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PERSPECTIVE

Innovative Coatings for a Greener Sky: The 2026 Strategic Roadmap for Thermal Spray and PVD Coatings

Andrew Ang[1] · Thibaut Archer[2] · Farzam Arhami[3] · Mettupalayam Balachander[4] · Kantesh Balani[5] · Dominique Billières[6] · Ann Bolcavage[7] · Giovanni Bolelli[8] · Marjorie Cavarroc-Weimer[9] · Sophie Costil[10] · Nicholas Curry[11] · Alain Denoirjean[12] · Ali Dolatabadi[13] · Alice Dolmaire[14] · William Duarte[15] · David Dublanche[16] · Julien Escobar[17] · Alice Fabre[18] · Gaël Fick[19] · Guillaume Fradet[20] · Frank Gärtner[21] · Edward J. Gildersleeve[22] · Mohit Gupta[23] · Jonathan Gutleber[24] · Makoto Hasegawa[25] · Bryan J. Harder[26] · Brian Hazel[27] · Hendrik Heinemann[28] · Xianghui Hou[29] · Tanvir Hussain[30] · Eric Irissou[31] · Mehdi Jadidi[13] · Cédric Jaoul[12] · Maria Ophelia Jarligo[32] · Bertrand Jodoin[33] · Shrikant Joshi[23] · Andreas Killinger[34] · Jolanta E. Klemberg-Sapieha[35] · Komal Laul[4] · Chang-Jiu Li[36] · André C. Liberati[12] · Rocco Lupoi[37] · Gilles Mariaux[12] · Ludvik Martinu[35] · André McDonald[32] · Christian Moreau[3] · Majid Nabavi[38] · Aleksandra Nastic[32] · Ahmet Hilmi Paksoy[39] · Cédric Poupon[18] · Vincent Rat[12] · Óscar Rojas[40] · Céline Ruelle[9] · Pierre Sallot[9] · Daniel Scotson[39] · Christian Semmler[34] · Serge Selezneff[20] · Sophie Senani de Monredon[9] · Kentaro Shinoda[41] · Pawel Sokolowski[42] · Uwe Schulz[43] · Moussa Tembely[3] · Filofteia-Laura Toma[44] · Pascal Tristant[12] · Thibaut Van Hoof[45] · Armelle Vardelle[12] · Robert Vassen[46] · Scott Wilson[38] · Ping Xiao[39] · Guan-Jun Yang[36] · Shuo Yin[37] · Stephen Yue[47] · Tianqi Zhu[37]

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Abstract Decarbonizing aviation aims to reduce greenhouse gas emissions from aircraft operations, paving the way for sustainable air travel. This endeavor requires adopting advanced technologies, alternative fuels, high-performance coatings and efficient engineering solutions that minimize environmental impact while maintaining performance and safety standards. Two of the most prevalent and cost-effective methods for applying protective and functional coatings to aerospace components are thermal spray and physical vapor deposition. These techniques enhance the durability and efficiency of several components, resulting in fuel savings and an extended service life across the aviation industry. This supports the broader aim of transitioning the aviation industry to net-

This article is an invited paper selected to provide expert perspectives on target subjects relevant to thermal spray and the aerospace sector. The views expressed in the paper are those of the author(s). The sections of the article were written by independent experts and curated by Armelle Vardelle (armelle.vardelle@unilim.fr), University of Limoges/ENSIL.

✉ Armelle Vardelle
armelle.vardelle@unilim.fr

1 Swinburne University of Technology, Melbourne, Australia
2 ONERA -Université Paris-Saclay, Châtillon, France
3 Concordia University, Montreal, Canada
4 Delta Air Lines, Atlanta, GA, USA
5 Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India
6 Saint-Gobain Coatings Solutions, Avignon, France
7 Rolls-Royce Corporation, Indianapolis, IN, USA
8 University of Modena and Reggio Emilia, Modena, Italy
9 Safran Tech, Châteaufort, France
10 University of Technology of Belfort-Montbéliard (UTBM), Sévenans, France
11 Thermal Spray Innovations, Salzburg, Austria
12 University of Limoges - CNRS, Limoges, France
13 University of Toronto, Toronto, Canada
14 ONERA -Université Paris-Saclay, Palaiseau, France

zero emissions and sustainable growth. This roadmap explores how these two coating techniques can promote sustainable aviation and identifies the challenges and opportunities in the aerospace sector for researchers and manufacturers of thermal spray and physical vapor deposition (PVD) coatings. It also proposes research directions to address these challenges and discusses the role of AI, which is crucial for breakthrough technologies in process optimization and integration, new coating development and coating design optimization. The roadmap is organized into 20 concise subsections, each focusing on a specific topic. Renowned specialists in each area were invited to summarize the current status of their field, discuss the challenges it faces, and offer recommendations for necessary research and development to overcome these issues. Together, these contributions vividly highlight the essential elements of the field and the challenges that lie ahead. The innovative ideas and concepts outlined in the roadmap reveal that the future path is both expansive and far-reaching.

Keywords abradable coatings · aerosol deposition · AI-driven modeling · anti-icing coatings aeronautics · anti-oxidation coatings · chord plasma spray · cold spray · complex parts · environmental analysis · environmental barriers coatings · numerical twins · polymer substrate · refurbishment · substrate preparation · suspension plasma spray · thermal barrier coatings · thermal spray · vapor deposition · wear-resistant coatings

Novelty Statement A decade after the JTST released its roadmap on thermal spray, which emphasized the processes, coatings, and applications of thermal spray, the current roadmap shifts its focus to spray processes and vapor deposition methods aimed at decarbonizing aviation. Academic and industry experts are collaborating to share insights on how thermal spray and vapor deposition techniques and coatings can advance sustainable aviation and the necessary research to overcome associated challenges. This roadmap can serve as a valuable reference point for researchers aiming to understand the field's trajectory and identify critical gaps to address.

Introduction

Alain Denoirjean, Vincent Rat, Armelle Vardelle

The aviation sector is a vital element of global economic development that is expected to experience substantial growth in the coming years. Nevertheless, there are significant challenges in achieving decarbonization in the aviation sector as the global community advances toward

[15] Safran Aircraft Engines, Châtellerault, France
[16] Bodycote Surface Technology, Ambazac, France
[17] IRT Saint Exupéry, Toulouse, France
[18] Airbus SAS, Toulouse, France
[19] IRT M2P, Metz, France
[20] Safran Aircraft Engines, Corbeil-Essonnes, France
[21] Helmut Schmidt University, Hamburg, Germany
[22] GE Aerospace Research, Niskayuna, NY, USA
[23] University West, Trollhättan, Sweden
[24] Oerlikon Metco Inc., Westbury, NY, USA
[25] Yokohama National University, Yokohama, Japan
[26] NASA Glenn Research Center, Cleveland, OH, USA
[27] Pratt & Whitney, East Hartford, CT, USA
[28] Surface Engineering Institute (IOT), RWTH Aachen University, Aachen, Germany
[29] Northwestern Polytechnical University, Xi'an, China
[30] University of Nottingham, Nottingham, UK
[31] National Research Council of Canada, Boucherville, QC, Canada
[32] University of Alberta, Edmonton, AB, Canada
[33] University of Ottawa, Ottawa, Canada
[34] University of Stuttgart, Stuttgart, Germany
[35] Polytechnique Montreal, Montreal, QC, Canada
[36] Xi'an Jiaotong University, Xi'an, China
[37] Trinity College Dublin, The University of Dublin, Dublin, Ireland
[38] Oerlikon Metco AG, Wohlen, Switzerland
[39] University of Manchester, Manchester, UK
[40] Centre de Transfert de Technologies Céramiques (CTTC), Limoges, France
[41] National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan
[42] Wroclaw University of Technology, Wroclaw, Poland
[43] German Aerospace Center, Cologne, Germany
[44] Fraunhofer Institute for Material and Beam Technology IWS, Dresden, Germany
[45] Cenaero ASBL, Gosselies, Belgium
[46] Forschungszentrum Jülich, Jülich, Germany
[47] McGill University, Montreal, QC, Canada

the goal of net-zero emissions. Air transport was the first economic sector to collectively commit to specific environmental targets at the international level, whether through the International Civil Aviation Organization (ICAO), or the United Nations specialized agency for civil aviation. In 2009, the sector proposed a more ambitious long-term goal of a 50% reduction in CO2 emissions by 2050 compared to 2005, when global aviation emissions reached 650 MtCO2 (Ref 1). Achieving the aviation sector's ambitious environmental goals requires action on several fronts, including technological advances. One critical area where high-performance coatings can make a significant contribution, is the development of low-carbon aircraft, which includes alternative low-carbon propulsion methods (such as biofuels, e-fuels, hydrogen, electric aircraft, and hybridization), improved engine energy efficiency, and aircraft weight reduction (Ref 2). This requires significant technological advancements to provide advanced thermal barriers, oxidation-resistant bond layers, precise clearance control, improved wear resistance, and effective environmental barriers. These present both opportunities and challenges for thermal spray (TS) and physical vapor deposition (PVD) coating technologies. Advanced coating processes play a critical role in improving the performance and durability of aircraft components, particularly in a corrosive high-temperature environments. They offer opportunities to develop innovative coatings that can improve fuel efficiency, reduce emissions, and enhance the overall performance of next-generation aircrafts. However, challenges exist in optimizing these coating processes for new materials and geometries associated with low-carbon aircraft, as well as ensuring the compatibility of coatings with alternative fuels and propulsion systems.

In November 2024, a two-day symposium was organized by ASM International, the Institute of Research for Ceramics (IRCER, CNRS UM7315) of the University of Limoges, Safran and Oerlikon at the University of Limoges, France. This collaborative event aimed to provide a platform for experts from academia and industry specializing in TS and PVD coating technologies for applications in the aerospace industry. The primary objective was to enable comparison of solutions and propose coatings that could help to low-carbon aircraft.

Based on the results of this symposium, this roadmap addresses the opportunities and challenges associated with TS and PVD coating technologies for low-carbon aircraft. It consists of a series of 20 concise, formalized sections representing the individual perspectives of 73 leading experts in various subfields of TS and PVD science and technology. In all sections, as well as in the roadmap, the author names are listed in alphabetical order.

The sections are grouped under seven headings that deal with the following topics

- The potential of Thermal Spray and PVD Coatings for Sustainable Aviation
- Environmental Analysis of Thermal Spray and PVD Coatings
- Innovative Thermal Spray Coatings for Sustainable Aerospace
- Perspectives for Vapor-Deposited Coatings
- Refurbishment and Lifetime Enhancement of Aircraft Components
- Cutting-edge Thermal Spray Technologies
- Digital Integration

The aviation industry's dedication to environmental sustainability has brought advanced coating technologies to the forefront of research and manufacturing priorities. As researchers and manufacturers intensify their efforts, we can anticipate significant advancements in thermal spray and physical vapor deposition techniques specifically designed for aviation applications. The convergence of scientific activity and societal need in this field highlights the timeliness and relevance of this roadmap, which could serve as a comprehensive guide for future research directions, emphasizing key areas of focus. As these technologies continue to evolve, they are likely to contribute to the development of more efficient and environmentally friendly aircraft, aligning with global efforts to reduce carbon emissions in the aviation sector. Once developed, these coatings will likely be used by other industries, such as the energy sector to achieve global decarbonization goals. This roadmap not only reflects the current state of research but also anticipates future challenges and opportunities, making it an invaluable resource for stakeholders across the aviation industry.

The Potential of Thermal Spray and PVD Coatings for Sustainable Aviation

Ann Bolcavage, Cédric Poupon, and Serge Selezneff

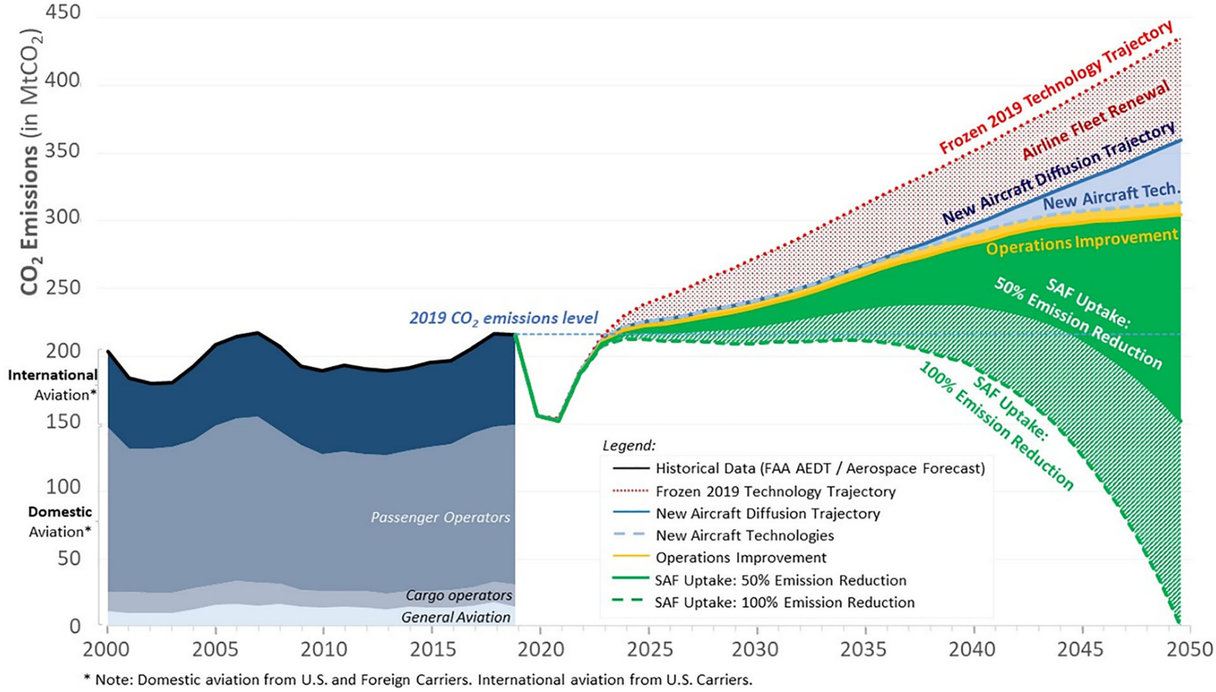

Fig. 1 Analysis of future US domestic and international aviation CO2 emissions (US Aviation Climate Action Plan). The predicted trajectory from 2023 onwards assumes a frozen trajectory from 2019 and recovery from the COVID-19 pandemic

Status of the Field

Thermal spray and physical vapor deposition (PVD) processes are among the most widespread and economical methods of applying protective and functional coatings to aerospace components. By 2032, it is estimated that the aerospace industry will claim a 33% market share of the $3.9 billion thermal spray industry. (Ref 3). Decades of use have yielded a variety of material solutions that ensure the durability, reliability, and performance of aircraft structure, system, and gas turbine engine components.

The goal of net-zero aviation by 2050 introduces a new framework for the industry, presenting challenges for aircraft and propulsion systems. This goal will require improved fuel efficiency from current products and carbon neutrality from sustainable aviation fuels and novel / hybrid propulsion systems (Ref 4, 5). Figure 1 illustrates the challenge from the US aviation perspective, including domestic and international carriers operating in the US, but it reflects the global scenario. A "frozen" trajectory from before the drop-off in travel during the pandemic, with no mitigations, is projected to result in over a 100% increase in current CO_2 emissions. Several developments are required to reach net-zero carbon emissions by 2050 relative to 2020 levels:

- Continued retirement of older, less fuel-efficient aircraft with engines and airframes that incur increasingly high maintenance costs.
- Introduction of new aircraft and propulsion systems with quieter, more fuel-efficient engines, and cleaner airframe designs with lighter materials and improved aerodynamics.
- Increased uptake of sustainable aviation fuel (SAF), which is manufactured from renewable non-petroleum sources. SAF can range from "drop-in blends" consisting of up to 50% SAF and 50% kerosene to 100% utilization of SAF.

Manufacturers of aircraft and gas turbine engines have launched technology demonstrator programs to meet the challenge of net-zero aviation, with the expectation that these concepts will ultimately become saleable products. In conjunction with architectural innovations, the new designs incorporate novel materials (many with coating systems) and manufacturing methods to reduce weight, handle higher mechanical loading, and increase high-temperature capability. Projects that illustrate the industry trajectory toward carbon neutrality include:

- Rolls-Royce's demonstration of its UltraFan® engine architecture (Fig. 2a) for future civil high-bypass engines in 2023 incorporating novel materials including carbon fiber composite fan blades, a carbon fiber composite fan case, and high-temperature ceramic matrix composite components (CMCs) with

[1] CFM International is a 50-50 joint company between GE Aerospace and Safran Aircraft Engines.

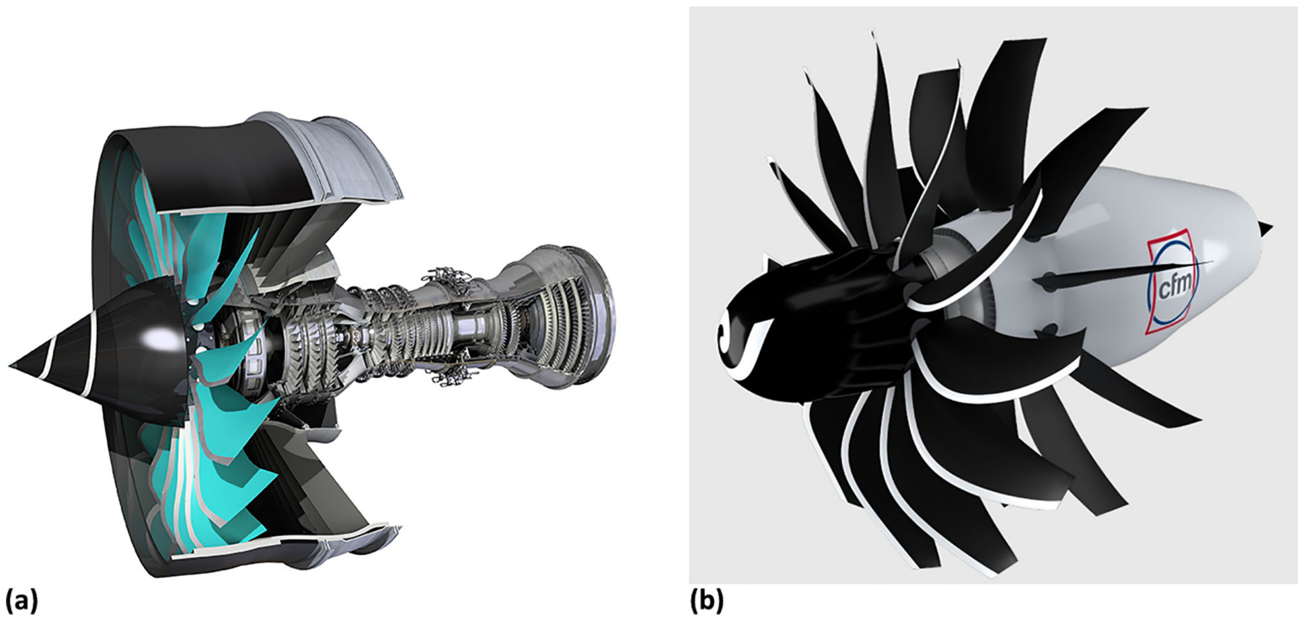

Fig. 2 Rolls-Royce UltraFan® (a) and CFM RISE (b) demonstrator engines

environmental barrier coating systems (EBCs). This concept contains scalable technologies capable of being developed to create an engine with a thrust range of $\sim$ 25,000 lb (11,340 kgf) to 11,000 lb (4,990 kgf) for narrowbody or widebody aircraft that may be developed from the 2030 s. Compared to the original Trent 700 engine that entered service in 1995, it is designed to be 25% more fuel efficient, produce 40% less NOx and 35% less noise, and be compatible with 100% SAF (Ref 6)

- CFM International[1] is currently developing technology for demonstration in RISE (Revolutionary Innovation for Sustainable Engines), an advanced open fan propulsion concept (Fig. 2b). Announced in 2021, this architecture and the advanced compact core within will aim to reduce fuel consumption by 20%, produce 20% lower carbon emissions, and be compatible with alternative fuels (SAF or Hydrogen) (Ref 7).
- Airbus' Wing of Tomorrow research and technology program targets improvements in new wing design for next-generation aircraft. In 2023, a Wing Technology Development Centre (WTDC) was opened in the UK to design, build, and test demonstrators to further improve their performance. The Wing of Tomorrow program also explores new manufacturing and assembly technologies, incorporating higher-strength and lighter materials, to optimize life and reduce drag (Ref 8).

Additionally, novel propulsion systems, such as hydrogen and electric, contribute to the de-carbonization of aviation in applications where the power density of kerosene-based fuels can be reasonably and safely substituted. Hydrogen fuel is considered to be more sustainable than kerosene-based liquids as the resulting combustion products are solely water and heat. With electric propulsion, emissions are greatly reduced or eliminated in 100% electric power applications. The benefits of these technologies are more greatly realized when the supply chain for battery and hydrogen production is also decarbonized.

Current and Future Challenges

The widespread adoption of coating materials and manufacturing technologies to support sustainable aviation will be influenced by both internal and external challenges. Within the industry, there are increasingly demanding functional, operational, and business requirements for advanced products and components. The following examples are just a few among many that present opportunities and barriers to overcome for current and proposed airframes and gas turbine engines.

- In the engine, higher turbine inlet temperatures coupled with reduced cooling air are needed to extract more work from the turbine blades, resulting in better overall cycle and fuel efficiency. This presents a challenge to the durability of thermal barrier coating systems on turbine blade and vane airfoil surfaces, for example increasing their susceptibility to CMAS attack and spallation. The challenge persists with the comparatively higher operating temperature capability of silicon carbide matrix / silicon carbide fiber (SiC/SiC) ceramic

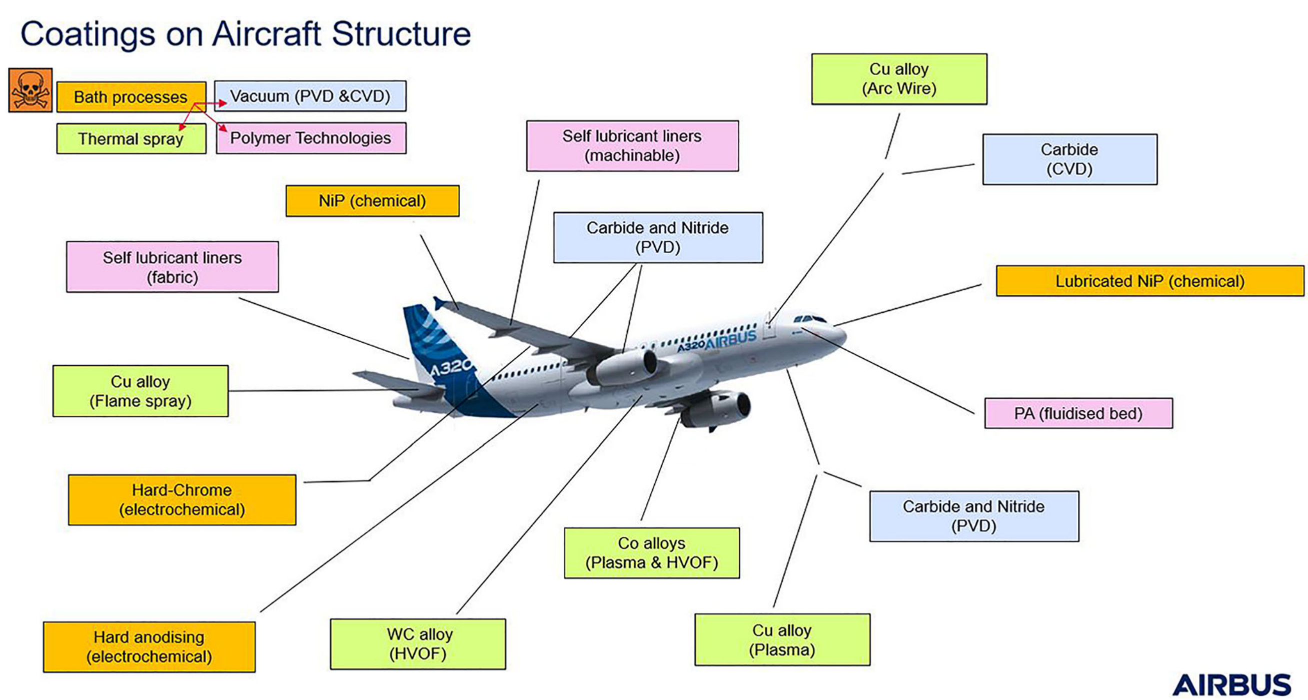

Fig. 3 Locations of various wear and corrosion resistant coatings on a typical Airbus airframe

matrix composite (CMC) components and environmental barrier coating systems (EBCs

- With new engine architecture, sealing technology for temperatures above 350-400 °C will be a key technology to increase engine efficiency. Abradable coatings are the preferred technology in current engines to limit leakage between rotor and stator parts. These coatings can range from less than 1 mm thick to few mm depending on the localization through the engine. Thermal spray is particularly suitable for this range of thickness and widely used for compressor and turbine abradable fabrication. At temperatures above 350-400 °C, aluminum-based abradables cannot be used and existing solutions such as MCrAlY or ceramics have some limitations, lowering the expected gain on efficiency. Therefore, there will be challenges to develop and fabricate new sealing technologies with low roughness, withstanding temperatures above 350 °C and tolerant to contact.
- A wide variety of coatings are used to address wear and corrosion mechanisms in structural and articulating components in aircraft (Fig. 3). Adhesive wear, abrasion, fretting, galling, high contact pressures, inconsistent lubrication, and sub-optimal material choice can impact component durability and result in increased maintenance due to harsher environmental conditions throughout the globe. However, many of the commonly used 'bath processes', such as electrochemical plating, electroless plating, and chemical conversion coatings, involve the use or production of hazardous or carcinogenic substances such as hexavalent chromium. Commitments must be made to respect regulatory limits introduced by initiatives such as REACh (Registration, Evaluation, Authorization, and Restriction of Chemicals) using available and sustainable materials. In aircraft and gas turbine engine repair and overhaul operations, components are often scrapped before reaching declared life limits due to environmental damage (oxidation and corrosion), fatigue and creep, or dimensional loss from wear. Sustainable consumption and waste reduction actions have traditionally consisted of recycling scrapped parts to recover valuable materials, as well as dimensional restoration on features for components that are still considered to be usable. As thermal spray technologies are among the most cost-effective and flexible with respect to coating material choices, there is great interest in using more of these processes to extend the life of high-value components that have to date been difficult to repair.

