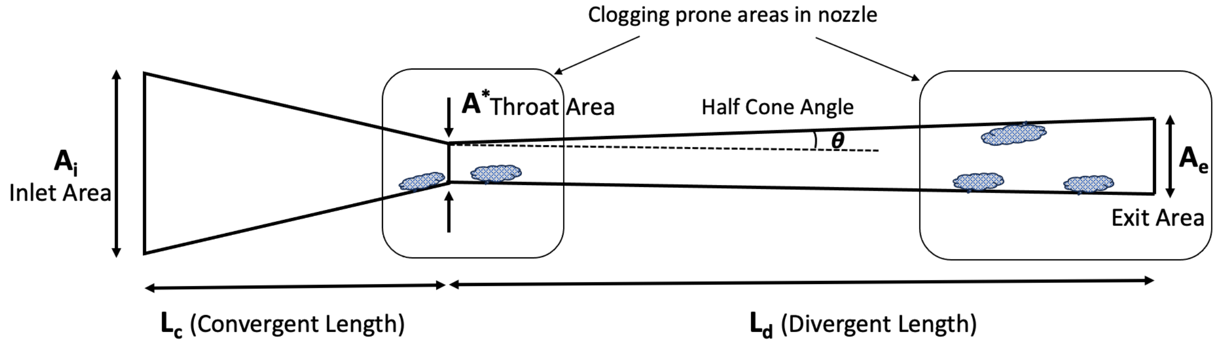

Figure 1: Schematic illustration of CD Nozzle clogging in Cold Spray process

cooling the nozzle walls and suppressing the acoustic signature of the supersonic jet.

This study investigates the impact of co-flow assisted reduced divergent lengths on particle acceleration using CFD simulations, comparing various particle sizes. The findings suggest that a shorter nozzle with a co-flow design effectively mitigates velocity loss, reduces clogging, and improves overall performance, marking a significant advancement in cold spray technology.

Design and Modelling Method

All the numerical simulations carried out in this study are performed using ANSYS Fluent 2021 R1 with gas and particle simulations carried out using a two-dimensional axisymmetric computational domain [9-11].

Geometry and Computational Domain

The simulations are performed for a standard convergent-divergent nozzle along with a co-flow nozzle by integrating an annular passage as shown in Fig. 2. The original convergent-divergent nozzle has a divergent length (DL) of 189 mm. The operating conditions for primary flow that accelerate the Inconel 718 powder particles are adopted according to a high-pressure cold spray system operating at 6 MPa of stagnation pressure and 1273 K of stagnation temperature. The exit-to-throat area ratio and the convergent section were kept constant for all nozzle designs while the divergent length was varied from 15D to 42D, where D is the nozzle exit diameter. Until a specific reduction in divergent length is reached, the particle speed exhibits minimal decline or, in certain instances, remains unchanged. In our parametric investigation, we observed a small decrement (approximately 2.5 %) in particle velocity with divergent length reduction up to 129 mm. However, noteworthy disparities emerged with a reduction from divergent a length of 109 mm (DL 109) onwards. Consequently, nozzles with a divergent length less than or equal to 109 mm are included in this study. The study includes simulations of three distinct divergent length nozzles DL 109, DL 99, and DL 69 in addition to the original length DL 189 nozzle.

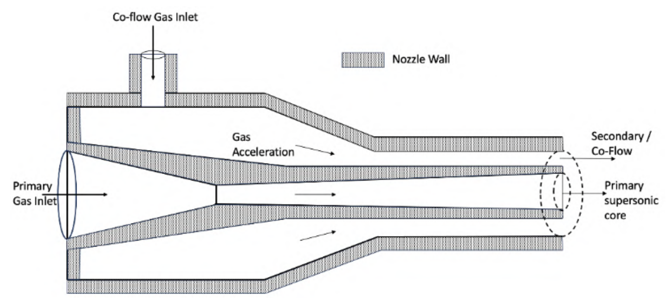

Figure 1: Representative diagram of Co-Flow nozzle for Cold Spray application

Figure 3 shows the computational domain and computational grid for the co-flow nozzle used in the simulations. A straight chamber is attached at the beginning of the convergent section of the nozzle to stabilize the gas flow. The computational domain comprises a stagnation chamber, a particle discharge tube, the nozzle along with the co-flow region, and an extended expansion region.