Mitigation of the challenges in these examples is impacted by the very small fraction of ores that are mined to produce essential metallic and ceramic aerospace coatings such as such as cobalt, nickel, chromium, and platinum (Ref 9). Substitution is made difficult not only by the chemical, physical, and functional properties demanded in each of the high-performance coatings described here, but also by external political factors which can impact the supply chain.

In summary, driving net-zero thinking and behaviors into the culture of the aerospace industry requires a holistic approach. Therefore, all potential technical and commercial opportunities to reduce the carbon footprint ought to be considered.

Advances in Science and Technology to Address Challenges

Substantial progress has been made to develop, validate, and introduce novel coatings. The examples listed below describe how thermal spray and PVD deposition technologies produce functional solutions for the challenges of increasing temperatures in gas turbine engines, identifying REACh compliant solutions to address wear in airframe components, and choosing restoration rather than scrap for high-value components.

CMAS-Resistant Thermal Barrier Coatings

The presence of CMAS-containing debris in the environment presents a practical ceiling for thermal efficiency improvement for gas turbine engines. Once TBC surface temperatures on combustor and turbine components reach approximately 1200 °C, with a strong dependence on the operational route and time of year, deposited CMAS glass on coating surfaces will begin to melt and gradually remove TBCs via chemical reaction, infiltration, and cracking. The level of damage can vary on a component depending on the local temperature, and significant characterization is needed to understand how damage initiates and progresses before considering effective solutions with enhanced durability against the predominant mechanism.

Gadolinium zirconate layers are well-known as first-generation CMAS barriers and have been flying for over a decade (Ref 10). These layers are applied onto components using electron beam physical vapor deposition (EBPVD), air plasma spray (APS), or suspension plasma spray (SPS), depending on the part geometry and microstructural requirements. As temperatures rise, mitigations that increase TBC thermomechanical toughness while providing a thermochemical reaction barrier are needed for increased durability. Various approaches, including phase transformation toughening, high-entropy compositions, substitutional lattice doping, and ferroelastic toughening have been proposed and are being investigated (Ref 11). Fortunately, each of these concepts are expected to be easily applied using plasma spray deposition and/or EBPVD technologies depending on the desired final composition / microstructure and material stability during the deposition process. Developments to optimize the deposition process so as to achieve a predictable and functional microstructure are desired.

Environmental Barrier Coatings for CMCs

The need to push turbine section temperatures ever higher yet conserve cooling air will place incredible demands on gas turbine engine component durability and performance, driving the requirement for more components manufactured using CMCs. The coating system that protects the gas-washed surfaces must be prime reliant for the component to avoid early removal due to high velocity and pressure water vapor-driven corrosion and recession of the substrate (Ref 12). Modern coatings for SiC matrix / SiC fiber CMCs are based on silicon bond coatings and rare-earth silicates and are typically complex, multi-layered systems applied using plasma spray deposition. The design is driven by the simultaneous functional requirements for these EBC systems, including high hermeticity against water vapor ingress, CMAS attack resistance, and close CTE matching to the underlying CMC substrate to avoid thermo-mechanical stress and cracking.

Novel coating material development is ongoing to support goals to increase the component lifecycle, especially for engine operations in increasingly austere environments. Thermal spray remains the preferred processing method due to economics and a robust supply chain for equipment, raw materials, and services. But some materials that suffer disassociation into constituents or subsequent phase changes with volume-driven stresses upon cooling (for example mullite) may require alternative methods such as slurry deposition and CVD. Therefore, improvements in thermal spray technology as well as innovative PVD technologies that can deposit complex materials and architectures are highly sought.

Robust Coating Systems to Improve Sealing at Higher Temperatures

Abradables are complex materials made of a matrix that gives the mechanical properties needed from the thermal loading, the erosion and the oxidation resistance, and some "dislocators", for example polymer, solid lubricant or porosity, that will help in case of contact to limit or prevent damage to the blade tip. Matrix and disclocator materials have specific, and in a way opposite, objectives. Abradable development is therefore focused on not only finding an optimum for the coating composition (especially above 350 °C), but also the process parameters to generate a rigid yet preferentially yielding microstructure during blade contact. A the abradable powder is made of a complex blend of materials with very different properties, having a fine understanding of the influence of the thermal spray operating parameters on the coating microstructure is a critical point to ensure robust abradable coating fabrication. To facilitate thermal spray industrialization of new coatings, with complex chemistry, the link between process development and process modeling must be developed and validated. Research initiatives working on the development of a numerical twin of thermal spray will pave the way for industrialization of new abradable coatings with complex architectures in future engines.

REACH Compliant Wear-Resistant Materials and Processes

Given the wide diversity of coatings used for wear resistance in a typical airframe and the complex nature of degradation mechanisms, 'tribosystem thinking' has become a basic principle in new materials development to improve wear and corrosion resistance while respecting environmental and legislative directives, as long-term functionality and durability is only assured when a solution is designed with the end-purpose of the system in mind (Ref 13). A pervasive example has been the use of thermally sprayed wear-resistant coatings onto actuating component surfaces. Coatings such as cemented carbides have dramatically reduced the amount of base alloy needed and offer opportunities for repairability, rather than replacement, for in-service aircraft.

Another example consists of the replacement of per- and polyfluoroalkyl substances, or PFAS, for components such as wear strips and bushes. PFAS are a large class of synthetic chemicals that have been detected as environmental pollutants, with some linked to negative effects on human health (Ref 14). Increasing regulation and restrictions are driving the development of alternative solutions, and the versatility of thermal spray and PVD processes to deposit novel coatings which are free from pollutants or concerning elements is a major asset.

Cold Spray Processes and Coatings for Repair and Dimensional Restoration

Cold spray is a promising method for the repair and restoration of aerospace components, especially for high-value parts such as rotating engine blisks, difficult to weld materials such as magnesium alloys, and for legacy engine and aircraft components with unacceptably long procurement lead times. Since components are refurbished rather than replaced, there are significant cost, energy, and environmental benefit contributions to using more sustainable manufacturing methods. (Ref 15).

One example where cold spray deposition has demonstrated economic and sustainability benefits is the repair of ZE41A magnesium alloy components for gas turbine engine front structural frames. Operations in austere environments over time result in erosive wear and foreign object damage on exposed surfaces, along with mating wear attachments to the engine. Al 6061 can be applied via cold spray onto affected surfaces to areas including hubs, supporting struts, bolt holes, and outer diameter flanges to build up to the original dimensions with subsequent machining. Importantly, the resulting fatigue properties of the repaired areas are nearly matched to that of the parent magnesium alloy.

Concluding Remarks and Future Perspectives

The airframe and propulsion system products that will lead the way toward net-zero aviation will continue to be heavily reliant on advanced thermal spray and PVD coatings technologies to ensure durability and performance in increasingly challenging conditions of higher temperatures and more highly loaded structures with novel TBC, EBCs, and abradables, while meeting goals for reducing environmental impact via REACh compliant materials / processes and component restoration methods. As materials selection for the underlying component is based upon aspects such as safety, weight, mechanical integrity, manufacturability, and cost, coatings solutions will continue to evolve to meet the emerging technical and sustainability requirements.

As these current and near future challenges are addressed, new opportunities will continue to emerge. As noted, more electric / electric-hybrid propulsion systems are in development, especially for smaller planes and short-range regional flights. Additionally, hydrogen will merit serious consideration as an alternate fuel due to cleanliness and higher specific impulse. Research that focuses on the response and expected lifecycle of current coating systems in electric and hydrogen propulsion systems and infrastructure is in its infancy and more information is needed to determine their adequacy. In some instances, improved and unique coating solutions tailored for these applications will be required. Examples include protective surface treatments for cryogenic hydrogen delivery systems, more oxidation-resistant alloys for downstream turbine components exposed to higher concentrations of water vapor combustion product, and protective coatings compatible with high electric and magnetic fields

It is also expected that novel future coatings will require an increase in design complexity (i.e., multiple layers and/ or processing methods within one coating system). To develop these coatings for more demanding aerospace applications while respecting existing and future regulations, materials and process modeling will become essential to shorten the development and validation cycle.

Environmental Analysis of Thermal Spray and PVD Coatings Used in Aviation Sector

Alice Fabre, Gaël Fick, Armelle Vardelle

Status of the Field

Aviation contributes 2-3% of global Greenhouse Gas (GHG) emissions, with a total climate impact 2-4 times higher when non-CO2 effects are considered. This impact is expected to increase as global passenger traffic grows at 5-6% per year (Ref 16). The aviation industry faces pressure to reduce its environmental footprint owing to public awareness, regulatory measures, and climate change mitigation needs. To address this, the industry is increasingly adopting lightweight materials such as carbon fiber composites and advanced aluminum alloys to reduce fuel consumption and emissions. However, they face significant vulnerabilities owing to their dependence on geopolitically sensitive materials, such as titanium and rare-earth elements, in their supply chains. The main challenges include the high cost of sustainable alternatives, energy-intensive production processes, and limited recycling options for advanced composites. These challenges create tensions between environmental goals and economic and strategic security concerns.

Currently, major aircraft manufacturers have improved their transparency in terms of environmental impacts. The adoption of lifecycle assessment (LCA) methodologies allows the evaluation of the environmental footprint of an aircraft from production to end-of-life (Ref 17, 18). By integrating eco-design principles early in development, these companies aim to minimize environmental impact throughout the product lifecycle; an accurate assessment is crucial for developing mitigation strategies, setting emission reduction targets, and evaluating technological and operational improvements. Commercial aircraft typically last between 20 and 30 years, and those that are well-maintained may operate for even longer. This conservative, long-term operational approach significantly impacts material choices because materials selected today must perform reliably for two to three decades. Environmental improvements must also be considered alongside decades of operational requirements.

A major contributor to sustainability is the use of thermal spray (TS) and physical vapor deposition (PVD) coatings. These coatings enhance the performance and longevity of aircraft components by improving their resistance to wear, corrosion, and high temperature. From an environmental perspective, TS and PVD coatings enhance sustainability by extending the component lifespans, reducing maintenance, and improving fuel efficiency. In addition, by enabling weight reduction in aircrafts, these coatings lower fuel consumption and, consequently, GHG emissions. For example, a reduction of 1 kilogram in weight results in savings of 600-800 liters of fuel and 2-2.5 tons of CO_2 emissions over the 20-year lifespan of a short-haul aircraft (A320 or B737), and 1,400-1,800 liters of fuel and 4.5-5.7 tons of CO_2 emissions for long-haul aircraft (B787, A350, or A330). In addition, coating processes often use materials that are more efficient than traditional methods. Indeed, they allow the design of components from widely available raw materials and the adaptation of the component surface to service conditions by applying only a thin layer with the required properties, thereby reducing waste and resource consumption. Although TS and PVD coatings offer sustainability benefits, their application also has an environmental footprint that can be evaluated using different methodologies.

- Blacklists are an essential tool for identifying and managing hazardous substances and processes in various industries, including aviation. These lists were compiled using multiple criteria derived from the regulatory guidelines, industry standards, and international regulations. Key sources for blacklist criteria include registration, evaluation, authorization, and restriction of chemicals (REACH), the OSHA Hazard Communication Standard, and EU RoHS (Restriction of Hazardous Substances). Industry-specific standards such as Aerospace Materials Specification (AMS) and SAE International Regulations also contribute to the development of these lists. By employing these comprehensive criteria, blacklists can effectively identify materials that are environmentally harmful or pose health risks. These blacklists are part of a risk-based, multi-criteria decision-making process involving technical performance analysis, regulatory compliance, lifecycle evaluation, and certification pathways. This approach ensures that materials banned for safety or environmental reasons are replaced without compromising flight safety, mission-critical reliability, or compliance with aerospace standards and company policies, thereby ultimately contributing to improved environmental and health safety practices.
- Monocriteria methods focus on evaluating a single environmental impact factor. These methods simplify the assessment process by focusing on specific aspects such as toxicity, energy consumption, and carbon footprint. For example, the Greenhouse Gas Protocol

or IPCC (Intergovernmental Panel on Climate Change (IPCC) Guidelines are commonly used monocriteria approaches that specifically measure carbon emissions or global warming potential. Although monocriteria methods provide a straightforward evaluation of a particular environmental concern, they do not offer a comprehensive view of the overall environmental impact of a product or process. This limitation can potentially lead to overlooking other significant environmental effects. However, monocriteria methods can be useful for targeted assessments or when a specific environmental aspect is of primary concern, such as when evaluating strategies to reduce carbon emissions in the aviation industry.

- Multicriteria methods: A more comprehensive approach to environmental impact assessment by simultaneously evaluating multiple impact categories. By considering multiple impact categories, multicriteria methods allow for a more nuanced understanding of environmental trade-offs and help identify potential burden shifts between different environmental aspects. This comprehensive approach is particularly valuable in the aviation industry, where the complex interplay of various environmental factors necessitates a thorough evaluation to make informed decisions regarding sustainable practices and technologies. LCA is recognized as one of the most thorough multi-criteria methods and provides a more holistic view of the environmental consequences associated with TS and PVD coatings in the aviation sector. This holistic approach ensures that sustainability efforts in aviation consider both the direct environmental effects of aircraft operations and the indirect impacts of supporting technologies such as TS and PVD coatings. LCA, as defined by the ISO 14040/14044 standards (Ref 19), provides a systematic evaluation of the environmental aspects and potential impacts of a product, process, or service throughout its life cycle, from the extraction of raw materials to disposal (i.e., from cradle-to-grave). This comprehensive process includes setting goals and scope, gathering data, assessing environmental impacts with tools like Simapro and LCA for Experts, interpreting the results, and optionally performing a critical review. The data collection phase is the most time-intensive and essential step, necessitating the acquisition of accurate data on industrial processes about the consumables and direct emissions associated with current and new processes and materials. This includes the type and quantity of energy and raw materials needed, as well as any other inputs necessary to carry out the process. It also includes the type and quantity of direct emissions (e.g., combustion fumes, dust, and gases) and waste produced by the process, along with any other outputs generated. In competitive industries like aeronautics, where proprietary processes and materials are prevalent, obtaining the necessary data can be difficult, with only a limited amount available as "open data."

Using a global and systemic approach can serve several objectives: to assess the overall environmental impact of a coating or a coating process, identify the origin of the main impacts, and focus on future developments to efficiently reduce them; to compare product impacts against competitors; or to evaluate new production strategies and avoid burden shifting between lifecycle stages or impact categories. A full cradle-to-grave LCA of aviation shows that most of the impacts occur during operation, with kerosene production and combustion in aircraft engines, while aircraft production accounts for less than 1% of the total impact (Ref 17, 18). However, new propulsion technologies or alternative fuels (Sustainable Aviation Fuels (SAF)) will significantly reduce the impact of the operational phase, thus mathematically increasing the contribution of the production phase. This is currently observed in battery electric cars (Ref 20), whose production impacts are twice as important as those of internal combustion engine vehicles, partially offsetting the benefits of electrification. Focusing on production processes, the LCA of aircraft components with thermal barrier coatings (Ref 21) showed that the coating process can contribute significantly to the part impacts (10 to 30%) (Fig. 4), necessitating such a methodology to more accurately assess their contribution and verify the environmental relevance of developing coating processes (Fig. 5). When assessing the environmental impacts of new solutions, they must be compared based on the same function and performance, as defined by the "functional unit. For example, in the case of thermal barrier coatings, the comparison should be based on the same specific surface area (e.g., 1 m^2) while considering performance in terms of thermal resistance and lifespan (equal to or better than the initial solution). Depending on

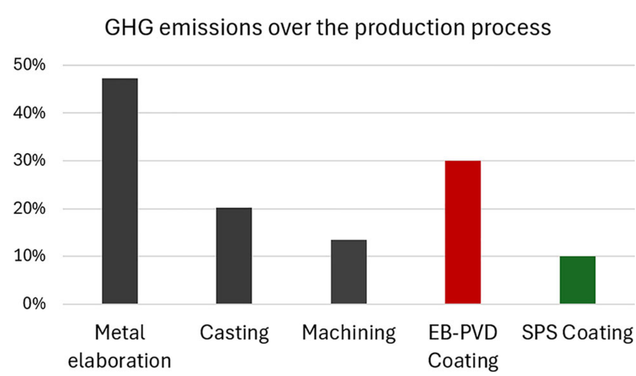

Fig. 4 GHG emissions during the production of an aircraft turbine blade with Electron Beam-PVD (EB-PVD) and Suspension Plasma Spray (SPS) thermal barrier coating

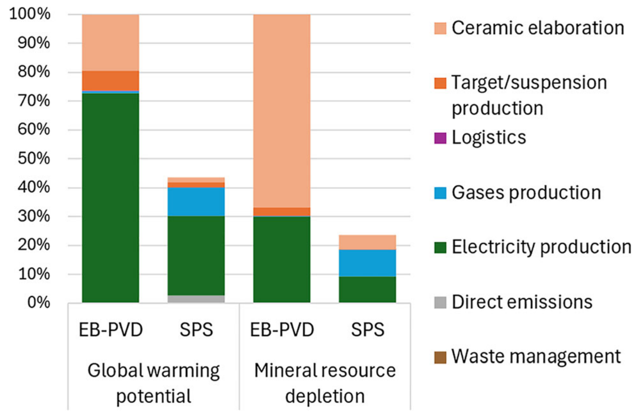

Fig. 5 Impact distribution of EB-PVD and SPS coating processes on climate change and mineral resource use

the type of system being compared and the extent of the evolution being investigated, whether it is a process or a component of a full aircraft, the scope of a lifecycle assessment (LCA) study can vary. It can be "gate-to-gate" (focusing only on changes within a production plant), "cradle-to-gate" (from resource extraction to the end product), or "cradle-to-grave" (the full life cycle).

EB-PVD thermal barrier coatings are used on the most demanding parts of aircraft engines, such as blades and vanes, because their columnar microstructure makes them resistant to mechanical and thermal stress. The SPS technology, which uses a liquid suspension as feedstock, aims to reproduce the microstructure of EB-PVD coatings at a lower cost and higher deposition rate (Ref 21). Calculations were performed using LCA for Experts and the Environmental Footprint 3.1 method (Ref 22) with a cradle-to-gate approach based on industrial data at pilot and industrial scale.)

Current and Future Challenges

To ensure the consistency and comparability of LCA studies, the ISO 14040 series of standards was developed in 1997 and updated in 2006. It provides the basic principles and requirements for a standardized LCA while allowing flexibility for the development of the methodology. This leads to heterogeneous practices and has several limitations.

Lifecycle assessment databases play a crucial role in the impact assessment process by providing standardized datasets on elementary flows for basic processes and product manufacturing. These databases serve as a foundation for LCA practitioners by offering valuable information on resource consumption, emissions, and other environmental effects associated with various industrial activities. However, the limitations of these databases become apparent when dealing with high-tech processes and materials that are often inadequately represented in standard datasets.

To address this gap, LCA practitioners must supplement industry standards databases with proprietary models tailored to specific high-tech applications. This approach, which is necessary for a more comprehensive analysis, introduces potential discrepancies in the methods and results of various studies. The use of proprietary models can lead to variations in data quality, assumptions, and calculation methods, making it challenging to compare and validate results across different LCA studies. Furthermore, the lack of transparency in proprietary models may hinder the reproducibility and peer review of LCA findings, potentially affecting the credibility and reliability of the assessment outcomes.

Lifecycle assessment (LCA) requires characterization factors to translate LCA models into environmental impacts. The effectiveness of LCA depends heavily on these characterization factors, which are essential for translating complex data from LCA models into meaningful environmental impact indicators. These factors are organized into "characterization methods, " which are continuously refined and updated as the scientific understanding of environmental processes improves. However, the dynamic nature of these methods can lead to challenges in maintaining consistency and comparability across LCA studies (Ref 23, 24). The lack of a global consensus on which characterization methods can be used further complicates this situation. Different regions, industries, or research groups may prefer certain methods to others, leading to potential discrepancies when comparing LCA results for similar products or processes. This variability in methodology can make it difficult for decision makers to draw accurate conclusions or make informed choices based on the LCA results.

Critical resource depletion and circularity in lifecycle assessment (LCA) present multifaceted challenges that require careful consideration. Although recycling is often viewed as a sustainable solution, the reality is more nuanced. Many recycling processes involve intricate logistics networks and energy-intensive high-temperature treatments that can potentially outweigh the environmental benefits of conventional end-of-life disposal methods. This complexity necessitates a thorough evaluation of the entire recycling chain in order to determine its true environmental impact.

LCA practitioners must accurately account for recycling benefits in their assessments. Various methodologies exist to quantify these benefits and allocate credit to avoid primary-material production. These approaches may consider factors such as the quality of recycled materials, the efficiency of recycling processes, and the potential displacement of virgin materials in the market. The choice of method can significantly influence the results of an LCA study, highlighting the importance of transparent and well-justified decision making in this area. As the field evolves, there is an ongoing need for standardized approaches that can effectively capture the nuances of resource circularity and its implications for sustainable resource management.

Advances in Science and Technology to Address Challenges

High-quality data remain a challenge for valuable lifecycle assessments of TS and PVD coatings. With the development of LCA, new material and process datasets are being created every year, and data quality is being increasingly scrutinized. The involvement of major aircraft OEMs must be aligned with the creation of common, open, and verified datasets. European or publicly funded projects, as well as thermal spray associations such as ASM-TSS, DVS, and the Japan thermal spray association, could help develop open datasets/databases. For climate change impacts, all characterization methods use IPCC data; however, for other impact categories, there is no global consensus. In Europe, Environmental Footprint 3.1 is gaining traction, while North American practitioners often prefer IMPACT World + and TRACI. The work of the Joint Research Centre (JRC) of the European Commission to harmonize practices and methodologies at the European level is important, but discussions should include other actors and stakeholders. One strategy involves the broader implementation of Environmental Product Declarations (EPDs), which are environmental datasets grounded in lifecycle assessment (LCA) methodology and additional standards (ISO 14021-25), within a more stringent framework. EPDs are predicated on Product Category Rules (PCR), which establish the calculation rules, methods, characterization techniques, and reporting formats for specific product categories. While EPDs are extensively utilized in the construction sector, their application in the aviation industry remains limited despite the existence of a PCR for business jets (Ref 17). The adoption of EPDs for coated components in the aerospace sector is currently minimal; however, it is increasing as procurement teams, particularly in Europe, begin to require environmental data in response to regulatory demands and Environmental, Social, and Governance (ESG) objectives. Finally, the wider adoption of the GHG Protocol (Ref 25)–a method and tool for organizations and companies to account for GHG emissions–provides an opportunity for a standardized framework and reporting on a simplified but monocriteria approach compared to LCA.

Concluding Remarks and Future Perspectives

Lifecycle assessments of TS and PVD coatings on aircraft are instrumental in optimizing material efficiency, energy consumption, durability, and environmental impact, contributing to more sustainable aviation practices. These assessments also drive innovation, ensure regulatory compliance, and promote circular economy practices, enabling manufacturers and airlines to improve sustainability while maintaining a competitive advantage.

Recognizing the lessons learned from LCA, the next logical step is to explore how these lessons can inform eco-efficient strategies. This related principle integrates environmental performance with economic value and serves as a natural extension of sustainability efforts highlighted by LCA (Ref 26). It aims to maximize the value of products or services while minimizing their environmental footprints. In the context of coatings, eco-efficiency strategies can include improving application techniques to reduce material waste, improving durability to extend service life, and exploring recyclable alternatives while eliminating the use of blacklisted substances.