In the experimental work, 15-35 µm Inconel powder particle was utilized with a mean particle size of 22 µm with the largest being 35 µm. Thus, for the computational analysis these three sizes i.e., 22 µm, 35 µm, and a variation of 15-35 µm were intentionally chosen and injected from the nozzle inlet at 60 g/min to encompass the range of particle sizes encountered in the actual experiments. For the study of 22 µm and 35 µm particle size, 100 particles were injected through surface injection, while for the simulation of particles with a size range of 15-35 µm 1000 particles were injected via group injection method and distribution according to the Rosin-Rammler approach.

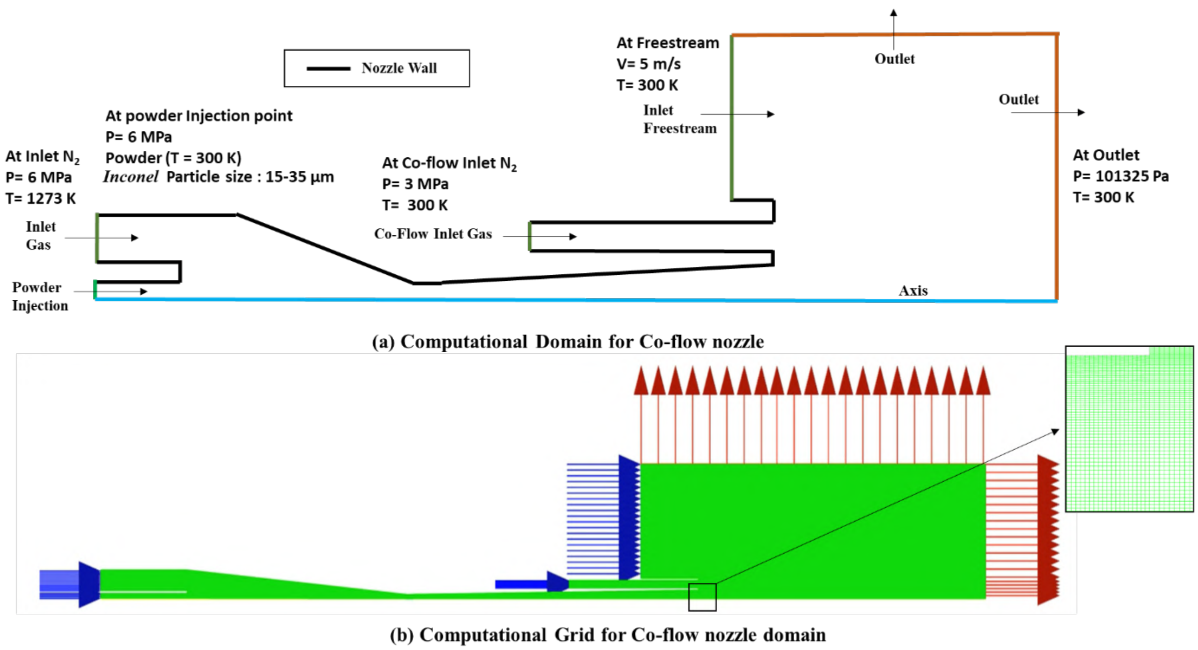

Figure 3 a) Computational domain and b) Computational grid for Co-Flow Nozzle

To validate the numerical model, a single simulation was conducted, simulating 5000 particles within the size range of 15-35 μm for the DL 189 case. This simulation was further compared to the results with experimental data and it was found that the simulation results are well matched to the experimental results where simulated mean particle speeds were found to be within 4% of the mean velocity obtained from the particle velocity probe thereby confirming the validation of the numerical model for the current nozzle design study.

Result and Discussion

Reducing the divergent length in cold spray nozzles has been examined through comprehensive numerical simulations, shedding light on its impact on particle acceleration and nozzle performance. The investigation encompassed various particle sizes and nozzle configurations, aiming to understand the dynamics of gas and particle velocities. For particle sizes ranging from 22 μm to 35 μm and a broader range of 15-35 μm, simulations consistently demonstrated the influence of divergent length reduction on gas and particle velocities. Across all cases, shorter divergent lengths correlated with higher gas exit velocities due to reduced boundary layer effects and friction losses. However, this increase in gas velocity was accompanied by a decrease in particle velocities, attributed to the shorter residence time for particle acceleration.
Analyzing particle velocities at nozzle exit and standoff distances showed varying degrees of velocity reduction across different nozzle lengths. DL 189 consistently exhibited the highest particle velocities, with reductions observed as the divergent length decreased. However, DL 99 and DL 109 showed comparable performance, demonstrating potential for maintaining particle velocities similar to DL 189. To address velocity losses in shorter divergent nozzles, co-flow was introduced as a mitigating strategy. The addition of co-flow aimed to extend the supersonic core length, thereby facilitating particle acceleration over longer distances and mitigating issues related to frictional losses and clogging. Numerical simulations confirmed that DL 99 with co-flow (DL 99 CF) achieved particle velocities comparable to the original longer divergent length nozzle (DL 189), indicating improved performance and deposition capability. Co-flow effectively preserved momentum and enhanced nozzle performance, showcasing its potential as a viable strategy for optimizing cold spray processes. Further analysis of co-flow effects revealed significant improvements in nozzle performance, particularly in extending the supersonic core length and mitigating velocity losses. DL 99 with co-flow emerged as an optimal choice, demonstrating enhanced deposition capability over larger distances.

Conclusions

The study demonstrated that reducing the divergent length of cold spray nozzles can impact particle acceleration, with velocity reductions observed as nozzle length decreases. However, introducing co-flow

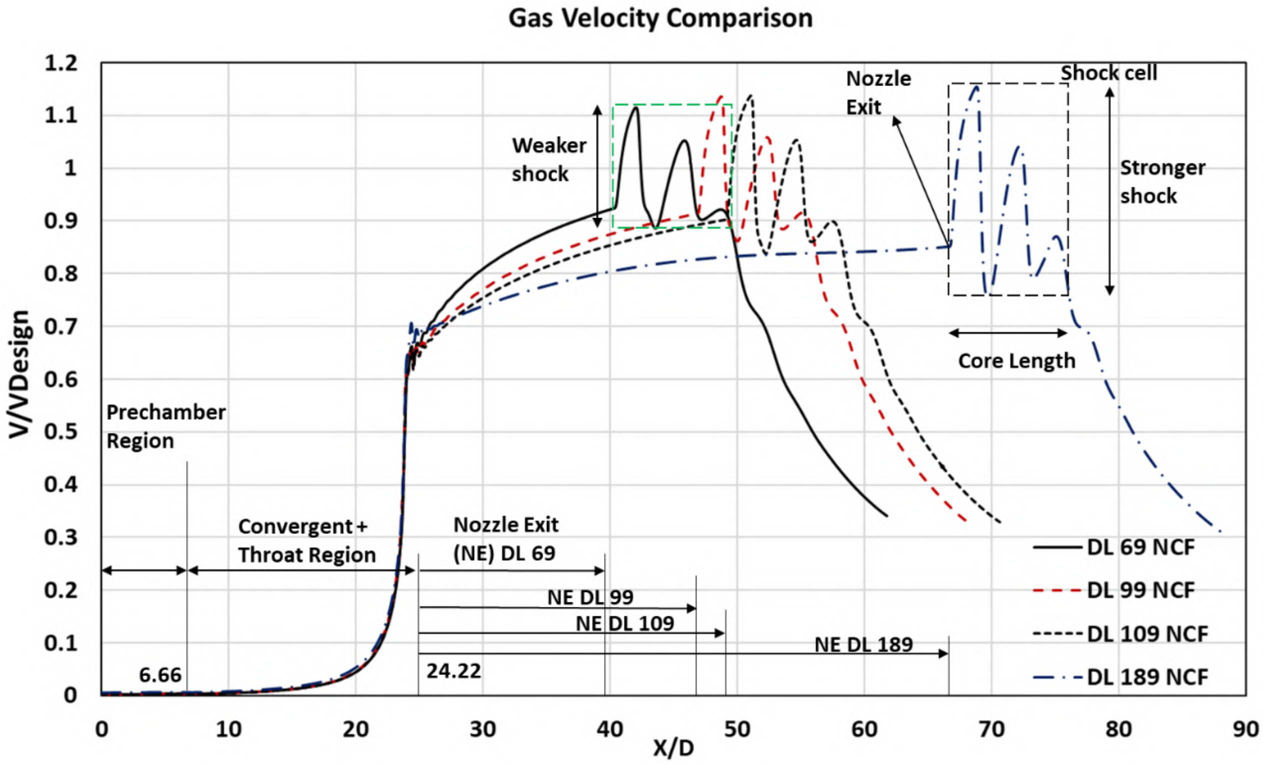

Figure 4: Axial gas velocity of DL 69, 99, 109 & 189 at 6 MPa 1273K Inconel for 22 µm particle size