To understand the broader environmental impact of these eco-efficiency strategies, the IPAT equation (Impact = Population × Affluence × Technology) offers a valuable framework. The implementation of eco-efficiency strategies directly influences the 'Technology' component of the IPAT equation, demonstrating a deliberate approach to mitigating environmental impact in the face of growing population and affluence. Population growth drives an increased demand for air travel, whereas affluence contributes to higher consumption patterns. Technological advancements, such as the development of longer-lasting coatings and more efficient application technologies, directly reduce waste and energy use and illustrate the tangible mitigation of environmental impacts. By enhancing coating durability through eco-efficiency strategies, the aviation industry not only leverages technology to reduce environmental impact but also addresses the affluence factor by making sustainable practices more economically viable for a broader segment of the population. This aligns with the goals of LCA and eco-efficiency, demonstrating how technological progress can offset the environmental pressures of population growth and increased affluence, ultimately contributing to more sustainable aviation practices.

Innovative Thermal Spray Coatings for Sustainable Aerospace

Substrate Preparation: Improvement of Coating Adhesion and Fatigue Resistance

Sophie Costil, Eric Irissou, Pawel Sokolowski

Status of the Field

Surface preparation is a paramount step in the thermal spray deposition process, essential primarily for ensuring the proper adhesion strength of coatings. This step involves modifying the substrate surface's topography and/or chemistry through various methods that remove adsorbed contaminants and/or oxide layers, impart specific surface topography or roughness, and possibly activate the surface through induced chemical modification. To meet the ever-increasing demands of industrial applications of thermal spray coatings, novel approaches to surface preparation are constantly being developed.

Surface preparation methods commonly used (Ref 27) or under investigation for thermal spray coatings can be categorized into three main approaches: mechanical, chemical, and physical. Mechanical methods include particulate (grit) blasting, dry blasting using supercritical CO_2 or N_2, and wet blasting with high-pressure water jets. Chemical approaches involve processes like degreasing and etching. Physical methods encompass techniques such as laser heating, cleaning, and texturing, as well as the use of atmospheric-pressure plasma jets.

For industrial applications involving thermal spray coatings, degreasing and grit blasting remain the most common surface preparation methods. These techniques enhance bonding by altering surface roughness and removing contaminants, oxides, and hydroxide layers. This process offers high throughput and provides adequate bond strength, but novel surface preparation methods have been explored over the past two decades, to meet the demand for extending the service life and improving the performance of coated parts. These methods have also been tailored to accommodate the specific requirements of emerging thermal spray processes, such as cold spray and Suspension Plasma Spray (SPS) or Solution Precursor Plasma Spraying (SPPS), as well as for coatings on internal diameter parts. Additionally, they have been adapted to suit new substrate materials, including Ceramic Matrix Composites (CMCs), Metal Matrix Composites (MMC), Carbon Fiber Reinforced-Polymer (CFRP) and new alloys, as well as new coating materials. Among these novel surface preparation methods, laser technology stands out for its versatility and effectiveness, offering a comprehensive range of approaches, such as cleaning or precise surface texturing.

Current and Future Challenges

Substrate preparation is critical for achieving high-quality and durable thermal spray coatings, especially in aerospace applications. Traditional grit blasting is inherently stochastic, resulting in unpredictable surface patterns and variability in surface roughness. Achieving uniform surface cleanliness remains difficult due to variety in substrate materials and specific requirements imposed by different thermal spray processes. Grit blasting can also introduce residual stresses and distortions, particularly in lightweight materials and composite structures, which can negatively affect both adhesion and fatigue resistance. The improper preparation of the substrate surface can lead to poorly bonded interface regions or create stress concentration sites, particularly at sharp surface irregularities, where micro-cracks originate. These cracks can propagate more rapidly under cyclic mechanical and thermomechanical loads, drastically reducing coating fatigue lifetime, which is of significant importance in extreme aerospace operational conditions. So, the proper substrate preparation not only enhances adhesion but also improves the overall fatigue performance of the coated components. Addressing these issues requires still more comprehensive understanding of substrate-coating interactions and the development of tailored surface treatments methods. Looking ahead, several challenges in the substrate preparation can be identified: (i) adapting substrate preparation processes for novel aerospace materials, (ii) the use of more sustainable materials and greener processes during substrate preparation stage and (iii) automation and diagnostics dedicated for substrate preparation processes.

The emphasis on weight reduction in aerospace and aviation components and system design is clearly visible. As for example, the general use of aluminum alloys in Boeing aircrafts dropped significantly from over 80% in the Boeing 747 to around 20% in the Boeing 787, meanwhile the use of composites has increased importantly, becoming the dominant material in the Boeing 787 at over 50%. Similarly, the share of titanium alloys has nearly tripled when comparing Boeing 747 with 787 (Ref 28). Along with the introduction of novel materials having improved properties, novel substrate preparation processes must be proposed. The increasing use of novel aerospace materials, such as hybrid structures, additive-manufactured components, and CMCs, demands significant adaptations in substrate preparation processes. Additive-manufactured parts often exhibit as-built surface and subsurface microstructures containing defects, residual stresses, or oxide layers that can hinder adhesion and fatigue resistance of coatings, if not properly addressed during the preparation stage. Controlled surface treatments, such as chemical or electrochemical etching, can selectively modify surface roughness and eliminate detrimental oxides to enhance bonding performance. Similarly, in the case of CMCs, advanced surface functionalization techniques, such as plasma treatments or fine-tuning of interface by laser micromachining hold promise for proper adhesion and mechanical properties. Advances in industrial laser technology have significantly enhanced resolution, performance and durability, enabling their use for large-scale substrate treatment. Concurrently, the cost of lasers has dropped substantially, making them also economically viable for industrial applications. Nonetheless, ensuring the qualification, scalability and cost-effectiveness of these methods, while maintaining the high reliability demanded by aerospace applications, remains a critical challenge.

Considering substrate preparation for thermal spraying, there is significant potential for improvements in terms of sustainability and green solutions. Grit blasting produces hazardous waste and airborne contaminants, raising environmental and regulatory concerns. The sustainability initiatives in abrasive blasting industry primarily focus on utilizing greener, i.e., bio-based abrasives, especially abrasives with zero free silica to significantly mitigate health, safety, and environmental (HSE) concerns. These efforts are complemented by more efficient use of blasting media, enhancing productivity and recyclability (Ref 29). Nonetheless, laser cleaning/texturing and water-based surface treatments are gaining more interest as eco-friendly substrate preparation methods. In contrast to grit blasting, laser technology offers a wide range of possibilities for creating surface roughness or complex textures in a highly controlled and reproducible manner. Laser texturing can be precisely tailored to the particle size scale, ranging from microscale for cold spray to nanoscale for SPS and SPPS, allowing tighter control over surface roughness, morphology, and patterning than conventional grit blasting. This adaptability enables optimization of substrate topography to meet the specific bonding and microstructural requirements of these emerging processes, while complementing the established practices used for HVOF and APS. It eliminates the need for grits or other consumables, thereby reducing waste and preventing mechanically induced defects or property changes at the substrate–coating interface Water-based pre-treatment methods as compared to traditional blasting media reduce significantly HSE risk and impact while providing cleaner finishes, low contamination and minimal surface damage. The transition to these sustainable alternatives not only aligns with aerospace industry sustainability goals but also contributes to improved surface integrity and cleanliness, reducing unintended effects that could weaken adhesion.

Automation, process integrity and real-time diagnostics are playing an increasingly vital role in ensuring the consistency and efficiency of substrate preparation processes. Robotic, or even autonomous to-some-extent systems, enhance precision and repeatability in surface pre-treatments, minimizing variability and making the substrate preparation of different materials effective. Additionally, real-time monitoring technologies, such as optical and thermal sensors, facilitate the early detection of deviations, enabling immediate process adjustments to maintain optimal substrate conditions. Adaptive control systems are being developed to fine-tune surface treatments dynamically, ensuring that preparation parameters are optimized for different materials and coating requirements. By integrating automation and advanced diagnostics, the aerospace industry can achieve higher process reliability, reduce waste, and enhance the durability of thermal spray coatings in next-generation applications. Such technology integration was demonstrated already for grit blasting processes (Ref 30) but still facing issues regarding cleaning stage, grit contamination or mandatory masking stage. In this context, laser technology appears to be more suitable for implementation in thermal spray operation and can be considered as the sole substrate preparation stage directly preceding the coating process.

Advances in Laser Technology to Address Challenges

Laser technology is currently the most researched and advanced method for substrate preparation in thermal spray coating, notably for high-end applications. It offers significant potential for more reliable processing of conventional material substrates and enhances coating adhesion on newer materials, such as composites and ceramics, which have been recently introduced to improve, e.g., gas turbine efficiency and reduce weight. The important influence of laser texturing on coating adhesion was demonstrated in the literature already, with reported improvements: app. 1.5- to 2-fold increase in adhesion for various YSZ feedstocks deposited on ceramic substrates when comparing to grit-blasted ones (Ref 31), a 3- to 5-fold increase for Y_2O_3, YSZ and $Gd_2Zr_2O_7$ deposited on Al_2O_3/ Al_2O_3 CMC substrates when comparing to unstructured ones (Ref 32) and more than 4-fold increase for Al_2O_3 suspensions deposited on aluminum (Al-2024) substrates when comparing to grit-blasted ones (Ref 33). Additionally, laser texturing can be adapted as pre-treatment process for other purposes that are recently used in aviation industry, such as cold spray additive manufacturing or structural repair applications. Furthermore, laser-based substrate preparation is considered one of the most environmentally friendly methods available nowadays.

The main parameters to consider in laser ablation/texturing are pulse duration (ns-fs), repetition rate (kHz), fluence (J/cm^2), and laser wavelength. Today, both femtosecond and nanosecond industrial lasers allow for repetition rates exceeding 100 kHz, enabling full surface treatment at a rate of 1 cm^2/s. At lower fluence, laser treatment results in the removal of surface contaminants and oxide layers, which significantly improve adhesive strength of cold spray coatings. At higher fluence, leveraging the fine laser spot size, texturing the surface with controlled predefined patterns at high rates is feasible (Fig. 6a and b) (Ref 34). Precise texturing can be applied to the substrate to improve coating adhesion by creating controlled roughness or design with tailored depth, width, and pitch, allowing optimal droplet penetration and interlocking upon impact. Additionally, orientation-specific patterns can be produced to better resist shear or tensile stresses during service. Beyond adhesion, surface texturing can favor desirable coating structure or topography - particularly with SPS, SPPS or even Low Pressure Plasma Spraying (LPPS) used for TBCs. In these cases it is done by adopting the surface topography according to the feedstock size and its flow behavior upon impact. Laser treatments can also be performed on top coating surfaces to enhance properties such as strain tolerance of TBCs, CMAS resistance, antifouling, and many more.

In addition, thermal effects during pre-treatment can be tailored to the material's thermal properties by adjusting the laser interaction time (pulse duration). Indeed, laser

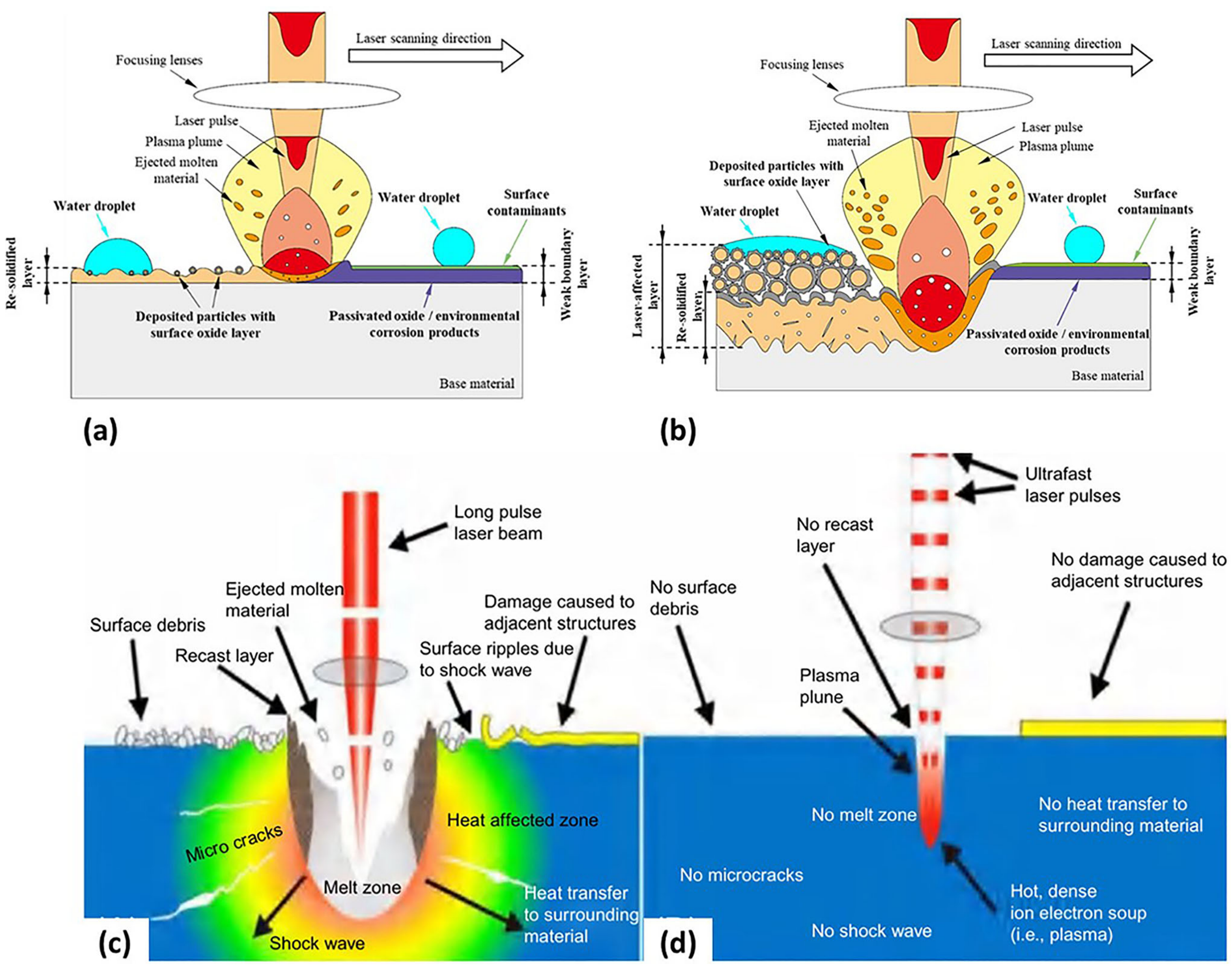

Fig. 6 The effect of laser-substrate interaction at a (a) lower fluence, (b) higher fluence, (c) long pulse duration and (d) short pulse duration (Ref 34, 35). Reprinted from *Opt. Laser Technol.*, 128, J. Min et al., Application of Laser Ablation in Adhesive Bonding of Metallic Materials: A Review, p 106188, Copyright (2020), with permission from Elsevier. Reprinted from *Advances in Laser Materials Processing (Second Edition)*, M. Mehrpouya et al., Chapter 25 - Microstructural Characterization and Mechanical Reliability of Laser-Machined Structures, p 731-761, Copyright (2018), with permission from Elsevier

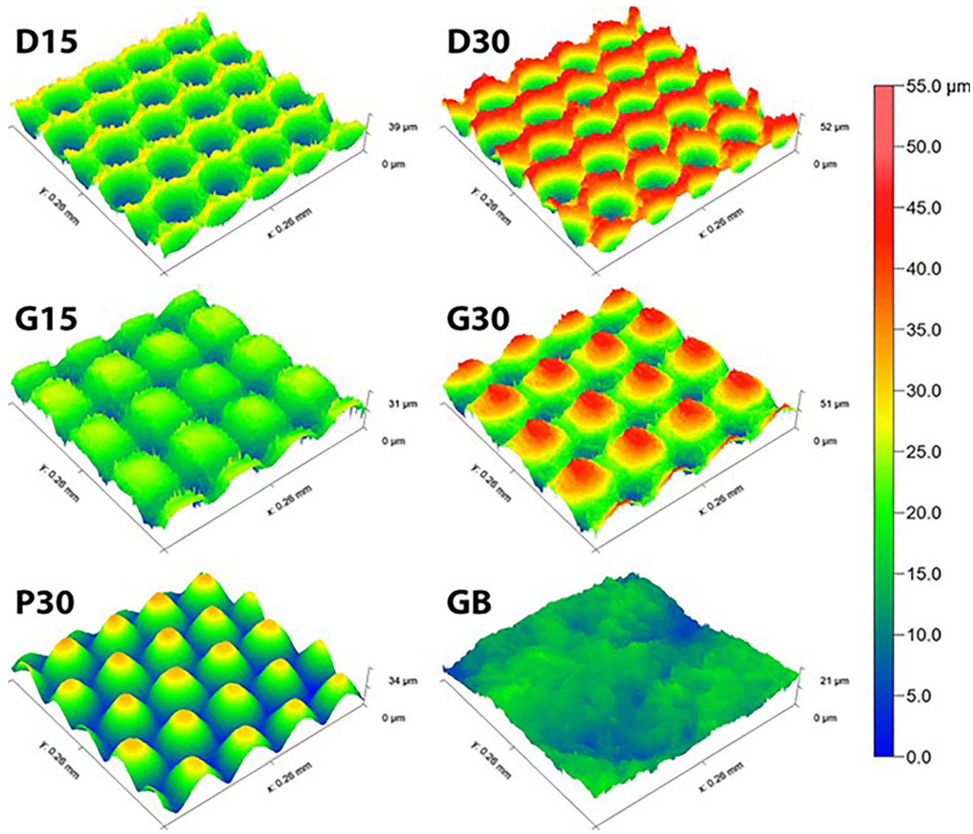

Fig. 7 The different precise surface patterns (D15, D30, G15. G30, P30) created by means of high-speed laser texturing in contrast to conventional grit blasting (GB) (Ref 31). Reprinted with permission from R. Musalek et al., High-Speed Laser Patterning of YSZ Ceramic Substrates for Plasma Spraying: Microstructure Manipulation and Adhesion of YSZ Coatings, *J. Therm. Spray Technol.*, 33(7), p 2331-2349, 2024, Springer Nature

pulse duration is one of the most critical process parameters as it determines the peak power and energy density of the laser pulse. Shorter pulse durations result in higher peak powers and energy densities, leading to enhanced material removal rates and improved quality of processed surfaces due to limited transferred energy. In contrast, laser pulses ranging from milliseconds to nanoseconds are characterized by thermal ablation dominated by heat conduction, melting, evaporation, and plasma formation. This process creates a temperature field in the workpiece known as the Heat Affected Zone (HAZ), involving the material surrounding the melt zone that is influenced by the heat source (Fig. 6c and d) (Ref 35). This thermal effect must be managed as an additional variable, depending on the application and the material being treated.

Considering mentioned parameters, several characteristics of resulting textures and surface morphologies (such as dimples, grids, and pillars, see Fig. 7 (Ref 31)) can be designed and adapted to materials (organic, ceramic, metallic) and material systems (multilayer, additively manufactured, etc.). Such processing may be done in micro- or even nanometer scale, either in a protective or under ambient atmosphere (Ref 36). Current research using laser technology in thermal spray applications focuses on innovative substrates such as materials increasingly considered in aerospace (ceramics, new compositions of metallic alloys, lightweight metal alloys, CMCs, CFRPs) (Ref 31, 32) and adaptable to various coating materials deposited by thermal spraying or PVD (Ref 33). To achieve performance improvements, not only must HAZ be considered, but also the mechanical impact induced by the laser treatment itself such as thermal expansion leading to residual stresses or shock waves within the material leading to deformation or fracturing. Indeed, the interaction of lasers with substrate materials can induce subsurface strain (usually less than 1 µm starting from the surface), which must be carefully controlled (e.g., by adapting the laser parameters to the specific material) to extend service life and prevent crack formation. Alongside residual stress levels, the surface morphology significantly affects the fatigue behavior and cracking process of coated components, necessitating optimization. In addition to enhancing bonding strength, effective surface preparations play a crucial role in controlling residual stresses to improve fatigue resistance. Both compressive stresses and the enhancement of coating microstructures are essential to minimize defects and improve performances. Consequently, laser surface preparation remains a research hotspot necessary for advancing processes and treatment of innovative materials to improve interface strength and fatigue resistance. New strategies can then be developed to create improved parts for sustainable aerospace applications.

Concluding Remarks and Future Perspectives

In conclusion, effective substrate surface preparation is pivotal in achieving high-quality and durable thermal spray coatings, particularly in aerospace applications, where extreme and constantly increasing operational conditions demand reliable adhesion and fatigue resistance.

Traditional grit blasting, although time- and cost-effective, qualified and broadly implemented, often results in unpredictable surface patterns and residual stresses, which can compromise coating performance in addition to HSE risks that need to be addressed for the sustainability objectives of the aerospace industry. As aerospace materials evolve to include composites, ceramics, additive-manufactured components, and others, surface preparation techniques must adapt accordingly. Emerging methods such as laser-based technology provide a one-step, highly precise, controllable, and environmentally sustainable alternative for enhancing adhesion by tailoring surface topography with adjustable, well-defined micro- and nanostructures, while simultaneously eliminating surface contaminants. However, more research is required in this field to fully develop turnkey solutions and ensure that the laser surface preparation processes and its applications meet industry standards. At least one industrial project—specifically the LaTex R&D initiative in Sweden—aimed at scaling up the process is currently underway. While its objectives have been made public, the results remain confidential.

The integration of automation and real-time diagnostics, if possible from the process side, can further enhance the consistency and efficiency of surface preparation, allowing for adaptive control systems that dynamically optimize treatment parameters. An overview and the authors' perspective on substrate preparation processes—both currently used and under development—are presented in Table 1.

Focusing on sustainability, automation, and tailored surface treatments is crucial for advancing substrate preparation. By adopting these innovations, the aerospace industry can improve the durability and performance of thermal spray coatings while aligning with environmental goals.

Advanced Thermal Barrier Coatings

Brian Hazel, Maria Ophelia Jarligo and Robert Vassen

Status of the Field

Thermal barrier coatings (TBCs) are multilayer ceramic-metallic material systems that are now essential for the performance and durability of modern aeroengines. They primarily function to insulate critical hot-section components such as turbine blades, vanes and combustor liners from extreme thermal and chemical environments. By reducing the temperature of load-bearing superalloy substrates by around 250-300 °C, TBCs enable engines to operate at higher turbine inlet temperatures (TITs), maintaining mechanical integrity and allowing significant improvements in thermodynamic efficiency and lower greenhouse gas emissions (Ref 37, 38). This technological imperative is a key driver of growth in the global TBC market, which is projected to expand from approximately USD 18 billion in 2025 to over USD 27 billion by 2032.

Table 1 Authors' perspective on selected aspects of broadly used or tested substrate preparation methods for thermal spray coatings

	Precision	Adhesion	Fatigue performance	Environmental impact	Versatility	Cost-effectiveness	Time effectiveness
Particulate (Grit) blasting	•••	•••••	•••	••	•••	•••••	•••••
Dry blasting (Supercritical CO_2/N_2)	••••	••••	••••	•••••	•••••	••	••••
Wet blasting (High-pressure water)	•••	••	••	•••	•••	•••	•••
Degreasing and etching	•••••	•••	••	••	•••	•••	•••••
Laser cleaning	•••••	•••••	••••	•••••	•••••	••	•••
Laser texturing	•••••	•••••	•••••*	•••••	••••	•	••
Atmospheric-pressure plasma jets	•••••	•••••	•••••	•••••	•••••	•	•••

• Poor; •• Moderate; ••• Good; •••• Very good; ••••• Excellent.

*Expected, still under laboratory verification.

Table 2 Conventional TBC systems in aeroengine components (Ref 37, 38, 40)

Engine component	TBC material	Bond coat Material	Surface temperature, °C	Bond coat temperature, °C	Coating thickness, µm	TBC fabrication method	TBC microstructure
Turbine Blades	YSZ; advanced ceramics	MCrAlY, Pt–Aluminide	~ 1500	800-900	130-380	EB-PVD	Columnar
Turbine Vanes	YSZ; GZO (next-gen)	Pt–Aluminide or MCrAlY	< 1300	950-1050	100-500	APS or EB-PVD	Columnar (EB-PVD); porous splat-based lamellae (APS)
Combustor Liner / Cans	YSZ; YSZ/rare-earth zirconates (multi-layer)	NiCoCrAlY	< 1300	900-1000	400- > 1000	APS	Porous lamellae; vertically cracked (APS)
Transition Duct	YSZ	NiCrAlY	< 1300	~ 850	200-400	APS	Porous, crack-networked

The aerospace sector is expected to account for the largest market share (Ref 39).

The conventional TBC architecture consists of a ceramic topcoat most typically 7-8 wt.% yttria-stabilized zirconia (YSZ) which is applied to a metallic bond coat This bond coat is usually made from MCrAlY alloys (NiCoCrAlY or CoNiCrAlY) or diffusion aluminides, which protects the underlying nickel- or cobalt-based superalloy substrates. The ceramic topcoat offers low thermal conductivity (approximately 2 W/m K at 1273 K), a high melting point (> 2700 °C), and the ability to withstand steep thermal gradients. The metallic bond coat provides oxidation and hot corrosion resistance, as well as ensuring compatibility with the ceramic. Together with the superalloy substrate, this layered system offers a balance of insulation, oxidation resistance, and mechanical support. The industrial application of TBCs has led to two main deposition processes being used: atmospheric plasma spray (APS) and electron-beam physical vapor deposition (EB-PVD). APS produces porous, lamellar coatings with high insulation properties and tunable microstructures through pore engineering. These coatings are typically applied in thicker sections (300-1000 µm) to combustor liners and transition ducts. By contrast EB-PVD yields columnar coatings with excellent strain tolerance and cycling resistance, making them the preferred choice for turbine blades and vanes, although the thickness is limited to 100-500 µm. The inherent process–structure–property relationships of these deposition techniques dictate performance and lifetime (Ref 40). Table 2 summarizes representative TBC systems used in aero-engine applications, showing the typical material combinations, temperature limits, thickness ranges, and processing routes.

Despite the success of YSZ-based systems, they cannot be used at temperatures exceeding 1200 °C due to phase instability (e.g., tetragonal-to-monoclinic transformation), sintering-induced densification, and associated microcracking. These degradation mechanisms limit the long-term performance of conventional TBCs in next-generation engines, which has led to intensive research into alternative ceramic compositions. Furthermore, external degradation mechanisms such as calcium– magnesium–alumino–silicate (CMAS) infiltration pose a significant reliability risk, especially in environments with high concentrations of airborne particulates. The transition to alternative propulsion technologies such as sustainable aviation fuels (SAFs) and hydrogen, introduces new degradation pathways due to the elevated water vapor content and altered combustion by-products. Despite decades of development, current TBC systems have significant limitations, necessitating a comprehensive technological roadmap for next-generation materials and processes.

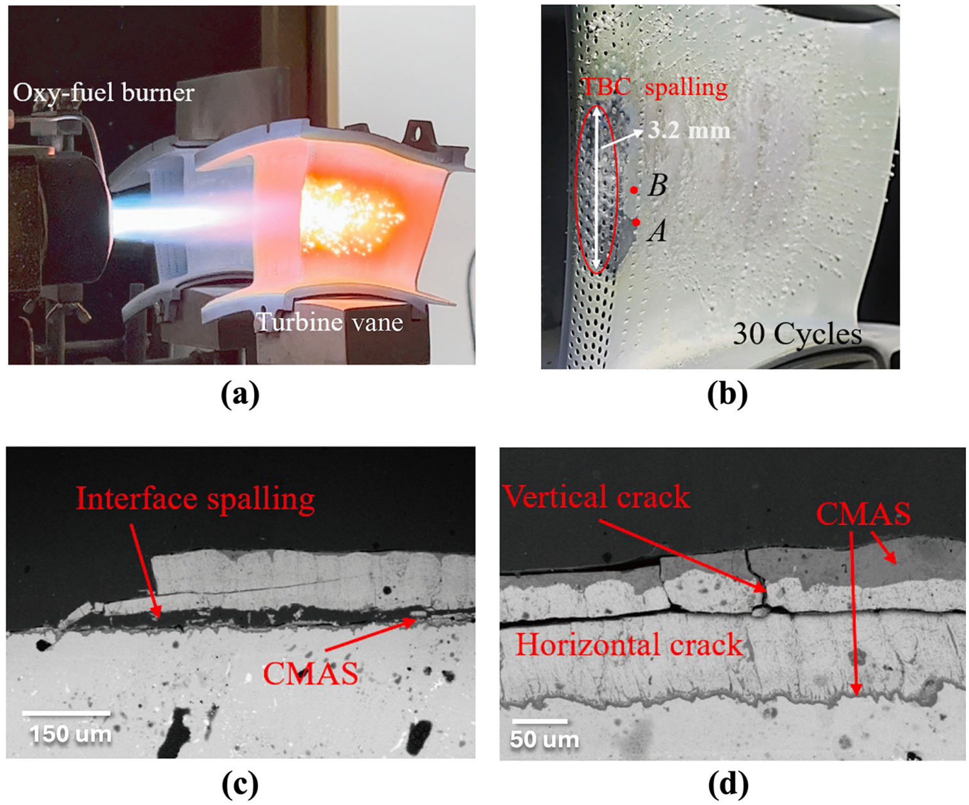

Fig. 8 Thermal shock test of a turbine vane with YSZ TBC topcoat and MCrAlY bond coat: (a) test set-up at 1150 °C surface temperature with CMAS infiltration, (b) CMAS deposition on the pressure side, (c) and (d) cross-section micrographs of points A and B, respectively (Ref 43). Reprinted with permission from Z. Liu, Y. Xiao, L. Yang, W. Liu, G. Yan, Y. Sun, and Y. Zhou, "Failure Prediction of Thermal Barrier Coatings on Turbine Blades Under Calcium-Magnesium-Alumina-Silicate Corrosion and Thermal Shock," *Acta Mech. Sin.*, 41(5), p. 424285, 2025, Springer Nature.

Current and Future Challenges

The evolving operational conditions of aeroengines are becoming an increasingly problematic issue for TBCs, particularly in next-generation engines which target gas inlet temperatures in excess of 1700 °C in order to achieve greater efficiency. Under such extreme conditions, traditional YSZ coatings undergo substantial degradation due to phase instability, densification caused by sintering, and microcracking. The long-term performance of TBCs under cyclic thermal and mechanical loads depends on their ability to maintain their initial microstructure and phase stability. Loss of strain tolerance due to microstructural coarsening and sintering can lead to spallation, meaning that durability becomes dependent on resistance to dynamic stress states rather than static temperature thresholds alone (Ref 41).

Low Thermal Conductivity TBC

Achieving low thermal conductivity in TBCs is essential for enhancing insulation and turbine efficiency. Heat transfer in ceramic TBCs occurs primarily through phonon transport. At moderate temperatures, phonon conduction dominates and is minimized through microstructural design such as increased porosity, and lamellar splat boundaries. Traditional YSZ TBCs exhibit thermal conductivities of approximately 2 W/(m K) at 1273 K, which is lower than metallic substrates. Doping with rare-earth oxides (e.g., Yb_2O_3, Nd_2O_3, or Gd_2O_3) further reduces conductivity by generating point defects that scatter phonons (Ref 42). Despite these strategies, current TBCs face challenges including limited phase stability, sintering, CMAS infiltration, and erosion. Future developments must focus on materials that retain low conductivity while offering high-temperature stability and environmental resistance, without overreliance on rare-earth elements.

CMAS Resistance

A significant failure mechanism for TBCs, especially in desert and volcanic regions, is CMAS attack, when the airborne particulates melt upon impingement and infiltrate the porous ceramic structure through capillary action. The pore-filling effect leads to increase in thermal conductivity and more critically increase in elastic modulus and the loss of strain compliance from partial depth infiltration, making TBCs prone to spallation. Upon thermal cycling, the increased modulus results in fracture. As the CMAS infiltration advances deeper into the ceramic/metallic interface, thermo-chemical reactions become significant. In YSZ, this results in the dissolution of stabilizing oxides (Y_2O_3 and ZrO_2) into the melt and subsequent crystallization of deleterious phases such as pyroxene and anorthite. Upon cooling, the formation of amorphous glassy phases and the transformation of the metastable tetragonal prime (t') phase to monoclinic zirconia due to depletion of yttria, further degrade the coating. This transformation induces a 4-5 vol.% expansion and thermal mismatch stresses that further drive delamination. This phenomenon is illustrated in Fig. 8**,** showing a thermal shock-test set-up (Fig. 8a) of a turbine vane at 1150 °C surface temperature with YSZ TBC topcoat and MCrAlY bond coat (Ref 43). CMAS was deposited across the entire pressure side of the vane. In the high-temperature region, CMAS fully infiltrated the TBC, leading to spallation (indicated by the white line in Fig. 8b). The cross-sectional SEM images at points A and B, shown in Fig. 8(c) and (d), reveal that CMAS penetrated all pores within the TBC and extended to the interface between the ceramic topcoat and the bond coat.

Radiative Heat Transfer

At surface temperatures beyond 1000 °C, radiative heat transfer becomes a significant mode of thermal transport through TBCs. Current YSZ TBCs are semi-transparent to thermal radiation in the crucial near infra-red spectrum. This translucency allows radiant heat from the hot gas stream to penetrate the coating and directly heat the underlying metal substrate. Since radiant heat transfer increases with the fourth power of temperature (T^4) and becomes more pronounced as engine temperatures rise for increased efficiency. This internal radiative heating effectively reduces the coating's insulating effectiveness, potentially shortening the component's lifespan and increasing thermal fatigue (Ref 44.)

Thicker TBCs

Increased TBC thickness ($\sim$ 2000 m) is of particular interest for components such as combustion chamber liners, where enhanced thermal insulation is critical, and for applications as abradable seal coatings, where controlled wear behavior is required. However, thicker coatings also increase the driving force for failure. Greater thermal gradients and residual stresses across the thickness often accelerate crack initiation and reduce spallation resistance. The design of thick TBCs must therefore be approached as a multi-objective optimization problem, balancing thermal insulation against structural integrity. This trade-off underscores the need for advanced microstructural design strategies that enhance strain tolerance without compromising heat resistance (Ref 45).

Processing versus Compositional Advances

Manufacturing constraints further complicate the implementation of next-generation TBCs. While EB-PVD remains the benchmark for producing columnar-structured TBCs with superior thermal cycling resistance, it is less suitable for depositing complex ceramic compositions such as high-entropy zirconates (HEZs), doped tantalates, and layered composites due to differential vapor pressures of constituent elements. This compositional inhomogeneity challenges stoichiometric control during deposition. In contrast, Suspension Plasma Spray (SPS) and Solution Precursor Plasma Spray (SPPS) allow for microstructure refinement and deposition of complex oxides with improved strain compliance and thermal performance (Ref 46). Additionally, these techniques enable non-line-of-sight application, critical for coating internal passages and complex geometries, and avoid blockage of cooling holes. However, the industrial-scale implementation of SPS and SPPS is hindered by the high cost of precursor materials and scalability limitations, emphasizing the need for further development in both feedstock engineering and process automation.

Thermally Grown Oxide (TGO)

The durability of TBC systems is closely tied to the behavior of the TGO layer, typically α-Al_2O_3, which forms at the interface between the ceramic topcoat and metallic bond coat at temperatures above 700 °C. TGO evolution is a coupled process involving grain boundary oxidation, internal oxidation, and volumetric expansion, all of which induce significant growth stresses. The mismatch in coefficients of thermal expansion (CTE) between TGO and adjacent layers leads to interfacial stresses, promoting microcracking and delamination. Although the TGO provides an initial protective barrier, it becomes the primary life-limiting factor during long-term exposure (Ref 47).

Testing and Diagnostics

Another barrier to progress in TBCs is the lack of cost-effective and comprehensive test environments that replicate the full spectrum of operational stressors especially emerging conditions associated with hydrogen-rich combustion, increased water vapor, and sustainable aviation fuels. Laboratory-scale lifetime performance testing typically focuses on simplified thermal cycling or CMAS exposure but fails to capture real-world synergistic degradation mechanisms. This limits the predictive accuracy of life assessment models, which are essential for "prime reliant" applications where TBC failure could lead to engine failure. Moreover, the field lacks robust nondestructive evaluation (NDE) methods for real-time monitoring of coating health, hindering condition-based maintenance strategies and reducing confidence in predictive modeling (Ref 48).

Lifetime Prediction

A major scientific challenge lies in predicting TBC lifetime. Failure results from complex, interacting phenomena such as oxidation, CMAS infiltration, sintering, creep, and phase transformations that occur across multiple length and time scales. Finite element modeling (FEM) captures some aspects but often oversimplifies multiphysics interactions. It often struggles with capturing the nonlinear behavior of TGO growth, CMAS infiltration, and phase transformations, especially across microstructural heterogeneities and evolving boundary conditions. Accurate simulations remain computationally intensive and impractical for component-level analysis without further development of integrated, multi-physics computational frameworks. Machine learning approaches trained on large experimental datasets, integrated with multiscale models, are emerging as more accurate predictive tools (Ref 49).

Advances in Science and Technology to Address Challenges

Addressing the multifaceted challenges facing TBCs requires advancements across materials design, processing technologies, and diagnostic methodologies. A key innovation in TBC material systems is the development of high-entropy oxides (HEOs). These ceramics, composed of multiple principal cations in near-equiatomic ratios, exhibit superior phase stability, intrinsically low thermal conductivity, and strong resistance to sintering, attributes that are essential for operation at elevated temperatures (Ref 50). HEO-based coatings have demonstrated improved thermal stability and insulation performance compared to conventional yttria-stabilized zirconia (YSZ). Other promising candidates include rare- earth co-doped zirconates, aluminates and tantalates such as $La(Al_{0.25}Mg_{0.50}Ta_{0.25})O_3$ (LAMT). Pyrochlore-structured compounds such as $Gd_2Zr_2O_7$ (GZO), along with more complex compositions like $(La_{0.2}Nd_{0.2}Sm_{0.2}Eu_{0.2}Gd_{0.2})_2Zr_2O_7$, offer low thermal conductivity, excellent phase stability, and high sintering resistance, surpassing the performance limitations of YSZ (Ref 40, 50, 51). Parallel efforts to enhance the bond coat layer have focused on high-entropy alloys (HEAs) (Ref 52). These metallic systems provide high strength, thermal stability, and corrosion resistance under oxidizing and sulfidizing conditions, thereby outperforming conventional

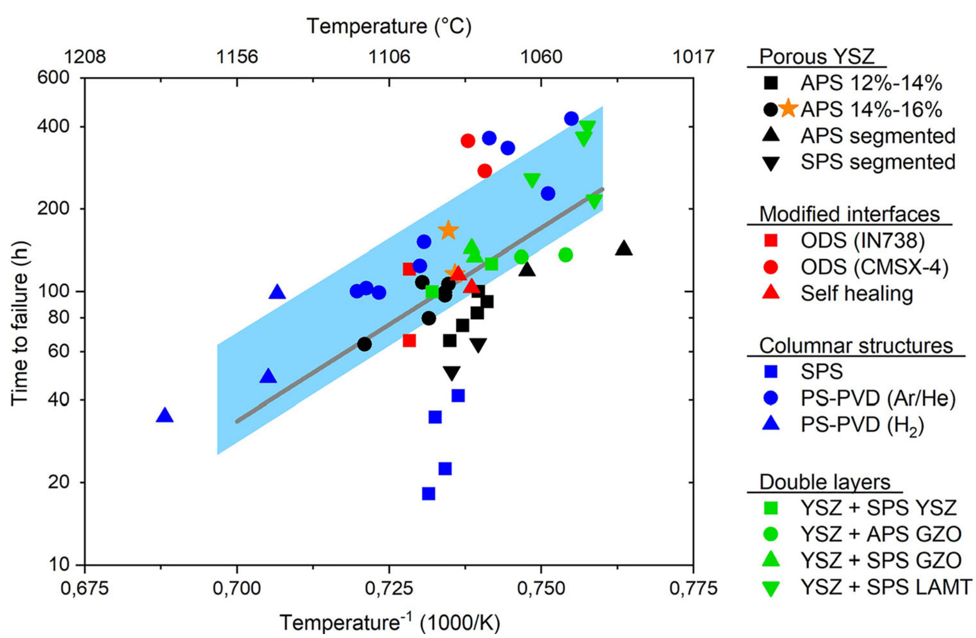

Fig. 9 Performance of different TBC systems under burner rig tests with 5 min dwell time and surface temperatures of about 1400 °C for different TBC systems as a function of bond coat temperature. The blue shaded area represents the lifetime of commercial EB-PVD coatings. Some of the tested samples have ceramic-bond coat interfaces modified by incorporating oxide dispersion strengthened (ODS) materials (Ref 40). Used with permission of Springer Nature, from "A Perspective on Thermally Sprayed Thermal Barrier Coatings: Current Status and Trends," R. Vaßen, E. Bakan, D.E. Mack, and O. Guillon, *Journal of Thermal Spray Technology*, 31(4), 2022; permission conveyed through Copyright Clearance Center, Inc

MCrAlY alloys in long-duration high-temperature service. Concurrently, advancements in deposition technologies are enabling precise control over coating architecture and microstructure. Thermal spray methods such as SPS and SPPS facilitate the formation of fine-grained columnar microstructures or with high strain tolerance and low thermal conductivity (Ref 46). SPS has been successfully employed to fabricate 1000 μm-thick 8YSZ coatings exhibiting 2.5 times longer thermal cycling life than dense vertically cracked (DVC) coatings produced via APS process. Additional processing innovations include plasma spray–physical vapor deposition (PS-PVD) (Ref 40) and double evaporation EB-PVD (Ref 53), which offer enhanced control of microstructure, composition, and coating thickness. These methods support the development of functionally graded coatings (FGCs) and multilayer architectures. Gradual compositional transitions in FGCs mitigate thermal mismatch stresses and improve adhesion at interfaces. Figure 9 shows the lifetime of various TBC systems as a function of bond coat temperature after thermal cyclic tests at surface temperature of about 1400 °C using a burner rig (Ref 40).

Current CMAS mitigation strategies involve the integration of CMAS-resistant topcoats, particularly rare-earth zirconates, and the design of reactive self-sealing coatings (Ref 54). For instance, the incorporation of GZO has been shown to induce a pronounced exothermic crystallization upon contact with silicate melts, which facilitates the rapid formation of crystalline reaction products that inhibit further CMAS penetration. Multilayer coatings combining YSZ with ceramics like GZO and HEOs have also demonstrated improved thermal insulation and resistance to CMAS infiltration.

To enhance thermal radiation resistance at elevated temperatures, photon transport can be mitigated by developing new coatings that incorporate materials with higher infrared absorption or designing structures that trap radiation, like columnar coatings that leverage a “blackbody effect” to enhance radiative cooling. Composite coatings consisting of 8YSZ and refined corundum particles for example, have been developed for scattering enhancement by incorporating low-refractive-index phases and optimized particle sizes (Ref 55). The design leverages Mie scattering, where particle sizes close to the IR wavelength (1-5 μm) significantly attenuate radiative heat flow. Experimental results indicate that the total and photon thermal conductivity of 8YSZ/corundum composites are substantially lower than those of monolithic 8YSZ, with photon conductivity reduced by approximately 96.4% at 1200 °C. Additionally, layered coating systems combining reflective ceramics with low-index materials are being designed to reflect incident radiation while maintaining low overall thermal conductivity.

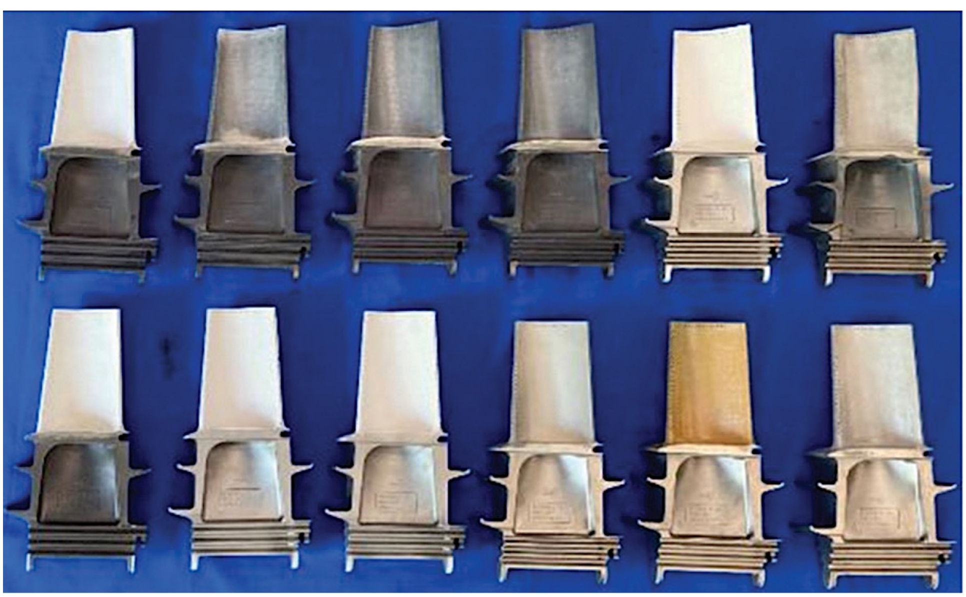

Fig. 10 First-stage turbine buckets used in TBC durability “Rainbow Test” under hydrogen combustion conditions, hosted by Dominion with EPRI as sponsor. Five buckets are coated with standard DVC TBCs, while seven are coated with a combination of DVC and advanced rare-earth stabilized TBCs. The coatings are applied side-by-side in segmented zones, enabling direct comparison of performance and durability under identical high-temperature operating conditions (Ref 56). Used with permission from EPRI, H. van Esch, S. Pietersen, J. Scheibel, and O. Barth, “Durability Test of Advanced TBC’s,” *Proc. ASME Turbo Expo 2024: Turbomach. Tech. Conf. Expo.*, London, UK. EPRI makes no warranty or representations, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in the Material. Additionally, EPRI assumes no liability with respect to the use of, or for damages resulting from the use of the Material

Diagnostics and real-time monitoring technologies are essential to validate and ensure the reliability of advanced TBC systems. Under hydrogen combustion environments, ongoing rainbow test deploy various advanced and conventional YSZ coatings on first-stage turbine buckets (Fig. 10), allowing for direct, side-by-side comparison of the coatings' performance and durability under identical high- temperature operating conditions (Ref 56). This accelerates validation and selection of advanced TBC architectures and compositions in realistic engine environments. In addition to field tests, embedded sensor technologies are also being explored (Ref 57). Phosphor thermometry enables in-situ monitoring of through-thickness thermal gradients by detecting temperature-dependent emissions from doped layers embedded up to 300 µm within the TBC. In parallel, dual-frequency eddy current (DFEC) methods are advancing for non-destructive quantification of ceramic and bond coat thickness and integrity (Ref 58).

To accelerate material discovery, optimize process parameters, and predict failure mechanisms, AI and ML are being integrated into TBC research. AI-based predictive modeling is particularly useful for identifying novel materials with superior thermal and mechanical properties, significantly reducing the time and cost associated with traditional experimental discovery. For instance, multiscale deep-learning methods are being developed for TBC failure prediction under complex conditions like CMAS corrosion and thermal shock (Ref 43, 49). These models use microscale data to describe local stress and damage, considering TBC microstructure and CMAS infiltration mechanisms, and then leverage deep learning to predict TBC lifetime. Such approaches have shown promising results, with predicted lifetimes being within 20% of observed experimental values, demonstrating their potential for effective lifetime prediction under real service conditions.

Concluding Remarks and Future Perspectives

The continuous evolution of TBC technology is crucial for meeting the demands of next-generation gas turbine engines and sustainability initiatives. Addressing key challenges such as CMAS infiltration, high-temperature degradation, radiative heat transfer and processing limitations will necessitate a multifaceted approach. This approach must combine material innovations such as high-entropy oxides and advanced rare-earth zirconates, with sophisticated manufacturing techniques like SPS/SPPS and PS-PVD that enable precise microstructural control. Furthermore, the integration of advanced diagnostic technologies, including smart coatings with embedded sensors and novel thermometry methods, is crucial for real-time monitoring and accurate life prediction. Future research should focus on further exploration of high-entropy oxides and other complex ceramic systems for enhanced intrinsic stability and lower thermal conductivity. The development of adaptive coatings that can respond to changing environmental conditions, perhaps through self-healing mechanisms or variable thermal properties, represents a significant frontier. Optimization of eco-friendly processing techniques is also vital to align TBC manufacturing with broader sustainability goals. Crucially, the integration of AI-driven material discovery and failure prediction models will accelerate the development cycle, enabling the rapid identification and validation of novel coating formulations. Finally, the adaptation of TBCs for emerging propulsion systems such as hydrogen-powered and electric aircraft will introduce new environmental considerations and degradation mechanisms that require dedicated research efforts. Success in implementing these advanced technologies requires sustained investment, international collaboration, and early engagement with certification authorities. By investing in these advancements, the aerospace industry can ensure that future TBCs provide superior protection, efficiency, and longevity in demanding operational environments, ultimately enabling greener aviation technologies and reducing emissions.

Environmental Barrier Coatings

Farzam Arhami, Bryan J. Harder, Edward J. Gildersleeve, Christian Moreau

Status of the Field

It is well-understood that SiC ceramic components exposed to water vapor at high-temperature undergo rapid oxidation to SiO_2 and subsequent volatilization into $Si(OH)_4$ that results in recession in flowing environments (Ref 59). Environmental barrier coatings (EBCs) have been in development for nearly three decades as the solution for this materials degradation challenge (Ref 60-62). EBCs have undergone two major 'generational' evolutions in the last 30 years. "Gen 1" EBCs implemented barium strontium aluminosilicate (BSAS)/Mullite as the primary coating materials and showed impressive durability with a substrate temperature below 1300 °C. However, above this temperature low-melting glass formation reduces the life and, at surface temperatures above 1400 °C, the topcoat undergoes some volatility (Ref 63). Consequentially, rare-earth silicates (e.g., $Yb_2Si_2O_7$) entered the forefront of the field as "Gen 2" EBCs. This system had a few major advantages over the Gen 1 EBCs, requiring only a single layer to be deposited on the silicon bond coat, and demonstrating improved resistance to water vapor recession (Ref 64, 65). Building on these benefits, Gen 2 EBCs have since been commercialized in aerospace applications (e.g., LEAP, 9X) (Ref 66).