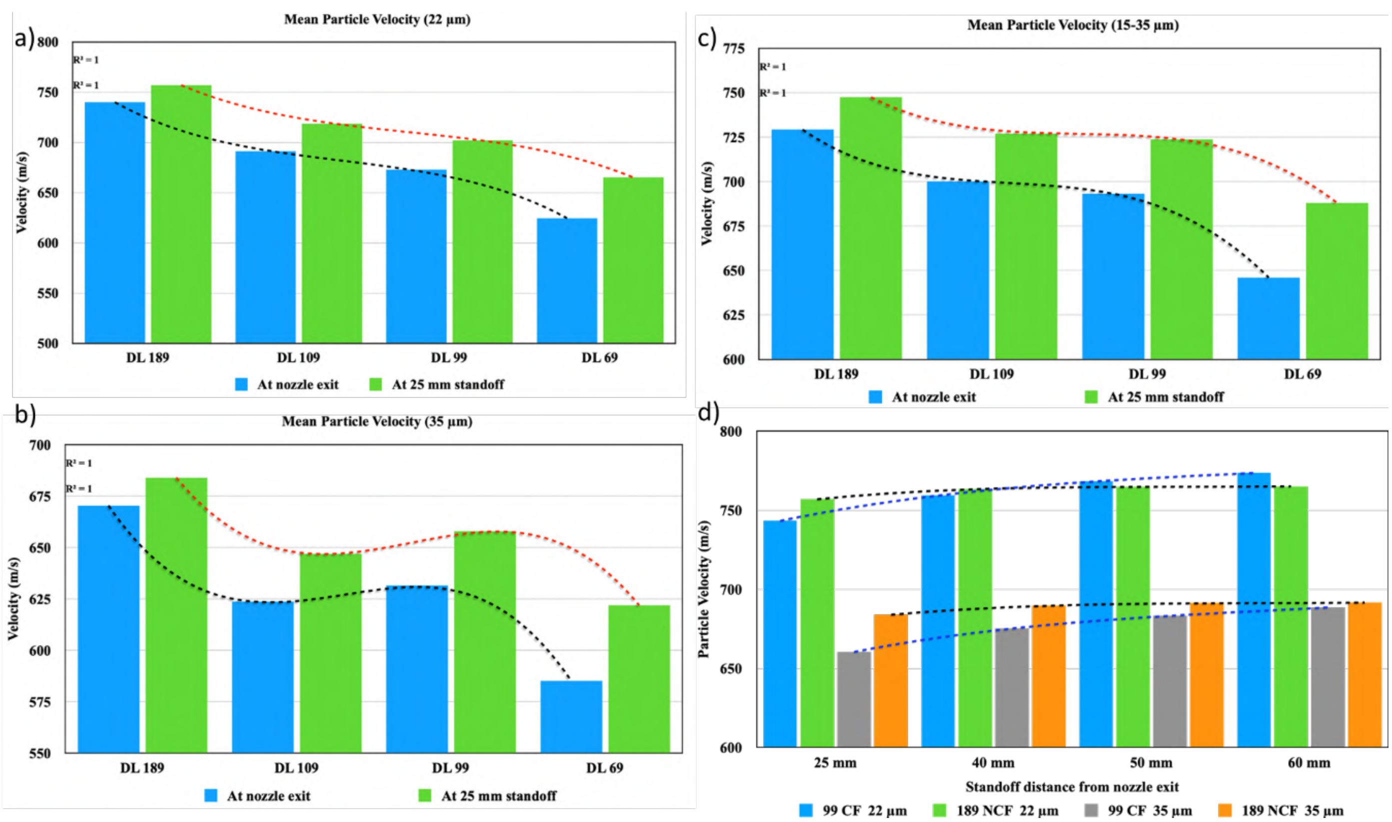

Figure 5: Mean particle velocity at nozzle exit and at 25 mm standoff distance a) for 22 µm particle size, b) for 35 µm particle size, c) for 15- 35 µm particle size, and d) Mean particle velocity at different standoff distance for 22 and 35 µm particle size.