Current and Future Challenges

Although thermally sprayed EBCs have been flying for nearly a decade, there are significant challenges for current applications as well as on the horizon. Current EBC research has shown that it is possible to process rare-earth silicates by various thermal spray processes. However, because they are line compounds formed from chemically dissimilar constituents (RE_2O_3 and SiO_2), achieving a homogeneous composition during deposition remains challenging (Ref 67). In conventional APS and SPS, studies indicate rare-earth silicates undergo inflight decomposition during deposition. For example, during spraying, SiO_2 is preferentially volatilized over Yb_2O_3 in the molten $Yb_2Si_2O_7$ droplets, resulting in a heterogeneous distribution of $Yb_2Si_2O_7$, Yb_2SiO_5, and even Yb_2O_3 splats within the final coating (Ref 67, 68).

Diagnostic techniques have hinted that the aforementioned decomposition can be controlled to some extent, but a key near-term challenge in spraying is to develop a 'condition roadmap' that accurately describes the volatilization behavior as a function of relevant input parameters, similar to the way that was shown by Mauer and Gildersleeve for plasma-sprayed TiO_2 (Ref 69). Another challenge in processing "Gen 2" EBCs, such as $Yb_2Si_2O_7$, is their high tendency to form an amorphous phase in the as-sprayed state. As a common approach, post-deposition heat treatments are applied to induce crystallization in as-sprayed amorphous rare-earth silicate coatings. Promoting dynamic in-situ crystallization during deposition has proven successful and offers the potential to eliminate the need for post-deposition heat treatments (Ref 70). However, the underlying mechanisms of dynamic crystallization in rare-earth silicates during thermal spraying remain poorly understood and insufficiently established.

These fundamental processing challenges are further compounded by inconsistent trends in the literature regarding EBC properties and performance. These inconsistencies are generally driven by variations in methodologies, material systems, and testing conditions. One such example involves the presence and distribution of Si-depleted secondary phases (e.g., Yb_2SiO_5) in disilicate EBCs mentioned above. While many studies show this phase to be detrimental to long-term cyclic durability due to strains induced by thermal expansion coefficient (CTE) mismatch (Ref 71), other studies have shown improved durability over single-phase $Yb_2Si_2O_7$ coatings. (Ref 72) This inconsistency shows the challenges with comparative studies of EBC composition based on processing method. Beyond inconsistencies in durability test results, experiments employing calcium-magnesium-aluminosilicate (CMAS) exposure have historically yielded mixed results. The numerous test characteristics in a CMAS test – including glass loading, composition, starting condition, humidity, etc. all play a major role in the test outcome; it is possible to see a coating pass one test and spectacularly fail a second similar test. Moreover, the literature shows conflicting results even with the composition of the EBC: Liu et al. (Ref 73) and Zhou et al (Ref 74) concluded that Yb_2SiO_5 outperforms $Yb_2Si_2O_7$ at 1300-1400 °C, yet Zhao et al. (Ref 75) and Stolzenburg et al. (Ref 76) reported superior performance for $Yb_2Si_2O_7$-rich coatings at 1300 °C. While all these studies have merit, the inconsistencies illustrate how fragmented the current literature is when it comes to understanding EBC performance. The absence of standardized testing methodologies under relevant conditions, such as thermal cycling, steam exposure, or CMAS infiltration, further complicates comparative analysis. In addition, the lack of consensus on optimal microstructural features, including porosity levels, phase composition, and the distribution of secondary phases, adds complexity to this effort. These challenges hinder the development of a general mechanistic understanding. By identifying these discrepancies and ambiguities here, we aim to underscore the urgent need for a more systematic and unified framework for evaluating EBCs. It would greatly benefit the research community if scholars reviewed and reconciled the existing body of work from the past three decades, aligning it with the specific mechanisms they intend to investigate before initiating new studies.

Aside from processing challenges, new materials need to be developed to address ever-increasing turbine inlet temperatures. The state-of-the-art "Gen 2" EBCs system relies upon a silicon bond coat that its operation is limited below 1400 °C and the rare-earth topcoats exhibit limited durability when exposed to harsh engine environments involving large thermal gradients, steam oxidation, erosion, glass corrosion, and foreign object damage (FOD) (Ref 77). Novel bond coat chemistries need to be developed and optimized for oxidation and water vapor protection beyond the capabilities of the conventional silicon layer.

Moreover, novel topcoat compositions and architectures capable of withstanding the extreme environments of the turbine hot section need to be explored. While prior work has primarily approached EBC development as a chemistry-driven challenge, future coating systems will require far greater emphasis on mechanical design, by deliberately incorporating thicker coatings, complex architectures, and integrated thermal barrier layers.

Several industrialization challenges must also be addressed to enable the successful deployment of future EBCs. Unlike thermal barrier coatings (TBCs), which were developed around decades of experience with superalloys in engines, both the coating and substrate in an EBC system are being co-developed simultaneously. Additionally, the EBC is regarded as a requirement for CMC components as opposed to a TBC, which are utilized to improve performance but not required for operation. Additionally, material sustainability concerns arise when considering industrialization of EBCs. As demand grows for ceramic-based engine components and the EBCs required to protect them, the availability of raw materials becomes more concerning. In particular, recyclability and reusability of materials, especially rare-earth thermal spray feedstock used in deposition-inefficient processes such as APS, are increasingly being questioned. Research into the recyclability and feasibility of repurposing feedstock overspray from the deposition process warrants serious consideration.

Advances in Science and Technology to Address Challenges

Over the past 5 years, significant efforts have established coating formation mechanisms (including microstructural evolution), crystallization pathways, splat layering dynamics, and phase transformations occurring during deposition or upon subsequent heat treatment. These insights led to the development of initial process maps that correlate process parameters with coating properties such as microstructural features, phase composition, and physical, chemical, or thermomechanical characteristics (Ref 67, 68). Early efforts have focused on optimizing current materials (e.g., $Yb_2Si_2O_7$) and deposition techniques to produce coatings with high crystallinity, favorable microstructures, and reduced silicon evaporation, in order to enhance the durability and performance of EBCs (Ref 78). As the field progresses, a natural next step is to extend these process optimization concepts toward establishing a next generation of process maps (e.g., second-order process maps) that link coating properties to long-term performance and durability under service-relevant environmental conditions.

An additional recent advancement is the use of Optical Emission Spectrometry (OES) in atmospheric plasma spraying. This technique has been demonstrated as an effective diagnostic tool for quantitative chemical evaluation of vaporizing components within the plasma plume (Ref 69). By coupling OES with chemical equilibrium analysis, the process maps mentioned above can be constructed to identify specific regimes where feedstock decomposition occurs (Ref 69). The application of this methodology to EBC systems could offer significant insights into feedstock behavior and real-time process optimization.

Finally, a third major advancement in recent years has been the development of novel coatings and architectures with established materials. Notably, multilayer architectures incorporating dissimilar materials, even those with non-matching CTEs, have demonstrated promising outcomes. It was recently shown that Yttria Stabilized Zirconia (YSZ, CTE $\sim$ 10 ppm/K), the most widely used TBC material, can be plasma-sprayed onto an EBC-coated SiC substrate (CTEs $\sim$ 5-6 ppm/K) (Ref 79). These thermal-environmental barrier multilayer coatings (T-EBCs) survived crystallization annealing and subsequent thermal cyclic exposure with no signs of spallation or delamination (Ref 79). In addition to the development of multilayer coating architectures, doped EBC compositions containing Al_2O_3 additives for oxidation resistance have shown significant promise by improving steam oxidation performance by a factor of 20x (Ref 77). These EBCs/T-EBCs, when combined with emerging high-temperature bond coat materials, are expected to set a new standard for current and next-generation engine conditions.

Concluding Remarks and Future Perspectives

Future researchers have the opportunity to build on these studies to address existing knowledge gaps and drive further innovation within the EBC community. Additional research is needed to deepen our understanding of coating buildup mechanisms in EBCs, particularly porosity formation and microstructural development under varying processing conditions, as well as their influence on the final chemical composition and phase distribution. These insights may lay the foundation for process maps that link spraying parameters to properties, and eventually environmental performance of EBCs, ultimately enabling standardized, widely accepted frameworks that define the optimal characteristics of EBCs needed for reliable performance under service-relevant conditions in next-generation turbine systems.

As the technology scales and CMCs continue to expand in their use in engines, the landscape of EBCs in thermal spray will continue to evolve. Research will continue to produce a high volume of publications, yet there remains a need for sustained advancement in the community's academic understanding of these coatings. As demand for EBCs grows and current materials are pushed to their limits, new materials will emerge with new processing

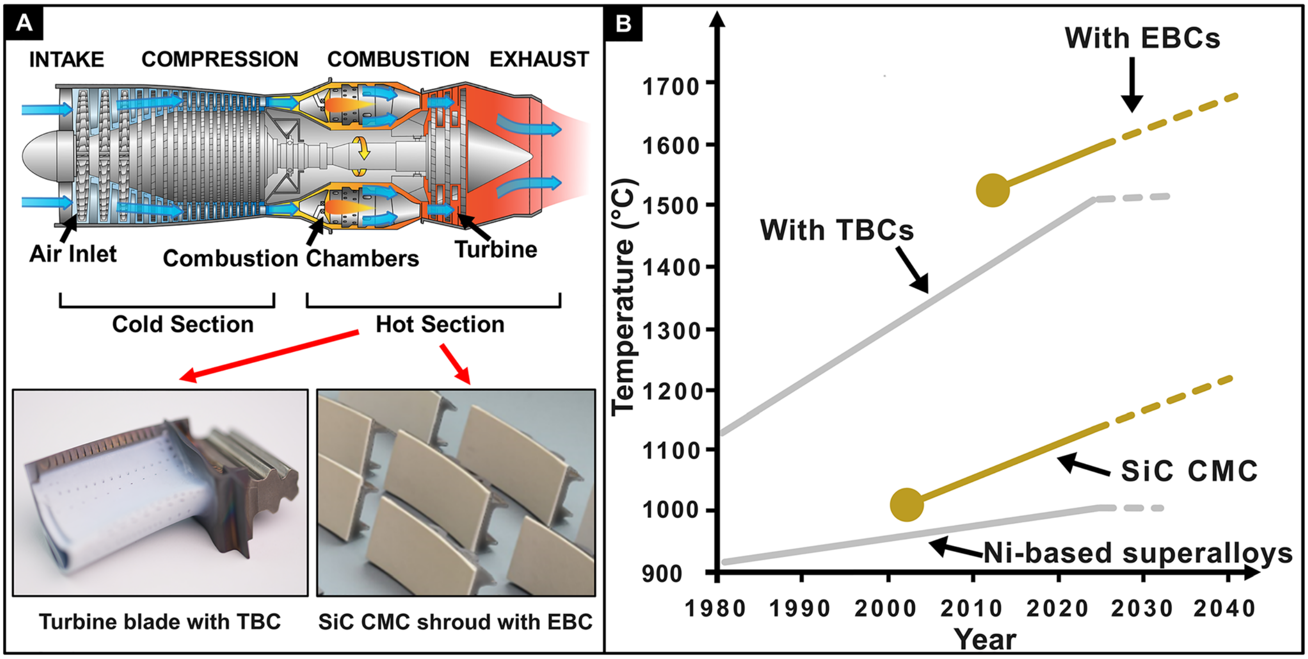

Fig. 11 Overview of the increasing temperature capability of gas turbine engines for greener aviation. (a) Schematic of the gas turbine engine identifying the hot section where components such as a nickel superalloy turbine blade are coated with a thermal barrier coating (TBC) and silicon carbide (SiC) ceramic matrix composite (CMC) shrouds are coated with an environmental barrier coating (EBC). (b) Evolution of the inlet gas temperature capability with time provided by coating nickel superalloys with TBCs (silver), and the further improvement in temperature capability with EBCs on SiC CMCs. Gas turbine engine image in (a) courtesy of Jeff Dahl, available under CC BY-SA 4.0 license at Wikimedia Commons

challenges. Although performance demands will continue to rise, the fundamental studies discussed above will provide meaningful lessons for improving durability and enabling CMCs into future engine technology.

Enhancing Characterization Strategies to Understand Coating Failure in Real-Service Conditions

Thibaut Archer, Alice Dolmaire, Ahmet Hilmi Paksoy, Daniel Scotson, Ping Xiao

Status of the Field

The desire to raise the temperature capability of gas turbine engines and lower their fuel consumption has increased the criticality of protective coatings. In this regard, Fig. 11 indicates the increased temperatures obtained within the engine's hot section by introducing coatings. Thermal barrier coatings (TBCs) protect nickel-based superalloys from temperatures around 1100 °C; while environmental barrier coatings (EBCs) shield silicon carbide (SiC) ceramic matrix composites (CMCs) from steam corrosion - with both coatings also providing resistance to ingested calcia, magnesia, iron oxides, alumina and silica (CMAS or CMFAS with iron oxide) (Ref 12, 40, 80). Without coatings, the underlying substrate rapidly degrades in the hostile gas turbine environment, so the failure of the coating is life-limiting for the entire component, where lifetimes of 25,000 h are expected.

In this regard, characterization techniques are key to evidencing the changes occurring to coatings during service (Ref 81). These essential tools enable an understanding of coating performance to guide the design and development of more durable coatings. As a result, this maximizes the coating's contribution to greener aviation by extending the coating's lifetime.

A key step for targeted coating improvements is identifying the critical damage mechanism. There are typically many competing mechanisms contributing to TBC and EBC failure, which also change as a function of environmental exposure. Conditions within the engine include steam corrosion and complex thermomechanical cycling, along with ingested materials causing CMFAS reaction and infiltration, erosion and foreign object damage (FOD) (Ref 12, 40, 80). The effect of these simultaneously occurring environmental conditions on multiple coating layers makes it difficult to predict or model coating failure (Ref 80). Therefore, before it is possible to accurately predict coating performance, a fundamental understanding of a critical

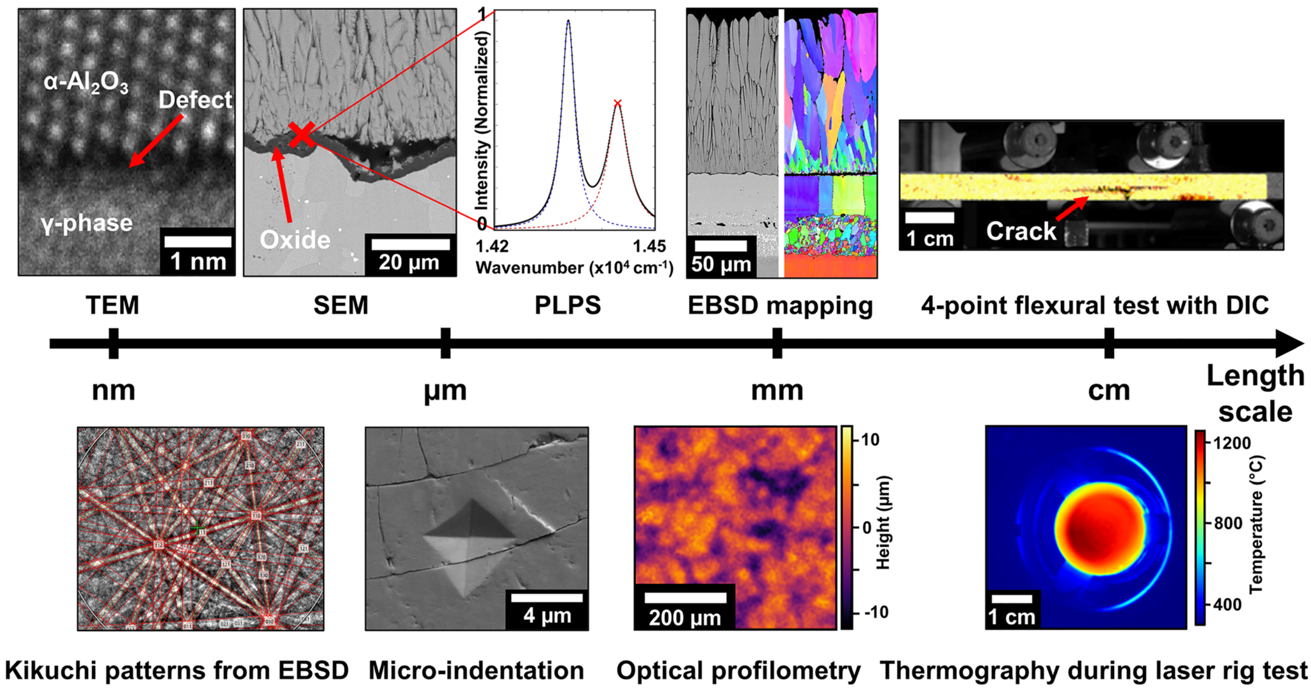

Fig. 12 A selection of characterization techniques improving the understanding of thermal barrier coating (TBC) and environmental barrier coating (EBC) failure on a range of length scales. These vary from nanometre length scales with transmission electron microscopy (TEM) all the way through to component testing on the centimeter length scale with four-point bending coupled with digital image correlation (DIC) and thermography testing. On micrometer length scales there is scanning electron microscopy (SEM), micro-indentation and photoluminescence piezospectroscopy (PLPS) for stress evaluation in TBC α-Al_2O_3 oxides. The mapping capability of many techniques also enables an evaluation on the millimeter length scale, for example, with optical profilometry for surface roughness and electron backscattered diffraction (EBSD) for phase and texture analysis

failure mechanism is required from evidence gathered by characterization techniques.

In this regard, there are many characterization techniques available for evaluating TBC and EBC failure. These can be summarized into capturing the microstructure and chemistry changes, evaluating the stress state, and mechanical testing to indicate cohesive failure (within a coating layer) or adhesive failure (at a coating interface) (Ref 81). All these factors require characterization on different length scales, as shown in Fig. 12, from composition analysis at the nanometre scale to macroscopic beam bending of the component at the centimeter scale. This is where the approaches of industry and academia may differ with industry typically working at larger length scales and more component-relevant samples, whereas academia works at smaller length scales to address a fundamental understanding of coating phenomena. It is vital these length scales are married to collect holistic evidence that first informs understanding and consequently is applied to extend coating lifetime and improve performance predictability.

The application of characterization techniques to TBCs and EBCs is ever improving our understanding of coating failure (Ref 4). For instance, the improved resolution and capability of electron microscopy techniques - such as scanning electron microscopy (SEM) with electron backscattered diffraction (EBSD), and transmission electron microscopy (TEM) coupled with energy-dispersive x-ray spectroscopy (EDS) - capture changes to the microstructure of the coating's surface and cross-section as well as identify the phase chemistry and texture. Additionally, techniques such as x-ray diffraction, Raman spectroscopy or Photoluminescence Piezospectroscopy (PLPS) not only facilitate the evolution of the phases and chemistry of the coating but also examine the stress states that have vital importance on both TBC and EBC lifetime, especially in thermal cycling conditions (Ref 80). Insights from these characterization techniques then help define requirements for the desirable microstructures and compositions for the top coat, bond coat and interfaces - ultimately enhancing coating durability in operating environments.

In addition to ex situ characterization techniques, in situ techniques are crucial for evidencing coating changes in the hostile environment of the gas turbine engine. For instance, many techniques can now operate at a variety of temperatures, such as evaluating the microstructure (SEM), analyzing phase changes (EBSD) or determining thermomechanical properties (x-ray diffraction or nanoindentation). These in situ techniques evaluate more representative coating behavior and reduce the need to extrapolate results from room temperature. Furthermore, adding a time dimension to this characterized material behavior with in situ digital image correlation (DIC), thermal fields monitoring and acoustic emission (AE) evaluates real-time displacements and cracking as a function of environmental exposure. These techniques can also be applied to macroscopic length scales to directly observe coating delamination or spallation under a controlled environment.

Besides optimizing each of these individual techniques, there is also growing interest in correlative characterization where multiple techniques are combined to enhance understanding from multiple perspectives. As described previously, characterizing the microstructure, stress and failure location are all necessary for an understanding of coating failure (Ref 81). Therefore, correlating these factors across multiple length scales is an essential yet scarcely applied approach to appreciating the complex and interrelated nature of coating failure.

Current and Future Challenges

Many characterization tools have already contributed to improving our understanding of coating failure. For instance, with TBCs there is a strong understanding of thermomechanical effects leading to failure, which has been applied to enhance coating design and extend lifetime. Meanwhile, the understanding of EBC failure is not as extensive, with solutions to extending lifetime largely focused on reducing the thermally grown SiO_2, although a mechanistic understanding of failure is lacking. Naturally, this understanding is expected to improve over time, but a key challenge lies in accelerating this progress, particularly with the urgent need for greener aviation technologies.

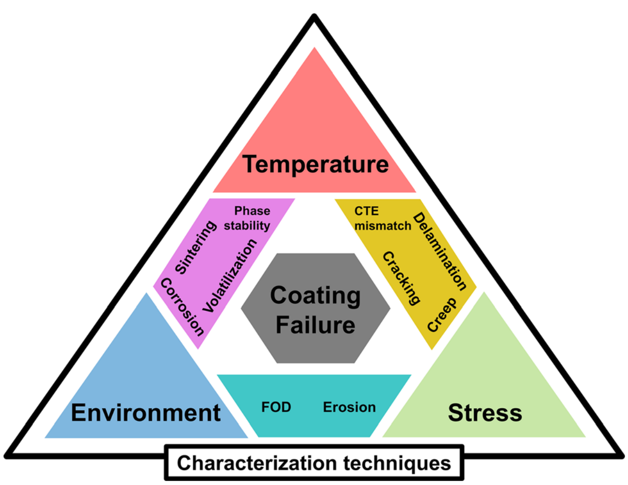

Fig. 13 Schematic interpretation of the complexity of factors within the gas turbine engine environment that all interrelate and influence the failure mechanisms of coatings. Characterization techniques are the overarching set of tools to investigate these factors to understand coating failure. Acronyms include the coefficient of thermal expansion (CTE) and foreign object damage (FOD)

A route for accelerating coating development is a more representative model of coating behavior to predict coating performance. The use of characterization techniques therefore is likely to evolve by not simply confirming coating performance and failure mechanisms but also informing and developing test-validated models. Reducing this feedback cycle between acquiring experimental data and iterating theoretical models is certainly necessary to develop the reliability of predictive modeling. Additionally, test-validated modeling is also beneficial in limiting costs from both a financial and time perspective of testing coatings for thousands of hours. However, the complexity of TBC and EBC microstructures alongside their complex in-service environments has historically made representative modeling challenging.

Therefore, testing in environments that closely replicate operating conditions is essential for capturing realistic coating behavior and developing a mechanistic understanding of coating performance. Achieving such representative testing conditions is difficult because of the complex working environment of the gas turbine engine. Consequently, this complexity results in many simultaneous environmental effects that influence the failure mechanisms (Ref 12, 80) as highlighted in Fig. 13.

Considering this set of environmental factors, the current approach to testing a coating system typically involves assessing failure modes in isolation. For example, tests may initially perform thermal cycling of the TBC to induce thermal mismatch stresses that drive the coating to failure (Ref 80). Ideally, for EBCs this should occur in steam cycling environments where silicon oxidation is faster in steam environments than in air. Then, the complexity of the test may be increased by inducing three-dimensional thermal gradients on the coating in a controlled environment, such as a burner rig (Ref 40), before other mechanical loads are applied such as pressure or flexural stress. As a final step, an engine test is performed to confirm coating durability in real service environments. However, difficulty can arise when attempting to relate the results from these different test environments for a better understanding of failure. Therefore, there is a challenge to develop new facilities that simultaneously expose coatings to a representative environment, while also performing reliable characterization tests (Ref 82).

Such techniques inevitably require specialized equipment collocated with experienced users to operate, acquire and interpret the corresponding data. As access to these techniques within industry can be limited, this requires partnerships between industry and academia to obtain representative manufactured components and unlock the understanding from advanced characterization tools. However, the need for such partnerships slows down the development of coatings since research is limited to the academic facilities or institutions involved in these industrial collaborations.

Furthermore, within an academic setting, limitations in experimental capability or skills shortages can typically be overcome with collaboration to engage with experts and access critical facilities. However, unlike routine academic collaboration, the industrial relevance and commercial sensitivity of TBCs and EBCs typically limit such activity to protect intellectual property and abide by export control policy. Accordingly, this can impede achieving a complete, holistic understanding of coating failure because a single academic-industry partnership may not be sufficient to access the wide range of necessary characterization tools at the required length scales. In addition, the limited sharing of understanding through typical communication routes such as publications and conferences may also result in knowledge silos within academia and industry, hampering the development of improved coatings.

Characterization techniques will continue their essential role in understanding coating failure, although the immediate need for decarbonising aviation requires a targeted use of such techniques to swiftly improve coatings. With the potential distraction of a wide variety of characterization techniques alongside the capability of recording vast amounts of data, it is critical for selective investigations. This requires expertise in performing key techniques without oversampling to obtain a representative appreciation of coating behavior. In this regard, reliably quantifying such behavior is also important, where the adoption of efficient machine learning tools may benefit our interpretation of data to accelerate coating development.