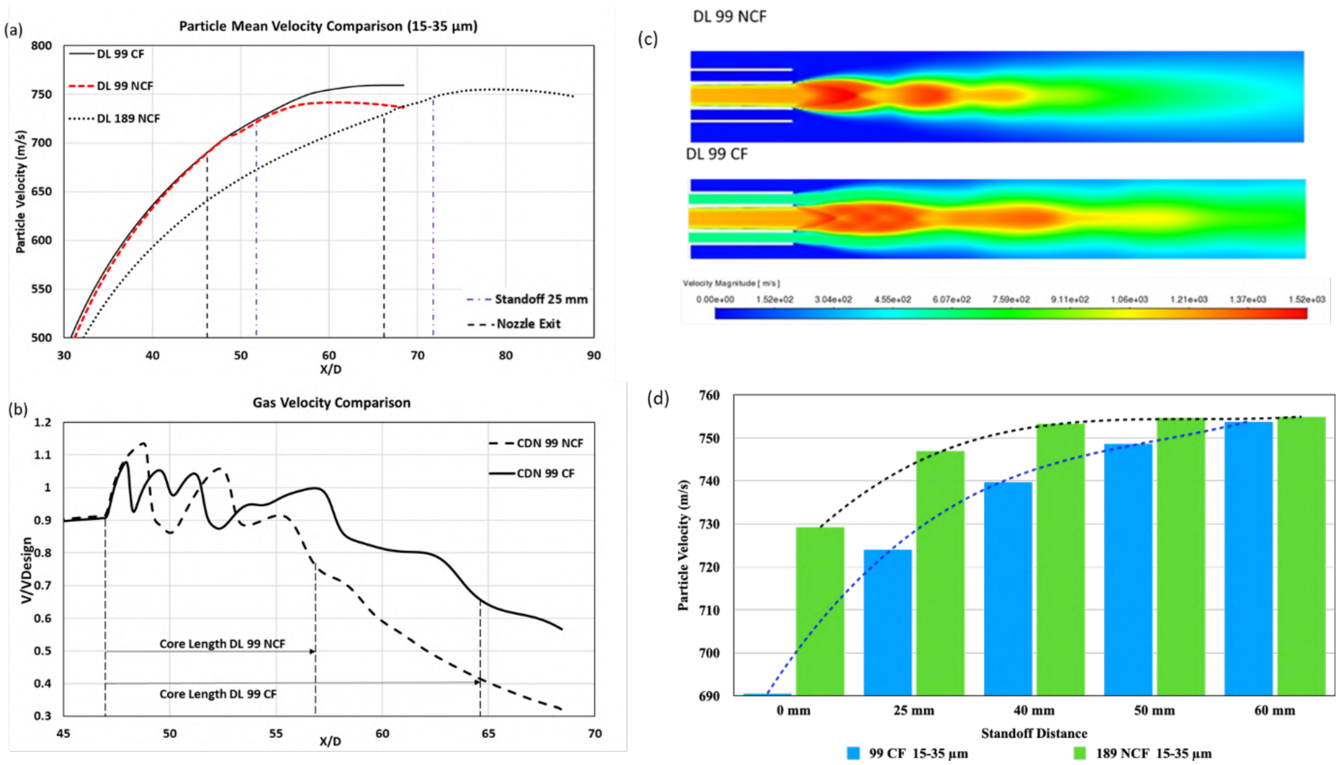

Figure 6: Mean particle velocity (a), Gas velocity (b) comparison between DL 99 NCF and DL99 CF, (c) Gas velocity comparison between DL 99 NCF and DL99 CF, (d) Mean particle velocity at different standoff distance for 15-35 µm particle size

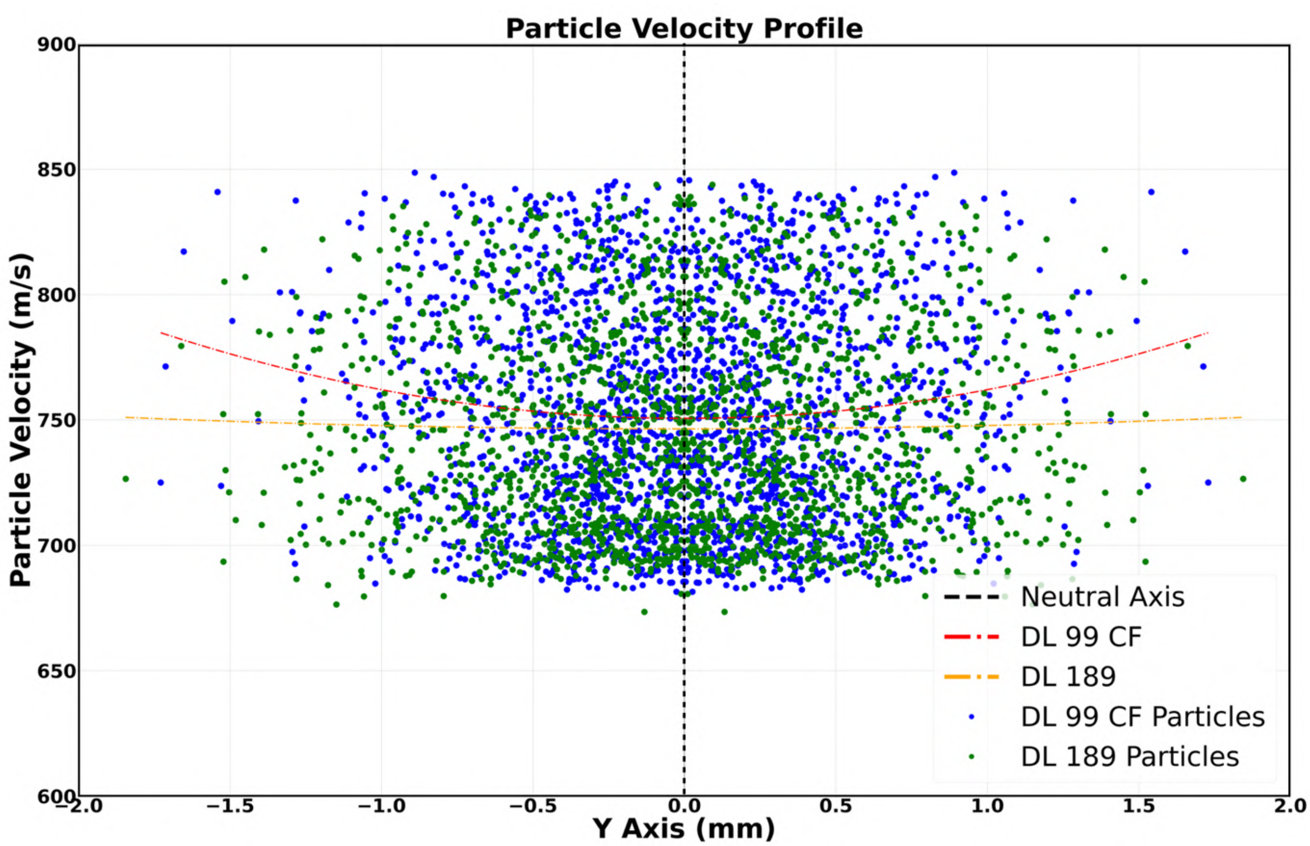

Figure 7: Particle velocity distribution for DL99 CF at 50 mm and DL 189 at 25mm standoff distance from the nozzle exit with the lateral axis

effectively compensated for velocity losses, enhancing nozzle performance and deposition capability.

Future studies can explore integrating co-flow into industrial cold spray systems, addressing design constraints and operational challenges. Additionally, experiments involving flat substrates at different standoff distances and flow visualization techniques can provide further insights into co-flow effects and optimization strategies.

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Critical Role of Ablation-Resistant Thermal Barrier Coatings in Enhancing Aerospace Performance

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Abstract
It is well known that thermal barrier coatings (TBCs) are crucial for the advancement of high-temperature applications, especially in aerospace and power generation industries. Yttria-Stabilized Zirconia (YSZ) is a widely used as topcoat material for TBCs application due to its excellent thermal insulation properties. However, the TBC integrity can be affected by ablation under extreme thermal and mechanical conditions. This article discusses the impact of rare earth dopants for the topcoat on improving ablation resistance.