Advances in Science and Technology to Address Challenges

Understanding the in-service performance of a coating is essential. However, the challenge remains in replicating the gas turbine engine's environment which combines several loads (i.e., thermal, mechanical and environmental). A recent example to address this challenge and test in more representative environments is a facility at the University of Virginia (Ref 82). Their improved coating testing capability involves a CO_2 laser heating the coating's top surface to above 1700 °C in addition to backside air cooling to generate both through thickness and radial thermal gradients. Oxidation is also performed simultaneously within a test chamber capable of high pressures (up to 30 atm) with a superheated (850 °C), high-velocity ($\sim$ 270 ms^{-1}) steam jet (Ref 82). Finally, a mechanical loading frame can also apply stresses over 400 MPa to the specimen to better study the TBCs or EBCs' failure in representative conditions (Ref 82). Such facilities significantly enhance our understanding of coating failure as each load can be studied individually or introduced iteratively to the controlled and multi-instrumented test environment.

Another complementary improvement in characterizing the evolution of coating performance is incorporating laser shock testing during cyclic oxidation (Ref 83). With a Laser Shock Adhesion Test (LASAT) technique, various stages of crack initiation and crack propagation can be imaged within the coating's layers and at its interfaces (Ref 83). The advantage here is tracking the evolution of the coating to failure. For instance, infrared and optical cameras first inform the adhesive properties of the as-deposited coatings, before then evaluating the changes in microstructure (for example, ceramic sintering and TGO ratcheting) with the thermal loading history (e.g., heating/cooling rate, dwell temperature and time), and consequently interrogate their effect on failure mechanisms. This new characterization methodology could enable faster screening of coatings under development or offer more complexity in the testing facilities described previously. Accordingly, the LASAT technique can be coupled with factors such as CMFAS infiltration or steam corrosion, while simultaneously characterizing any crack propagation which is critical for coating delamination and spallation.

Reliably quantifying coating properties, such as their adhesion, relies upon the accurate measurement of representative boundary conditions. For example, the estimation of the interfacial fracture energy is usually performed with analytical formulas and global testing without accurately determining boundary conditions such as loads or displacements. A solution is the measurement of displacement fields with digital image correlation (DIC) that are then inputted into finite element models to evaluate the fracture energy (Ref 84). Comparing these experimental displacements to modeled displacements is beneficial in evaluating other properties, such as the elastic modulus. This approach is advantageous because it can study thermomechanical behavior at TBC and EBC operating temperatures, where more conventional methods reach temperature limits around 1000 °C. The necessity of evaluating high-temperature performance only increases with EBCs and the possible introduction of hydrogen combustion will further increase coating surface temperatures.

Beyond more representative coating testing, improvements are also being made in methods for the reliable interpretation of data from characterization techniques.

One such area is in image analysis with enhanced tools for analyzing oxides, cracks and porosity that benefit from machine learning in accurately segmenting microstructural features (Ref 85). These effective tools are vital to improving analysis practice, quantifying microstructural features and digitizing coating performance. In the future, robust methodologies will remain essential across academia and industry to reliably interpret our characterization data to inform decision making and accelerate coating development.

Concluding Remarks and Future Perspectives

Characterization techniques are a fundamental set of tools to provide an evidence-based understanding of coating failure. In addition to identifying failure mechanisms, these techniques also validate modeling of coating behavior to reliably predict coating performance. The wider implication of characterization techniques is then informing decisions for coating design, composition and microstructure that lead to targeted improvements in coating lifetime.

The application of characterization techniques in representative conditions remains a challenge in the future. Accordingly, more sophisticated testing environments and in situ investigations are necessary to replicate the complexity of the gas turbine engine and the demands of more hostile environments. These extremes are only expected to increase, with the benefit of higher combustion temperatures and a move to new fuels such as hydrogen resulting in higher water vapor containing environments.

The inherent complexity of these environments on already complicated TBC and EBC microstructures provides challenges to develop modeling and digital twins that can predict coating lifetime. Considering this, establishing such models at two length scales is a suitable starting point. The first is at a microstructural length scale considering TGO growth, cracking and phase transformations. This could be informed by SEM, EBSD and Raman spectroscopy as in Fig. 12. The second is at a component length scale. In this case, a digital twin could be informed by thermomechanical field measurements from DIC, infrared (IR) thermography and acoustic emission where these techniques are in situ to a service environment and crucially non-destructive. As a result, the macroscopic failure of a specimen can be described under multiphysical loadings. However, given the impact of microstructure evolution on TBC and EBC failure, a link between these two lengths scales will be required. Embracing a correlative approach to such characterization is likely to realize this target for TBCs in a shorter timeframe, but for EBCs this represents a greater challenge given our current, weaker understanding of their failure mechanisms.

Of course, while extending the lifetime of these coatings is desirable, coating repair is another engineering strategy to extend a substrate's lifetime and reduce the environmental cost of new component manufacture. This represents new territory for characterization techniques in informing the repair process to optimize the repair frequency and determine the coating's performance post-repair. Regardless of new solutions to improve the sustainability of engineered components, these all contribute toward our immediate necessity for more sustainable aviation which makes certain the role of coating characterization into the future.

New Abradables Coatings and Abrasive Coating Solutions

Tanvir Hussain, Céline Ruelle, Scott Wilson

Status of the Field

In today's highly competitive Aero and Power Generation markets, turbine manufacturers strive to design for higher Overall Engine Pressure Ratios (OPR's) with longer-lasting components made from better materials. The key outcome of such efforts is reduction of engine Specific Fuel Consumption (SFC) and to surpass increasingly stringent emissions targets.

The onset and aftermath of the 1970's global fuel crisis generated intense efforts by designers to look closely at the gas-path sealing systems in their engines where the "gaps" between the rotor components, e.g., blades or labyrinth "knife" seals, and the static "stators" (or casing), of the engine, play a significant role in determining overall engine performance (Ref 86-89). If clearances are too large, they allow gases to leak around the rotor tips instead of being compressed and expelled. This results in a "leaky engine" with reduced gas compression, decreased fuel burn efficiency, higher unwanted emissions and reduced engine thrust. Abradable coating seals were developed and increasingly utilized in compressor and turbine sections of turbomachinery units to help mitigate sealing losses. The most utilized abradable coatings are thermal-sprayed materials, developed such that they can be sacrificially rubbed away during a rub event that minimizes the risk of blade tip damage. When the rotor components encounter an abradable coating, they create a temporary seal, minimizing gas leakage and contributing to increased OPRs. The result is improved fuel burn efficiency that helps promote an engine's competitive status in the market (Ref 86-90). For example, in high-pressure turbine, a reduction in blade tip clearance by 25 μm could lead to a 0.1% reduction in

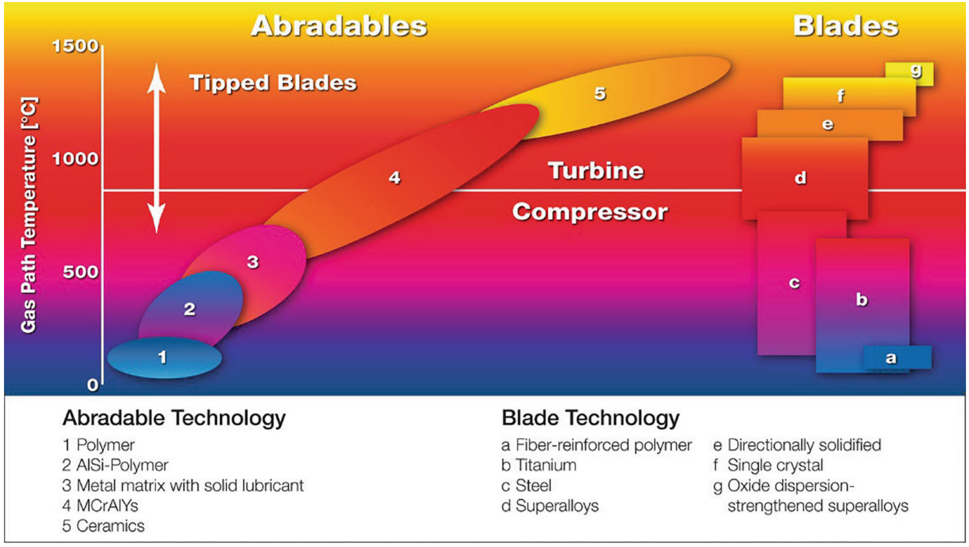

Fig. 14 Blade and abradable materials used at various temperatures (Ref 90). Reproduced by permission of Oerlikon Metco

specific fuel consumption and a 1 °C reduction in exhaust gas stream. (Ref 89).

An overview of the different material families used for abradables is given in Fig. 14. Each is designed to meet the specific conditions and materials used in different sections of a turbomachine. For example, at the "front end" of an aero engine is the low-pressure compressor or "booster" section, in which the dynamic rotor components are constructed from high-strength lightweight titanium alloys, operating in a temperature window from below freezing to approx. 400 °C. An abradable needs to be designed such that it is rub-compatible with for example, Ti alloy compressor blade tips. This means that there must be no excessive friction heat build-up or abrasion at the blade tips. In this instance soft aluminum alloys combined with robust high-temperature polymer powders are sprayed to produce composite abradable coatings that can be easily cut by Ti alloy components.

Commercially available abradables can be classed in terms of temperature (1) Low-temperature ($\leq$ 350 °C) for fan blade and low-pressure compressor (2) Mid-temperature ($\leq$ 700 °C) for high-pressure compressor and low-pressure turbine and (3) High-temperature (> 1000 °C) for high-pressure turbines. (Ref 89-93).

Current and Future Challenges

There is a myriad of requirements that need to be in place to reach manufacturing readiness for thermal sprayed abradables in turbomachinery sealing applications. The thermal spray powder needs to be manufactured using a robust, scalable process, with industry-wide accepted quality control and manufacturing standards in place that are audited on a frequent basis. Sourcing suitable raw materials is critical, with strong emphasis on supply chain security, compliance and quality. Robust, secure packaging of powders and shipping via a global distribution network are all mundane, but critical aspects, to "get the powder to the spray shop" in good time.

Upon reaching the spray shop, the incoming powder needs to be sprayed using a dedicated spray platform to meet the coating specifications required by the engine manufacturer or owner. For abradables this means meeting stringent requirements on coating mechanical properties – typically involving coating (superficial) hardness and tensile bond strength, using approved spray parameters.

The main design limitation faced by abradables is the operating temperature to which they are exposed to in service. For example, aluminum alloy-polyester composite combinations cannot be used in the high compressor section of a turbomachine where temperatures can easily reach 600 °C or more. They will degrade and may even melt if subjected to long exposure times. In the hotter sections abradable materials with higher temperature strength are needed, designed into abradable materials whose bulk properties are such that they can still be rub-compatible against rotor components. Classic materials employed are M-CrAl and M-CrAlY alloy systems with solid lubricant or soft ceramic fillers (Ref 91-93), engineered to produce porous microstructures that meet hardness and coating strength requirements, with desired rub compatibility under various rotor incursion conditions. A key challenge for these complex materials is maintaining coating microstructural control, which influences coating mechanical properties, while pushing for the highest spray productivity possible, i.e., parts coated per hour. Because of the complex composite nature of abradables, using spray parameters with excessively high powder and gas flow feeds can degrade the level of microstructural control and

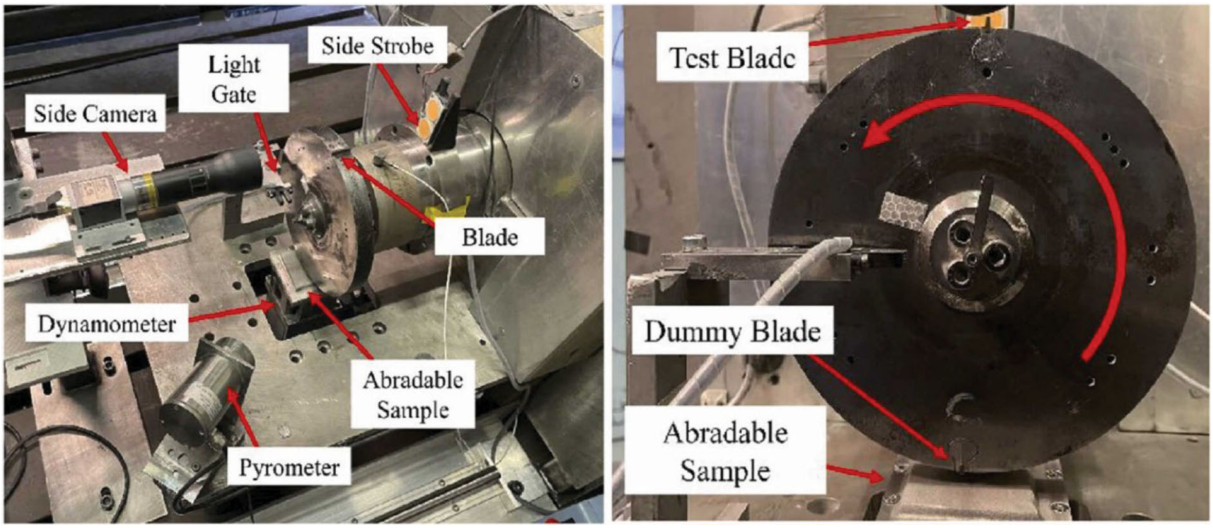

Fig. 15 Incursion rub test rig at the University of Sheffield, UK, with key components labeled (Ref 94). Reprinted from (Ref 94), available under CC BY 4.0 license at ScienceDirect

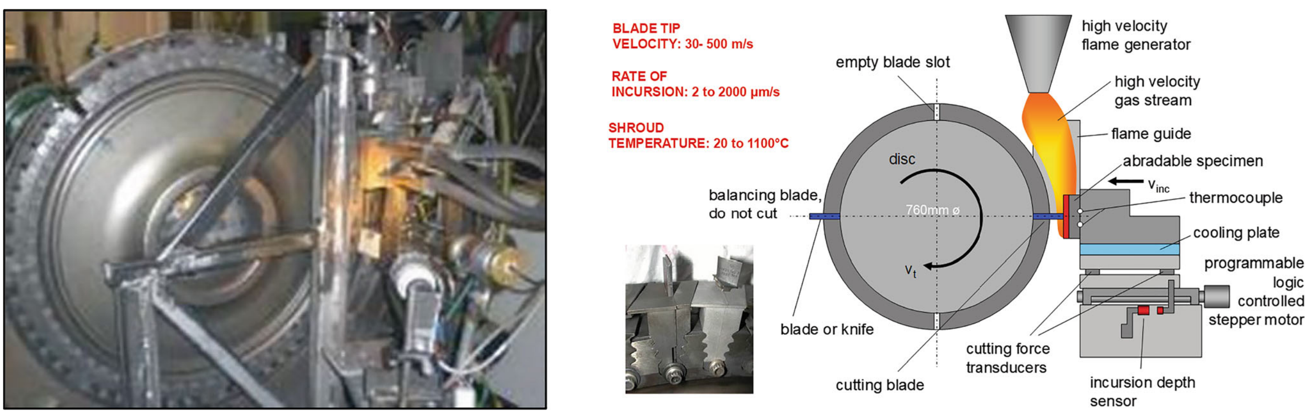

Fig. 16 Oerlikon abradable incursion test facility, based in Winterthur, Switzerland. The rig is capable of incursion testing up to gas temperatures of 1100 °C and blade tip speeds of 500 m/s (Ref 91, 92). Reproduced by permission of Oerlikon Metco

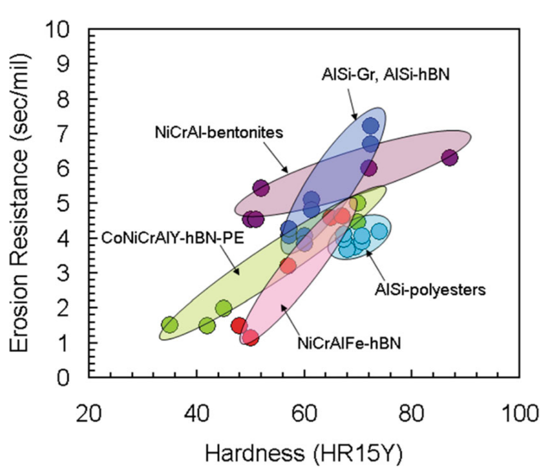

Fig. 17 The typical erosion resistance (test procedure meeting GE E50TF121) of the major compressor abradable families plotted as a function of coating superficial hardness (HR15Y) (Ref 91). Reproduced by permission of Oerlikon Metco

spray robustness. Here there are a lot of challenges for the industry to improve upon, from improved material design and use of "intelligent" spray platforms that rely far less on "human interference."

Other design limitations confronting abradables are the secondary environmental conditions they are exposed to in service which can degrade coatings faster than expected, resulting in reduced service times and increased maintenance costs. Aircraft engines will ingest air from a range of altitudes and locations often up to several times, or cycles, a day, exposing them to a range of humidities, air temperatures, fine dusts and corrosive compounds or gases, e.g., sea salt, sulfur dioxide. An industrial gas turbine sitting on an oil platform on the ocean will ingest salt laden humid air yet may only experience one start-stop cycle per year for routine maintenance. Coating lifetimes are largely determined by the start-stop frequency of each turbomachine, combined with temperature cycle and range of thermal gradients in each coating, with the added complexity of corrosion and oxidation attack with synergistic mechanisms. Key challenges are vastly improved methods needed to help model coating lifetimes in these highly complex environments which would help accelerate the new material development exponentially compared to current and historical "trial and error" approaches.

Design of abradable seal coating systems used in turbomachinery require several key technical criteria for consideration.

- Rub compatibility against rotor materials at various incursion conditions
- Have sufficient coating cohesive strength
- Meet oxidation and hot corrosion resistance criteria
- Meet thermal shock / cycle resistance criteria
- Have sufficient resistance to erosion damage, e.g., solid particles

Of all the testing requirements, rub incursion testing is the most critical part of abradable material development and qualification. There are various test rigs that have been developed since the 1970's by gas turbine manufacturers, material suppliers and universities - two currently used examples are given in Fig. 15 and 16. The bladed disk-type rub-rig is the most common, which can be configured for single or multiple points of contact per rotation. Both configurations can use simplified blade and casing geometries, while more advanced multiple contact point rigs can accept real engine hardware for simulated testing. In recent years there have been large strides toward more representative blade-casing rub tests in well-instrumented rigs to guide the development of new abradable.

Another key challenge with abradable coatings used in aircraft and helicopter engines is their resistance to erosion (Fig. 17). During operation, many particles can be ingested by the engine (such as sand or dust), which can lead to cracking or even delamination of the coatings. This phenomenon is even more pronounced with abradable coatings, which are designed to wear preferentially during rotor/stator interaction. Currently, it is common practice for some engine manufacturers to prioritize the erosion resistance of abradable coatings at the expense of their abradability. To evaluate erosion resistance a "grit blast" erosion test was developed in the late 1970's (Ref 95) which has now evolved into a widely accepted benchmark for evaluation of abradable coatings, now based on ASTM standard G76 (Ref 96) (and according to GE E50TF121 specification). The test involves the use of alumina grit impinging the coated surface at an angle of 20°, using a standardized blast gun equipment with constant air pressure. Of interest is the erosion resistance of various abradable material systems sprayed to different hardness levels and levels of porosity. Oxidation resistant M-CrAl and M-CrAlY coatings that operate at higher temperatures are harder, and would be able to better resist erosion damage. However, these materials need to be sprayed "soft", with porosity, so that the microstructures can be rubbed and cut by different rotor blade materials. As a result, the introduction of porosity will make the coating more friable and lower the coating erosion resistance yet enhance its abradability. For the optimum abradable design, there needs to be a balance between abradability and erosion resistance.

The past decade has also seen the introduction of CMC (Ceramic Matrix Composites) as shroud materials used in the hot section of the turbine for aerospace and power generation turbomachinery. Abradable coatings applied on CMCs (Ref 94, 97) have their own set of unique design challenges and must have sufficient

- CMAS (calcium-magnesium alumina silicate - dust) resistance, for service temperatures above 1200 °C
- Appropriate match of thermal expansion coefficients within the multiple functional layers typically associated with such coating systems.
- Ability to withstand exposure to water vapor (steam)

On the commercial side, abradables need to be capable of being produced at high volumes using a robust manufacturing process with accredited quality control measures in place. Raw materials need to be sourced from vendors and countries that must pass a set of stringent compliance measures. An emphasis on dual sourcing and sustainability of critical materials is required to minimize risk of disruption in supply. A key target is to ensure that the materials can be spray deposited on equipment platforms that deliver competitive performance for extended periods, while minimizing costs to the applicator as much as possible.

On the Original Equipment Manufacturer (OEM) side, the development of a new abradable or abrasive coating must meet the requirements of the Technology Readiness Level (TRL) (Ref 98). At each TRL level, an evaluation of the new solution is carried out based on five categories: components procurement, implementation and inspection expertise, controlling the design values, maintainability/ repairability and eco-design.

The use of abrasive coating on rotor parts can help obtaining the compromise between abradability and erosion resistance. Besides limiting rotor wear during interaction, abrasive coating offers the possibility of increasing the mechanical properties of abradable coating (to obtain better erosion resistance), while also improving the cutting behavior during a rotor/stator interaction. Hard abrasive protection of blade tips is essential for high-pressure turbine sealing applications where they rub against porous

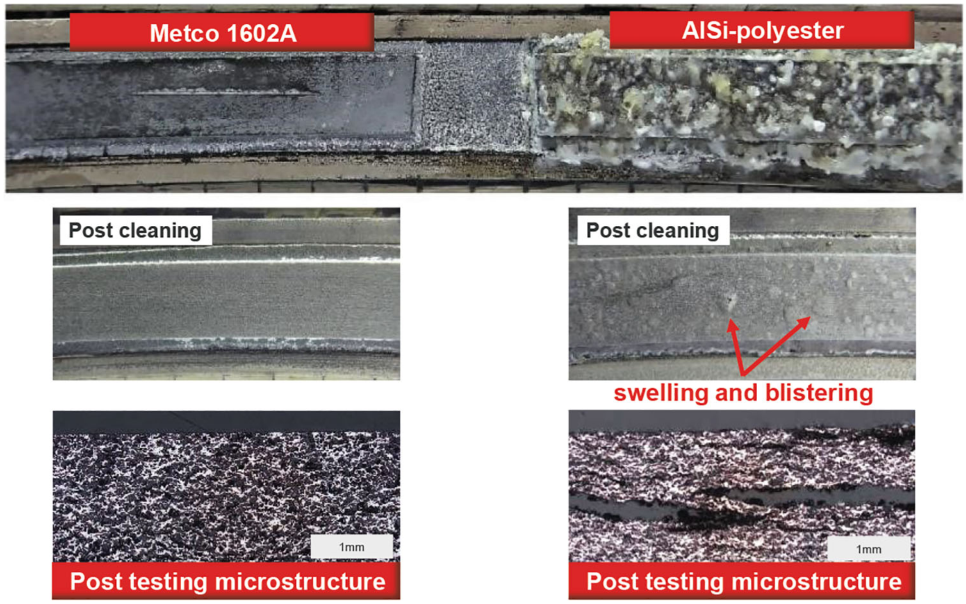

Fig. 18 Comparison between Metco 1602A and a traditional AlSi-polyester abradable coating, sprayed onto a Ti6AlV4 alloy compressor casing after salt bath immersion testing (5% NaCl-water solution, for three weeks at 35 °C). Metco 1602A coating exhibits no corrosion, whereas the traditional AlSi-polyester coating exhibits corrosion and blistering. Photomicrographs of the Metco 1602A coating shows an intact structure that is identical to that of the as-sprayed coating microstructure. The traditional AlSi-polyester coating microstructure exhibits blistering and delamination from corrosion attack.

ceramic-based abradables at temperatures exceeding 1000 °C. State of the art is the use of cubic boron nitride (cBN) abrasive tips (Ref 91) which operate effectively in such high-temperature environments.

Finally, the challenge is also to meet new requirements of engines with the increase of operating temperature or with the development of disruptive engines such as the open rotor.

Advances in Science and Technology to Address Challenges

In some applications, particularly high-cycle multi-environment operations influenced by geographical location, season, and turbine usage, susceptibility to ambient aqueous corrosion, hot corrosion and attack by corrosive dusts such as CMAS at very high temperatures are known factors. At the lower temperature end of compressor sections of both aero and industrial gas turbines, wet corrosion caused by operation in humid and marine environments is a challenge, it's here that alloys such as Cu-Al bronzes are used in combination with polymer fillers to produce composite abradable coatings. While exhibiting excellent corrosion resistance in the toughest of environments they are significantly "harder to cut" especially against Ti alloy rotor components; designers need to consider the use of protective tipping of rotor materials, e.g., through the use of abrasive thermally sprayed aluminum oxides or chromium carbides, or more recently developed hard thin film PVD coatings such as TiAlN (Ref 99), if corrosion protection is paramount, e.g., marine environments.

Other corrosion resistant solutions which allow for more "gentle rubs" against "bare" (untipped) Ti alloy or stainless-steel rotor components have also been developed (Ref 100, Fig. 18). Here a balance of properties needs to be engineered into the coating where rub compatibility is paramount, combined with overall improved general corrosion resistance.

For the newer generation of hydrogen burning turbines, higher surface temperature and higher moisture content as a consequence of hydrogen combustion will lead to more challenges for the turbine abradables used on CMCs. The abradables on CMCs need to be thoroughly tested for steam recession due to the relatively porous nature of the abradable coatings. To date, porous rare-earth silicates such as Ytterbium di-silicate (Ref 94, 97) have been used in various programs, with intense activity to develop improved versions of these that include alternative chemistries.

Concluding Remarks and Future Perspectives

Despite being hugely impactful for all gas turbines in the power generation and aviation sectors, the test rigs across the world for abradable testing are somewhat limited in number, and the abradability test results in published literature are also limited (Ref 91, 92). The pace of discovery and development for both blade tips and abradable coatings need to be accelerated to cope with the demand for "net-zero" aviation. It may be worthwhile considering bringing experts from various OEMs to possibly work together to develop the next generation of abradable systems, or at least to share experiences – hopefully accelerating the delivery of a step change in performance for the engines, which are required to operate hotter and using more sustainably sourced aviation fuel. The engines are required to operate hotter so we can keep the climate cooler.

The abradable developments for the new generation of engines are complex and costly, requiring access to specialist test rigs, which slows down the development of the field. In addition, the abradable failure mechanisms are complex, and validated models can be used to explore further how the materials fail over a range of temperatures and strain rates. The abradable coating chemical composition and microstructure have a strong influence on the mechanical response and the mode of rub interactions in abradable coatings for both compressors and turbines (Ref 90-92). As the abradable coating materials go through reinvigoration to find more efficient abradable coatings, we must not forget the materials that need to be used on the blade tip as the cutting material. A systematic approach is required to develop the blade tip coating and abradable coating in conjunction to rapidly advance the field.

Eco-Friendly Wear-Resistant Coatings

Giovanni Bolelli, David Dublanche, Chang-Jiu Li

Status of the Field

The development of wear-resistant coatings remains a crucial aspect of thermal spray technology. These coatings are widely used across industries, including aerospace. Depending on operating requirements, wear occurs through mechanisms like adhesion, abrasion, erosion, cavitation, fretting, fatigue, often combined with corrosion. Different wear mechanisms necessitate coatings with specific properties, materials, and microstructures.

For eco-friendly coating development, two key aspects must be addressed: devising novel materials, and improving the microstructure control to enhance intersplat bonding through processing. The eco-friendliness of coatings may encompass:

1. Using coating materials and deposition processes with minimal impact on health and environment. For example, coating material formulations containing health-hazardous constituents imply a risk for the operators both during handling of the feedstock powders, and during post-processing operations in which fine dust is generated (e.g., grinding/polishing). They can also pose a more widespread health risk for the general population when these constituents are released during service due to wear and/or corrosion. Coating processes that minimize the generation of overspray and the emission of hazardous dust and fumes are also desirable for improved operator safety.
2. Improving coated component efficiency to reduce energy consumption and emissions by decreasing friction and wear, thus preventing repair-related resource consumption.
3. Ensuring recyclability of worn coatings or coated parts to support circular economy and reduce resource consumption.

The development of eco-friendly coatings involves multiple considerations. A key example is finding replacements for electroplated hard chromium, which combines high hardness (usually in the range of 800-900 HV), machinability, low deposition cost, corrosion resistance, and adhesion strength across various industrial applications. The main concern is the raw material used. The chromium electroplating process uses large tanks of concentrated chromic acid solutions from CrO_3 dissolved in water, requiring 250 g/L of CrO_3. Due to CrO_3's highly toxic, carcinogenic, and mutagenic nature, these volumes are hazardous. While risks can be mitigated through wastewater treatment and safety measures, replacing this technology is often preferred. Regulatory bodies have included CrO_3 and derivatives in the list of substances requiring specific authorization for EU use (Annex XIV of REACH regulation: https://echa.europa.eu/authorisation-list). However, the final coating of metallic chromium is safe, even safer than nickel and cobalt-based coatings, which are sensitizing and carcinogenic agents. Additionally, chromium-plated steel parts can be recycled into new steel, as chromium is one of the major useful steel alloying elements.

Thermal spray processes, particularly High Velocity Oxy-Fuel (HVOF) spraying, have been key alternatives to electroplated chromium. Studies from the 1990 s validated replacing hard chromium with HVOF-sprayed hardmetals in landing gear pistons, followed by further recent research on High Velocity Air-Fuel (HVAF). Laser cladding reached industrial maturity as another alternative. Thermal spraying enables deposition of high hard-phase materials with minimal substrate alteration, while laser cladding produces tough composite coatings metallurgically bonded to the substrate. These processes are less hazardous, using powder or wire feedstock with lower risk of releases and minimal material requirements. Life-cycle analyses show that thermal spray processes are better for human health than Cr(VI)-based electroplating, though WC-Co-based feedstock production causes higher resource consumption and eco-toxicity impacts. Indeed, WC-10 wt.%Co-4 wt.%Cr is among the most common thermal spray materials for anti-wear applications, while laser cladding uses Ni- and Co-based metal matrices with carbide reinforcement. Thus, thermal spray and laser cladded coatings contain hazardous elements that pose risks during post-processing or service. This has driven research into alternative formulations using fewer hazardous materials. In addition to addressing health and safety, the efforts to develop sustainable metal alloy and hardmetal coatings for industrial applications also consider critical raw materials sustainability. Elements like Co and W are classified as critical by industrialized economies, including the EU and USA, due to economic importance and supply risks. Thus, sustainability requires materials that can be procured reliably and responsibly.

The research, carried out by both the industry and academic institution, has already led to innovations like HVOF-sprayed WC-FeCrAl and laser-cladded materials with Fe-based matrices for high-performance applications. Most of the literature reports so far indicate that HVOF-sprayed WC-FeCrAl coatings, for example, exhibit hardness values slightly above 1000 HV0.3; unidirectional ball-on-disk dry sliding wear rates in the range of $\sim 3 \times 10^{-8}$ mm^3/(N m) to $\sim 2 \times 10^{-7}$ mm^3/(N m), depending on the details of the deposition process and the test conditions; and corrosion current densities, measured by electrochemical polarization in various saline and acidic aqueous solutions, in the range of ~ 5 µA/cm^2 to ~ 20 µA/cm^2. These values indicate the potential applicability of HVOF-sprayed WC-FeCrAl coatings in various harsh conditions, though comparative tests with WC-CoCr under identical conditions usually indicate slightly poorer performance. For instance, HVOF-sprayed WC-CoCr coatings often exhibit dry sliding wear rates close to 10^{-8} mm^3/(N m), corrosion current densities ≤ 5 µA/cm^2 and hardness of 1100 - 1400 HV0.3.

The wear resistance of thermal spray coatings also depends on their microstructural features. Thermal spray coatings exhibit generally a lamellar porous structure with limited inter-lamellar bonding (Ref 101, 102). In metal coatings, oxide inclusions between lamellae degrade inter-splat bonding and reduce coating toughness, while ceramic coatings contain intra-splat microcrack networks. Since less than one-third of inter-splat interfaces in refractory ceramic coatings and less than 40% in metal coatings are bonded, unbonded interfaces promote premature spalling of splats during wear. This results in higher wear rates compared to bulk cast materials of identical compositions. In particular, the wear performance of thermal spray coatings depends more on applied load than bulk materials due to lamellar features. At lower loads, coating wear resembles bulk material behavior, but above a critical load, wear rate increases due to accelerated splats delamination. Conversely no such transition occurs in spray-fused bulk-like Ni-based self-fluxing alloy coatings (Ref 102), and thus laser-assisted plasma-sprayed Mo coating with improved inter-splat bonding also exhibits enhanced wear resistance (Ref 103). Therefore, achieving bulk-like coatings with sufficiently bonded splats is essential to increase wear resistance.

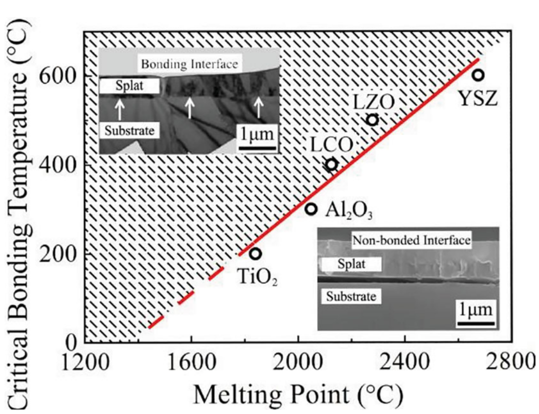

Fig. 19 Relationship between the critical bonding temperature over which ceramic splat bonds chemically to underneath ceramic splats and the melting point of ceramic materials (Ref 101)

Research has shown that sintered bulk-like ceramic coatings can be deposited using the critical bonding temperature (Ref 101), allowing chemical bonding at interfaces with tensile adhesive strengths over 100 MPa. For ceramics melting temperature above 1500 °C, the deposition temperature should exceed the critical bonding temperature shown in Fig. 19. Of course, the base material compatibility to the spraying temperature has to be considered. For oxide ceramics melting below 1500 °C, the impact of molten droplets at ambient temperatures creates chemically bonded splats, enabling sintered bulk-like ceramic coatings through thermal spraying.

For bulk-like metallic coatings, the in-flight oxidation of molten droplets must be prevented. An in-situ deoxidizing strategy using powders with deoxidizers generates oxide-free droplets (Ref 102), enabling dense metal coating deposition. Using Mo-clad Ni- or Fe-based alloy powders heated to ~ 2650 °C, coatings with $> 80\%$ inter-splat bonding can be achieved through shrouded plasma spraying.

Achieving bulk-like properties should especially be considered for wear under dynamic loading conditions such as in erosion, fretting, cavitation and fatigue wear, which are even more sensitive to the coating defects. For example, metallic coatings with oxide inclusions and limited interface bonding exhibit brittle behavior similar to a ceramic material. However, bulk-like dense metal coatings using Mo-clad NiCr powders with limited oxide inclusions and inter-splat bonding increased to 80% demonstrate erosion behavior similar to that of IN718 cast bulk, with higher erosion at shallow angles (Ref 102). In cavitation wear, which occurs for example in the rotating parts of hydraulic machinery and blades in gas turbine, the cavitation rate is proportional to the inter-splat bonding ratio and is sensitive to non-bonded lamellar interfaces. A stainless-steel-based coating with ~ 80% bonding ratio, deposited using Mo-clad stainless steel (SUS304), showed half the cavitation wear rate of a conventional SUS304 coating with < 40% bonding ratio. However, its wear rate remained higher than that of the high-temperature-annealed coating and bulk SUS304 even by a factor of one order (Ref 104). Non-perfect inter-splat bonding significantly degrades the cavitation wear resistance of the coating. Depositing thermal spray coatings with excellent cavitation resistance remains challenging and potentially requires alternatives such as high-speed laser cladding.

In the case of hard metal coatings, HVOF WC-based compositions already exhibit dense microstructures with limited decarburized phases and excellent wear performance. Post-spray annealing could further improve their wear performance through splat interface healing but is rarely used owing to substrate alterations, residual stress from thermal expansion differences, and potential matrix embrittlement from secondary carbides. Thus, creating WC-based cermet coatings with chemically bonded splats remains a challenge. If eco-friendly coatings are considered, the key issues with conventional WC-based hardmetals, as explained above, are health concerns related to Co-based matrices and the supply criticality of W and Co. One way to address them is by producing thin WC-based coatings with smooth surfaces to minimize the consumption of feedstock materials. Traditional WC-based coatings exceed 100 µm in thickness with Ra (Sa) ≈ 3-6 µm, Rz (Sz) ≈ 35-70 µm, but for hard chromium replacement, a sub-100 µm thickness is sufficient owing to the lower wear rates of the WC-based coatings. However, a minimum thickness is required for achieving corrosion resistance, for instance 70 µm on HVOF coated landing gear parts, and so thinner coatings need to be denser to get proper corrosion protection. Moreover, surface roughness requires material removal higher than the Rz (Sz) value during finishing. However, thin and smooth coatings have historically been challenging with thermal spraying, requiring fine powders with sub-micrometric WC particles that face feeding difficulties and thermal alterations during spraying. The HVAF process, with its limited heat input and efficient feeders for smaller particles, has enabled WC-CoCr coatings of 30-50 µm thickness with comparable wear resistance to thicker coatings and Ra (Sa) ≈ 1.5 µm (Ref 105). Although not as smooth as electroplated chromium, this finish requires less finishing material removal.

Another approach is to replace Co as the matrix material while retaining WC as the hard phase. This provides "drop-in" solutions to the issue of the carcinogenicity of cobalt, since Co-free hard metal feedstocks for thermal spraying are commercially available. A variety of WC-Ni compositions have existed since the 1980 s. Research shows that HVOF- and HVAF-sprayed coatings with WC in a Hastelloy-type Ni-alloy matrix perform similarly to WC-10Co4Cr (Ref 106). Owing to the health hazards of Ni, Fe-based compositions have also been introduced (Ref 106). WC-FeCrAl hard metals are commercially used in brake disks. Other Fe-based alloys, such as Fe-Ni-Cr-Mo alloys, have been tested and have occasionally been made available on the market, although they have not yet made a commercial breakthrough. In most cases, WC hard metals with Fe-based matrices are more brittle, exhibit higher tendency to oxidation during spraying, and are less corrosion resistant than those with Co-Cr or Ni-based matrices. Thus, more research is needed to design suitable Fe-based alloy compositions that overcome these problems.

Ti-based matrices (e.g., WC-Ti) could provide a series of benefits, including a lower density (the density of Ti and its most common alloys is in the range of 4.4 to 4.5 g/cm^3, as opposed to Co-8.8 g/cm^3, Ni-8.9 g/cm^3 and Fe-7.9 g/cm^3), which is beneficial both technically and economically. However, these compositions are typically not processable by HVOF and HVAF because of the high melting points of Ti and its alloys. They can be deposited by cold spray (CS) (Ref 107), although deposition efficiency considerations can dictate that the volume fraction of the hard phase is lower than that of conventional hard metals to have sufficient ductility for a fully solid-state deposition process.

Replacing Co as a matrix constituent and WC as a hard phase would solve the safety and criticality issues. However, it is difficult to find hard phases with the same hardness-toughness combination of WC, and hard phase–matrix combinations that exhibit as good a mutual wetting as that between WC and Co-based matrices. For example, the contact angle and work of adhesion between WC and Co at 1420 °C are reportedly 0° and 3.82 J/m^2, whereas for the TiC-Ni couple they are 23° and 3.47 J/m^2, respectively (Ref 108). Although their wear resistance is lower than WC hardmetals at ambient temperature, Cr_3C_2/NiCr compositions are a suitable alternative in number of industrial applications (Ref 109). TiC has been often used as the hard phase with Ni- and Fe-based matrices, such as Ni-20 wt.%Cr, FeCrAl, Fe-Ni-Cr (Ref 110, 111), while NbC was also recently used in NiCr and FeCrMo matrices (Ref 112). In all cases, however, their sliding and abrasive wear rates remain higher than those of WC-CoCr. For example, ball-on-disk testing of HVOF and HVAF TiC- and NbC-based coatings showed sliding wear rates ranging approximately from 10^{-7} to 2×10^{-6} mm^3/(N m), which are intermediate between those of WC-CoCr (close to 10^{-8} mm^3/(N m)) and Cr_3C_2-NiCr (10^{-5} mm^3/(N m),

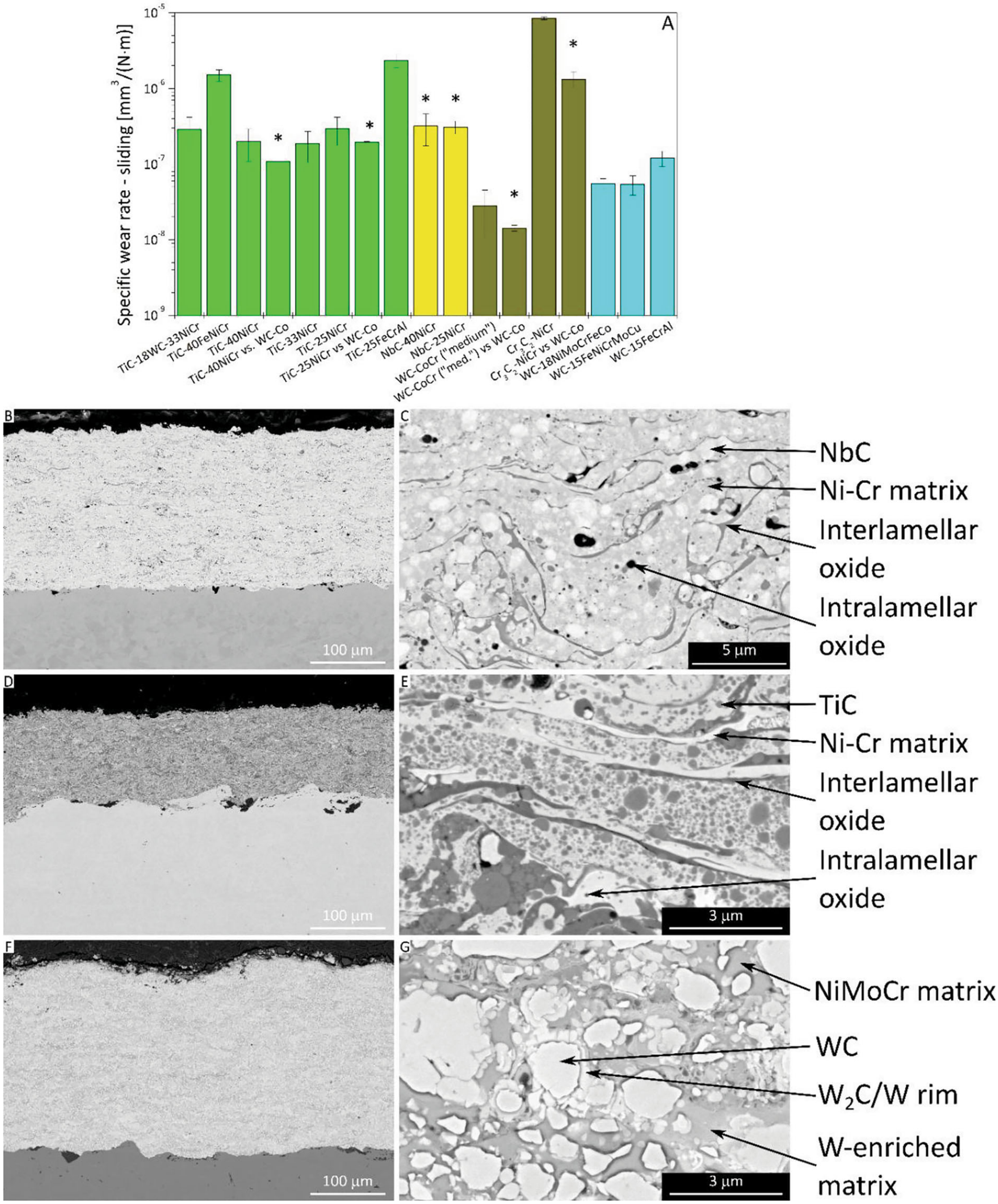

Fig. 20 Examples of alternative hardmetal coatings. Summary of the sliding wear rates measured in unidirectional ball-on-disk tests against Al_2O_3 or WC-6%Co (asterisks) balls, obtained from (Ref 105, 110-112) by averaging the wear rates for coatings with identical compositions but deposited with different parameters (a), and cross-sectional SEM micrographs of HVOF-sprayed NbC-40vol.%(Ni-20 wt.%Cr) (b-c), TiC-40 vol.%(Ni-20 wt.%Cr) (d-e), and WC-18 wt.%NiMoCrFeCo (Ref 106)

(Fig. 20A). Likewise, high-stress abrasion tests often return specific wear rates ~ 2-4 × 10^{-3} mm^3/(N m) for TiC- and NbC-based coatings, while values ≤ 10^{-3} mm^3/(N m) are found under the same conditions with HVOF- and HVAF-sprayed WC-CoCr. Poorer matrix-carbide wettability and increased oxide inclusions in comparison with WC-CoCr are the main issues (Fig. 20B-C, D-E, F-G). WC oxidation forms poorly adherent volatile WO_3, which may not be retained in the coating, whereas nonvolatile Ti- and Nb-based oxides create brittle inter-lamellar stringers. Use of HVAF technology could be beneficial to reduce this oxidation.

Research on bulk hard-metals shows that the wetting of TiC-based materials with metallic matrices is improved by the addition of Mo_2C during powder production. During sintering or spraying, Mo_2C dissolves and reacts with TiC particles to form a $(Mo,Ti)C_{1-x}$ shell, improving matrix wetting and potentially increasing the toughness, although oxidation-related brittleness remains unresolved. Development is needed for matrix/carbide combinations that yield tougher, less oxidized coatings that match the WC-CoCr performance. High-entropy materials, which combine equiatomic amounts of four to six elements, offer novel possibilities through their vast compositional space. High-entropy alloy (HEA) matrices can provide good wetting, ductility, and oxidation resistance, while high-entropy carbides (HECs) could better match the properties of WC. While the thermal spray deposition of HEAs has been extensively reviewed, studies on high-entropy hard metals remain limited. Recent findings show that a TiC-$Al_{0.5}CuCrFeNi_2$ formulation has better abrasive wear resistance than simpler TiC-NiCr systems because of a lower degree of oxidation during spraying. Given the vast possibilities of HEAs and HECs, physical modeling and machine learning methods must be used to identify the optimal coating compositions for specific applications.

Current and Future Challenges

Significant challenges remain in the industrialization of sustainable thermal spray coatings for wear protection. With wear-resistant applications, depositing coatings with a bulk-like microstructure is preferred. Key challenges for bulk-like ceramic coatings include the following:

1) Thermal spray systems must control the in-situ deposition temperature.
2) Low-melting-point oxide ceramics can form bulk-like coatings at ambient temperatures but have lower hardness than refractory ceramics. The development of high-strength low-melting-point ceramics with high toughness can expand their applications.
3) Bulk-like ceramic deposition may generate high thermal stress because it requires the coatings to be deposited at a high deposition temperature (e.g., high substrate surface temperature), requiring process optimization to enhance wear performance.

For bulk-like metal alloy coatings, the main challenge is to determine the plasma spray parameters to heat particles to approximately 2400 °C, necessitating advanced system development. Mo-clad Ni- and Fe-based materials achieve this temperature, producing coatings with high strengths over 150 MPa, but their effective manufacturing process should be developed.

Although WC-based coatings with Ni-based matrices can replace carcinogenic cobalt, they still contain suspected carcinogenic agents. Alternative solutions using Fe-based matrices or WC replacements require further development. Computational approaches combining physical models and machine learning may accelerate the discovery of new compositions to address issues with Fe-based alloys and hard phases like TiC or NbC, particularly brittleness and oxidation during HVOF and HVAF spraying. Novel formulations based on less critical materials can be cheaper, less subject to price fluctuations, and provide savings through low density. However, WC-based feedstock materials benefit from economies of scale owing to large production volumes, making new powder compositions initially more expensive. The success of novel materials depends on early market acceptance across applications to achieve economies of comparable scales. Regulatory changes, such as replacing electroplated hard chromium, are driving research, and additional pressure can arise from potential cobalt restrictions.

Concluding Remarks and Future Perspectives

Eco-friendly wear-resistant thermal spray coatings use materials with minimal health and environmental impact to produce dense microstructures with well bonded splats. For WC-based cermet coatings by HVOF or HVAF, substituting Co and WC with alternative binders and hard phases has been investigated, though novel compositions with superior wear resistance are still developing. Wear performance is dependent on the microstructure of the coating and wear loading conditions. Conventional metal and ceramic coatings show lamellar structures with limited intersplat bonding. Above a critical load, wear behavior transitions from individual splats-dominated to splats-delamination-dominated wear, significantly increasing wear rate. Reasonable wear resistance is achievable only under low-stress conditions below the critical load, while cavitation wear is particularly sensitive to defects. Recent

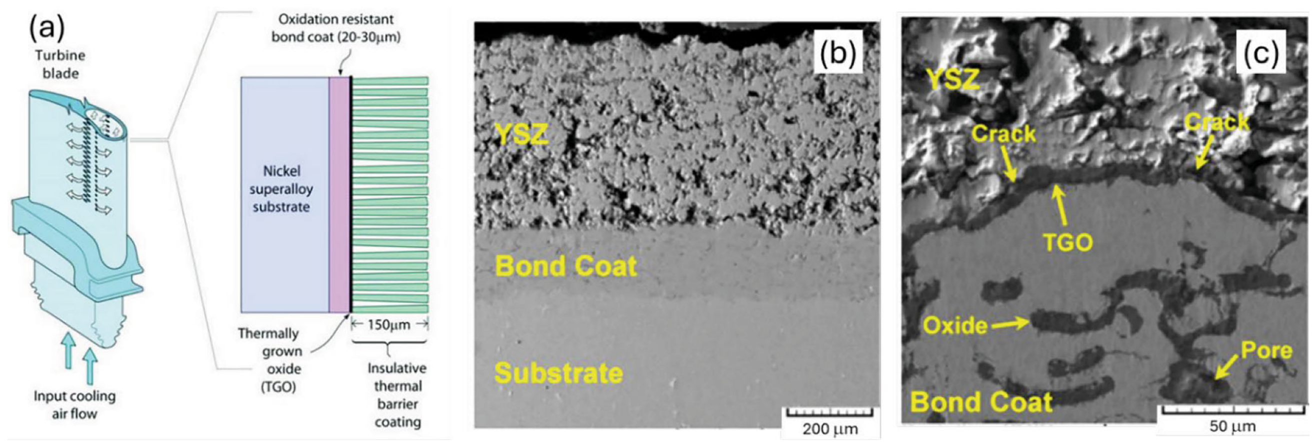

Fig. 21 (a) A schematic showing the architecture of thermal barrier coating in turbine blade, (b) Micrograph showing the bond coat and YSZ top coating on Ni-substrate, and (c) Evincing TGO (thermally grown oxide) after 192 h of oxidation at 1100 °C (Ref 118). (a) reprinted from Ref 113, available under CC BY 3.0 license at IOPScience. (b) and (c) reprinted from *Journal of Alloys and Compounds*, 509, A. Keyvani, M. Saremi, M. Heydarzadeh Sohi, "Oxidation resistance of YSZ-alumina composites compared to normal YSZ TBC coatings at 1100 °C," 8370-8377, Copyright (2011), with permission from Elsevier

studies demonstrate that sintered bulk-like ceramic and cast bulk-like metal alloy coatings can be achieved through material design and process control. Development of oxide ceramics with lower melting points but high strength may yield new wear-resistant materials, as ambient atmosphere spraying produces well-bonded coatings. By designing metal coating materials with deoxidizers and controlling droplet temperature, oxide-free molten metal droplets can be generated by APS. Utilizing spread-fusing, dense metal coatings with metallurgically bonded splats can be deposited, exhibiting ductile behavior and excellent erosion resistance against surface fatigue and dynamic loading conditions.