Introduction
Hypersonic aircraft and combustion chamber components of gas turbine engines have been predominantly manufactured from nickel-based superalloys. This choice of material is primarily attributed to the notable resistance to creep, high temperature strength and good fracture toughness. Exceeding the gas temperature above 1400 °C to achieve higher level of thermodynamic efficiency and performance, the nickel-based superalloy components are subjected to extreme conditions leading to adverse effects on functional capabilities over an extended duration [1-3]. Therefore, thermal barrier coatings (TBCs) are engineered on superalloys to protect aircraft and critical gas turbine engine components, particularly those subjected to harsh operating conditions such as high temperatures, thermal cycling, and corrosive environments, thereby improving the reliability and longevity [4]. The conventional 6-8% yttria-stabilized zirconia (YSZ) is extensively employed TBCs due to good combination of thermo-physical properties. The operating temperature limit exceeding 1200 °C in next generation gas turbine engines has restricted the use of YSZ TBC due to its inadequate high-temperature phase stability and poor corrosion resistance [5].

Ablation is a critical issue in aircraft, manifesting as material degradation due to intense thermal environments and corrosive layer deposition from molten salts. This damage can severely impact the aircraft's performance and safety by compromising the coating structure. Aiming to solve this problem, decreasing the ceramics' thermal conductivity and increasing their high-temperature stability may be the key solutions to encounter the damage. Due to the limited temperature range of YSZ TBCs, efforts are being made to enhance their performance by modifying the coatings and designing novel materials to create anti-ablation properties [6] Recent research has focused on developing advanced materials and coating techniques to improve the ablation resistance of TBCs.

Xueying Wang et al. [7] evaluated the antioxidant ablation and heat resistance of novel La1.7Dy0.3Zr2O7 (LDZ) coatings using an Oxygen-kerosene HVOF spray system at 1300 °C and 1500 °C. The study compared these coatings with YSZ coatings under similar conditions.

Figure 1 shows (A & B) as-sprayed YSZ and LDZ coatings, (C & D) surface photographs of these coatings ablated at 1300 °C, and (E & F) surface photographs of the coatings ablated at 1500 °C for 300 s. Figure 1 (C & D) shows that both YSZ and LDZ coatings exhibit good antioxidant ablation behaviour at 1300°C. However, Figure 1 (E & F) indicates that at 1500 °C, the YSZ coating failed, and the substrate burned through within 115 s, whereas the LDZ coating remained intact for 300 s before falling off from the centre. Table 1 shows the substrate temperatures of YSZ and LDZ coatings after the ablation experiment.

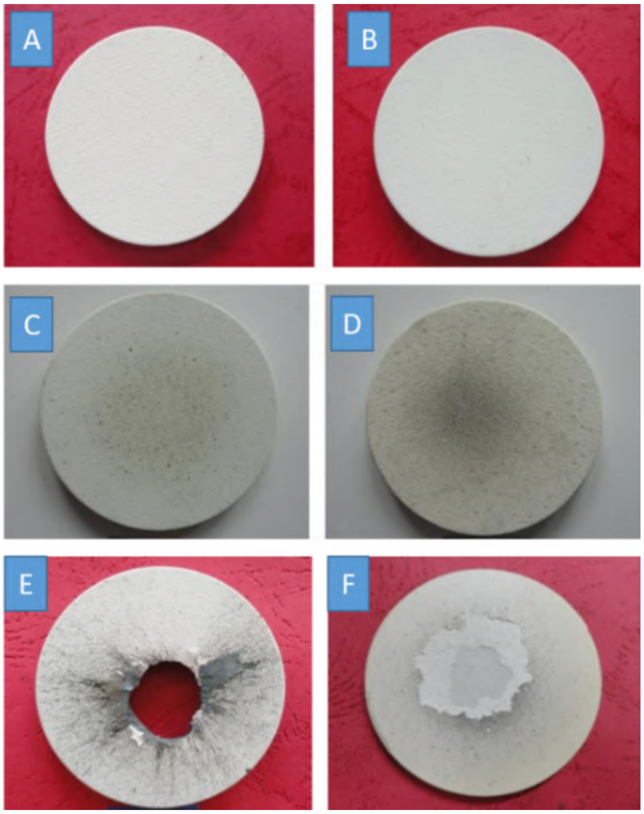

Figure 1: Surface photographs of as-sprayed YSZ and LDZ coatings (A & B); ablated YSZ and LDZ coatings at 1300 °C (C & D); ablated YSZ and LDZ coatings at 1500 °C (E & F) [7].

Table 1: Substrate temperature of YSZ and YSZ coating post ablation test [7]

Temperature	YSZ coating	LDZ coating
Substrate temperature after ablation test at 1300 °C for 300 s	910 °C	820 °C
Substrate temperature after ablation test at 1500 °C for 300 s	1205 °C	1126 °C

The LDZ coating demonstrates superior ablation and thermal insulation resistance due to its lower thermal conductivity. At 1300 °C, the thermal conductivity of LDZ is 0.9719 W/m·K, significantly lower than the 2.3 W/m·K of YSZ at 1000 °C. This indicates that the novel $La_{1.7}Dy_{0.3}Zr_2O_7$ (LDZ) material has excellent thermal properties and strong potential for use in TBCs.

In recent, Saisai Zhu et al. [8] developed a high entropy titanate $(Y_{0.2}Gd_{0.2}Ho_{0.2}Er_{0.2}Yb_{0.2})_2Ti_2O_7$ (YHT) coating using atmospheric plasma coating to investigate the coating ablation behaviour by plasma flame for 300s at 900 °C, 1200 °C, and 1400 °C, respectively. Figure 2 shows that the YHT coating colour changed due to oxidation after ablation. At 1200 °C, there was no macroscopic change, while at 1400 °C, slight blackening and minor ablation were observed.

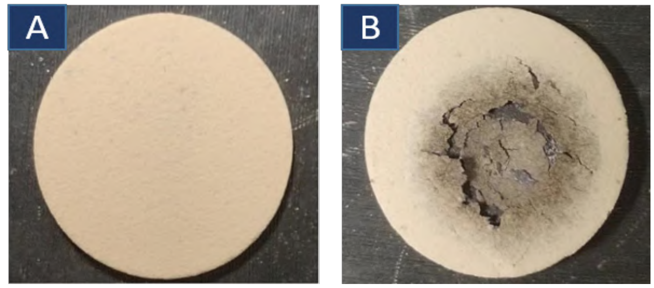

Figure 2: Surface image of ablated YHT coating (A) 1200 °C and (B) 1400°C [8]

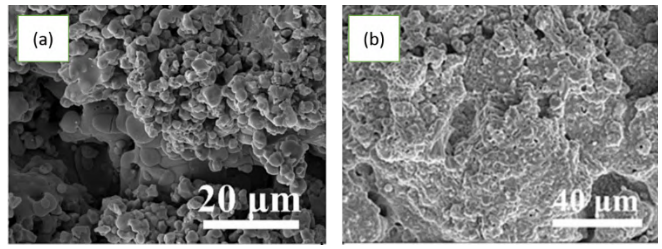

Figure 3: Post ablation microstructure of YHT coating at 1200 °C and 1400 °C [8].

It was observed from Figure 3 that at 1200°C, YHT coatings form spherical structures, and at 1400 °C, they experience mechanical failure due to strong thermal shock and grain growth at centre areas. It was also found that the YHT coating samples show temperature gradients of approximately 590 °C and 620 °C at the back temperature stabilization stage, indicating superior thermal insulation performance compared to YSZ coatings. This demonstrates that pyrochlore-structured high-entropy oxide coatings hold great promise for applications in the thermal protection field, meeting essential requirements for TBCs.

Conclusions

In conclusion, addressing the ablation issues in TBCs is crucial for enhancing the durability and reliability of high-temperature components in aerospace and other high-stress environments. The continuous progress in TBC materials, especially in the development of rare-earth doped coatings and high-entropy oxides, presents encouraging answers to the problems associated with ablation. These developments improve TBCs capacity for thermal protection, guaranteeing improved performance and durability in high-temperature applications. Through the development of superior materials and innovative coating techniques, it is possible to achieve the necessary protection and performance required for next-generation turbine engines and other high-temperature applications.

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