Acknowledgments

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Anti-oxidation Coatings for High Temperatures

Kantesh Balani, Jonathan Gutleber, Guan-Jun Yang

Status of the Field

High-temperature nickel-based superalloys for gas turbines employ thermal barrier coatings (TBCs), as shown in Fig. 21, to protect against structural deterioration at high-temperature in turbine blades (Ref 113, 114). Directionally solidified columnar grains, equiaxed/single crystals of Ni-alloys and Ti-Al alloys, as well as aluminides (γ-TiAl and Ni_3Al) are also worthy of mention as potential aircraft materials (Ref 115). However, they are not discussed in the current article. YSZ (Yttria-stabilized zirconia)-based top TBCs (100-300 µm) can provide a temperature reduction of 50-600 °C (thermal gradient of 1-2 °C/µm) (Ref 116, 117), thus, enhancing the efficiency of the engine by enabling a higher working temperature. The YSZ-based TBC material is chosen based on the matching of its coefficient of thermal expansion (CTE $\sim$ 7-12 $\times$ 10^{-6} K^{-1}) with that of the Ni-superalloy substrate ($\sim$ 12-16 $\times$ 10^{-6} K^{-1}) while also providing thermal insulation (κ $\sim$ 0.8-1.7 Wm^{-1} K^{-1}) (Ref 114, 117). An MCrAlY-based (M = Ni, Co) metallic bond-coat ($\sim$ 150 µm), shown in Fig. 21(b) (Ref 118), is usually deposited on a Ni-based substrate to serve as a transitional layer to bridge the mechanical and chemical differences between the metallic substrate and the ceramic top coat for thermal barrier applications (Ref 114). A 10 µm thick thermally grown oxide (TGO), Fig. 21(c) (Ref 118), of α-Al_2O_3 with possible oxides of Cr/Ni and $Ni(Al,Cr)_2O_4$ spinel, restricts oxide ion diffusion to the substrate and serves as a naturally integrated interface between the MCrAlY-based bond coat and the top YSZ-based top coat ceramic coating (Ref 114).

Current and Future Challenges

Thermally sprayed YSZ coatings mainly contain a metastable tetragonal prime (*t*') phase and a small fraction of cubic (*c*) and tetragonal (*t*) phases resulting from the

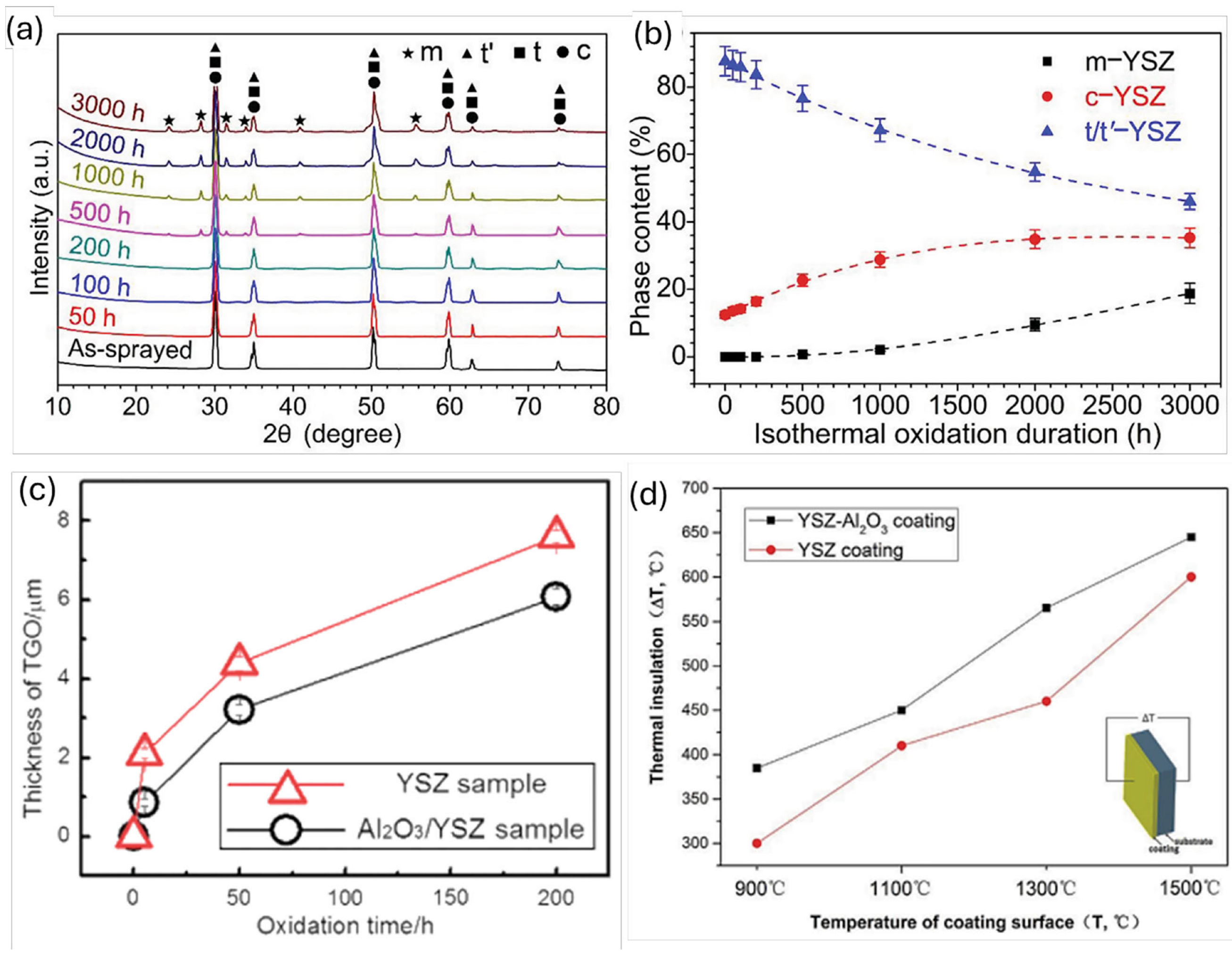

Fig. 22 (a) Effect of thermal oxidation of YSZ on phase change and m-ZrO_2 formation at 1100 °C, (b) corresponding phase content showing increased m- and c-ZrO2 (Ref 116), (c) Estimated thickness of thermally grown oxide (TGO) for isothermal oxidation of Al_2O_3/YSZ and YSZ at 1200 °C (Ref 114), and (d) Thermal insulation of Al_2O_3/YSZ and YSZ coatings (Ref 117). (a) and (b) reprinted from *Ceramics International*, 45, Y.Z. Liu, X.B. Hu, Y.L. Zhu, H. Wei, Vinayak P. Dravid, W.W. Zhang, "Effects of isothermal oxidation on microstructure and mechanical properties of thermal barrier coatings," 8815-8823, Copyright (2019), with permission from Elsevier. (c) reprinted from *Surface & Coatings Technology*, 212, C. Zhu, A. Javed, P. Li, F. Yang, G.Y. Lian, P. Xiao, "A study of the microstructure and oxidation behavior of alumina/yttria-stabilized zirconia (Al2O3/YSZ) thermal barrier coatings," 214-222, Copyright (2012), with permission from Elsevier. (d) reprinted from *Ceramics International*, 43, X. Song, Z. Liu, M. Kong, C. Lin, L. Huang, X. Zheng, Y. Zeng, "Thermal stability of yttria-stabilized zirconia (YSZ) and YSZ-Al2O3 coatings," 14321-14325, Copyright (2017), with permission from Elsevier

unmelted powder (Fig. 22a), which affects the formation of the monoclinic phase (*m*) during thermal oxidation at 1100 °C (Fig. 22b) at the expense of the *t'* phases (Ref 116). Researchers have reported that the TGO thickness (δ_{eq}) in Al_2O_3/YSZ systems is lower than that of YSZ, as estimated in Fig. 2(c) for isothermal oxidation at 1200 °C, using Eq 1 (Ref 114):

$$\delta_{eq} = \frac{\sum S_{ox}}{\sum L_i} \quad \text{(Eq 1)}$$

where S_{ox} is the cross-sectional area of the TGO, and L_i is the cross-sectional interface length of bond coat and top coat. Such an estimation becomes essential because the interface between the bond coat and top coat is not flat/smooth and image-processing estimates make it easier to quantify and compare.

Given that *t* is time in hour, *a* and *b* are constants, and $\boldsymbol{K_p}$ is the reaction rate constant, Kim et al (Ref 119) have concluded that estimating TGO thickness (*d,* in μm) via the Deal Grove model ($d = (\boldsymbol{K_p} \bullet \mathbf{t})^{0.5}$), which mathematically describes the parabolic growth of an oxide layer on a material's surface, is insufficient because it uses constant exponential terms of 0.5. Replacing the oxidation power law behavior ($d = a \bullet t^b$) with the Arrhenius analysis model

($d = k \bullet t^b$), in which the reaction rate constant **"k"** compensates for the dependence on temperature, still requires determining the constant "b" through experimentation (Ref 119).

If $k = A\exp((-E_a)/RT)$, where A is a constant, E_a is the activation energy, R is the gas constant (8.314 kJ/mol K), and T is the temperature (K), then k can be inserted as $k = 1/T \log(P/P_0)$, where P is the characteristic value (e.g., thickness) of the TGO and P_0 is the initial characteristic value of the TGO (Ref 119). Accordingly, k can be expressed as a linear function: $\log k = 20.358 - 35543/T$, which is required for predicting TGO growth. The structure constant (n) is inversely proportional to the unit thickness per 100 μm (h) and the percentage porosity (V) of the top coating. In other words, a thin, porous top coat will facilitate the permeation of O_2 for TGO growth. It can be predicted as follows: $n = 0.2157 + 1.3898$ (1/hV) (Ref 119). The structure constant was evaluated as 0.386 for TC (#1) and 0.274 for TC (#2) at 1100 °C. TGO thickness (d) can now be estimated as $d = A.k^n\ t^n$, where k accounts for temperature dependence and n accounts for structural characteristics. A comparison with the experimental measurement of TGO thickness (with a least squares fit for the TC (#1) sample measured over a prolonged degradation period) provided a value for the constant A of 4.616. The errors in predicting the TGO thicknesses of TC (#1) and TC (#2) were 12.8 and 8.7%, respectively. It should be noted that for temperature ranges of 1100-1200 °C, the thickness of TGO increased from 2.5-5 μm after 100 h to 5-7.5 μm after 400-600 h. Even after 1200 h at 1100 °C, the TGO thickness was ~ 7 μm (Ref 119). The outer oxygen-resistant top coat of the YAG as dual ceramic layer with YSZ also exhibited reduced TGO growth (Fig. 22c).

In addition, the lower ionic conductivity and interlamellar scattering of the top Al_2O_3/YSZ coating ($\sim 1.1 \times 10^{-4}$ Sm^{-1}, (Ref 114) result in superior thermal insulation via phonon scattering (Ref 117) (Fig. 22d) compared to that of the YSZ coating ($\sim 3.2 \times 10^{-4}$ Sm^{-1}, (Ref 114)). Phase stability of the tetragonal (t') zirconia phase can be determined by x-ray diffraction analysis, where the phase fraction of the monoclinic (m) zirconia phase (v_m) can be calculated using Eq 2 and 3 (Ref 114, 120):

$$v_m = \frac{1.311\chi_m}{1 + 0.311\chi_m} \quad \text{(Eq 2)}$$

where

$$\chi_m = \frac{I_m(\bar{1}11) + I_m(111)}{I_m(\bar{1}11) + I_m(111) + I_{t'}(111)} \quad \text{(Eq 3)}$$

where I_m and $I_{t'}$ are the intensity of the m-zirconia and t'-zirconia phases, respectively.

The initial phases in YSZ and Al_2O_3/YSZ coatings were retained after annealing at 1500 °C annealing for 50 h. However, $t' \rightarrow$ m-ZrO_2 phase transformation was observed in YSZ coatings after annealing at 1700 °C for 50 h (Ref 116). Conversely, t'-ZrO_2 retention was observed in Al_2O_3/YSZ coatings after annealing at 1700 °C for 50 h (Ref 117), thus, confirming the role of Al_2O_3 in stabilizing the tetragonal (t') zirconia phase. In addition, significant improvements in spallation and cracking resistance were observed in the Al_2O_3/YSZ coatings even after 244 h of oxidation at 1100 °C (Ref 118), which may be due to its low thermal conductivity ($\sim$ 0.9 Wm^{-1} K^{-1}) (Ref 117). CeO_2 doping in YSZ results in lower TGO growth and enhanced t'-zirconia stability leading to superior TBC performance (Ref 121).

Advances in Science and Technology to Address Challenges

Although it is still in the initial stage and has not yet been proven or applied in industry, the enhanced reliability of Al_2O_3/YSZ-based thermal barrier coatings is indicated by an engineering bi-modal microstructure (Fig. 23a). In this microstructure, the nanostructured regions (NR) are expected to absorb damage and provide compliance, while the microstructured (MR) regions are expected to act as strengthening scaffolds (Ref 122). Concurrently, the nanostructured regions in Fig. 23(b) have an enhanced Weibull modulus (~ 6.3 and 4.0 for hardness (H) and Young's modulus (E), respectively), compared to the microstructured regions (~ 4.1 and 2.4 for H and E, respectively), in Al_2O_3-YSZ coatings (Ref 122). Deposition of Al_2O_3/YSZ alone (Fig. 3c) has been shown to delaminate at the bond coat (Fig. 23d) after 51 cycles of 15-min exposure at 1100 °C followed by water quenching. However, using the YSZ interlayer to match the CTE between bond coat and Al_2O_3/YSZ topcoat (Fig. 23e) appears to resist delamination (Fig. 23f) after this cyclic exposure (Ref 123). Thus, depositing compositionally graded layers from the bond coat to the top coat may be useful, but it would require appropriate powder feeding and control. $MoSi_2$/WSi_2 coatings have shown considerable protection up to ~ 1700 °C for 50 h. However, to achieve enhanced protection, a NbB_2-Nb_3B_2 barrier layer is deposited with 10% ZrB_2 + 5% YSZ-modified Si-Mo-18%W coatings on Nb-alloys (Ref 124).

Lanthanum zirconate ($La_2Zr_2O_7$) is a promising alternative to traditional thermal barrier coatings due to its low thermal conductivity (1.5-1.8 Wm^{-1} K^{-1}) and lack of phase transformation until its melting point of approximately 2250 °C. It is a promising substitute for yttria-stabilized zirconia (YSZ), which has a thermal conductivity of

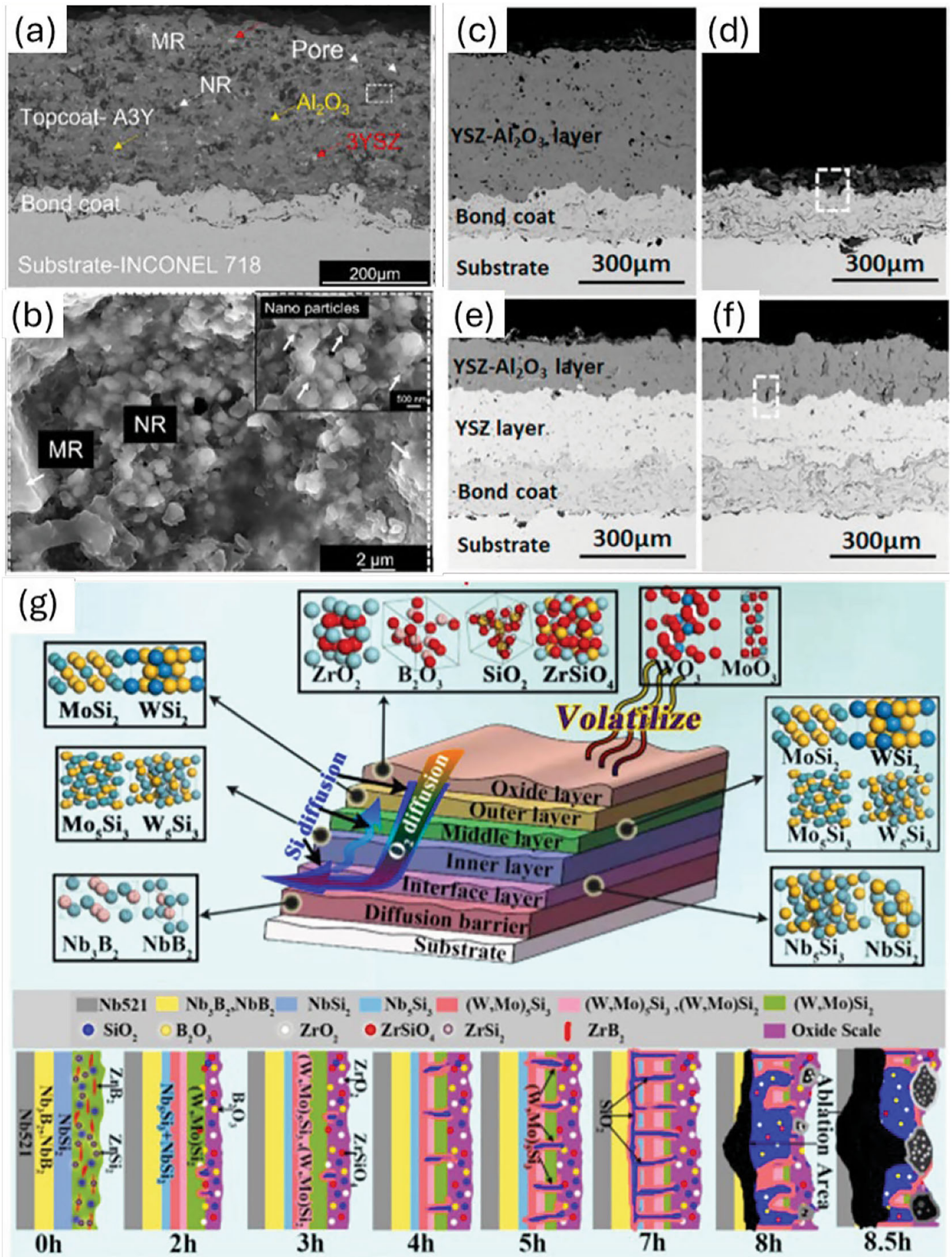

Fig. 23 (a) Bimodal microstructure showing nanostructured (NR) and microstructured regions (MR) with (b) presence of partially sintered NR in Al_2O_3-YSZ plasma sprayed coating (Ref 122), (c) Deposition of Al_2O_3/YSZ, and d) its delamination at interface of bond-coat and top-coat, (e) deposition of Al_2O_3/YSZ with YSZ interlayer exhibiting: (f) intact top-coat after 51 thermal cycles of 15 min exposure at 1100 °C followed by water-quenching (Ref 123), and (g) schematic of cross-section of 10ZrB2-5%YSZ with boride (NbB_2-Nb_3B_2) diffusion barrier on Si-Mo-18%W coating on Nb alloy (Ref 124). (a) and (b) reprinted from *Surface & Coatings Technology*, 462, S. Ponnapureddy, A. Bhadauria, S. Bajpai, A. Tiwari, K.K. Pandey, A.K. Keshri, K. Balani, "Enhanced reliability with bimodal microstructure and transformation-induced toughening in Al2O3-YSZ-based thermal barrier coatings," 129488, Copyright (2023), with permission from Elsevier. (c-f) reprinted from *Vacuum*, 162, X. Song, J. Zhang, Z. Liu, C. Jiang, C. Lin, Y. Zeng, "Thermal shock resistance of YSZ, YSZ-Al2O3 and YSZ-Al2O3/YSZ coatings," 150-155, Copyright (2019), with permission from Elsevier. (g) reprinted from *Corrosion Science*, 195, Y. Zhang, S. Liu, X. Zhoua, G. Zhao, J. Liu, H. Shen, Z. Cai, X. Zhao, L. Xiao, "Ultra-high temperature oxidation behavior of ZrB2/YSZ modified Si-Mo-W coating with a diffusion barrier on niobium alloy," 109977, Copyright (2022), with permission from Elsevier

0.9-1.2 Wm^{-1} K^{-1} and undergoes a phase transition from the tetragonal to cubic phase above 1200 °C. (Ref 125). Similarly, $GdAlO_3/Gd_2Zr_2O_7$ -based thermal barrier coatings also exhibit low thermal conductivity (~ 1.5-2.5 Wm^{-1} K^{-1}) at 1000 °C and phase stability up to 1300 °C (Ref 126). Wang et. al (Ref 127) have utilized a data-driven approach to identify five potential high-entropy ceramic silicates as thermally insulating materials with a thermal conductivity of 0.93-1.22 Wm^{-1} K^{-1}, and three that are stable (with no phase change) up to 1500 °C. These are: (i) $(Yb_{0.2}Lu_{0.2}Ho_{0.2}Gd_{0.2}Dy_{0.2})_2Si_2O_7$, (ii) $(Yb_{0.2}Y_{0.2}Er_{0.2}Lu_{0.2}Dy_{0.2})_2Si_2O_7$, and (iii) $(Yb_{0.2}Y_{0.2}Sc_{0.2}Lu_{0.2}Dy_{0.2})_2Si_2O_7$, but with a lower thermal expansion coefficient of 3.14-3.84 × 10^{-6} K^{-1}, from room temperature up to 1500 °C. Furthermore, Sharobem, et al. (Ref 128) demonstrated a computational oxide development process for complex oxide TBC materials with low thermal conductivity (~ 0.75-1.17 Wm^{-1} K^{-1}). This is the first work to demonstrate the deposition and properties of plasma-sprayed high-entropy oxide materials.

Plasma-enhanced chemical vapor deposition (PE-CVD) has emerged as a technique that can generate a fully cubic nanostructured YSZ structure, which is not typically achieved via traditional thermal processing techniques (Ref 124). Though PE-CVD YSZ coatings are promising, they are currently limited to laboratory-scale production and require further development for commercialization. Their properties, performance, and reliability under real-life conditions also need to be evaluated for industrial systems. Metallorganic precursors can react and deposit high-purity nanostructured cubic zirconia with a columnar microstructure at temperatures of ~ 500-800 °C and plasma powers of 50-250 W, which is preferred for thermal barrier applications (Ref 129). Electron beam physical vapor deposition (EB-PVD) and air plasma spray are popular techniques because they produce columnar-grained microstructures. Spallation occurs at the TGO and topcoat interface (Ref 130).

The formation of new, dense alumina (α-Al_2O_3) due to the diffusion of oxide ions (from the atmosphere or zirconia) to aluminum ions in the bond coat reduces the TGO growth rate. However, the formation of mixed oxides such as $(Cr, Al)_2O_3$, $Ni(Cr, Al)_2O_4$, and NiO results in a sharp increase in the TGO growth rate (Ref 131, 132). The protrusions, voids, and microcracks that are typical of an air plasma sprayed structure enhance oxidation and the formation of a TGO (Fig. 24a-d) (Ref 130). Modeling the TGO growth and swelling with each thermal cycle (two hours at 1000 °C followed by cooling to 20 °C in five minutes) shows that TGO growth and lateral growth strain develop due to thickening with an increase in total oxidation time (Fig. 24e and f) (Ref 130). Computational modeling of the thermal expansion coefficient mismatch between the TGO (~ 9.80 × 10^{-6} K^{-1} at ~ 1100 °C) and the top coat (~ 10.34 × 10^{-6} K^{-1}) (Ref 130, 132) has shown that the mismatch induces sufficient growth stresses. Normal compressive stresses reach a maximum of − 907 MPa (Fig. 24g) and shear stresses reach a maximum of 771 MPa (Fig. 24h) (Ref 132). These stresses can trigger premature cracking (Fig. 24i) and result in TBC spallation after ~ 100 thermal cycles (Ref 20). Conversely, TGO creep delays interface cracking by accommodating defect regions and shifting the fracture location (Ref 132).

Concluding Remarks and Future Perspectives

In summary, thermal barrier applications require service temperatures exceeding 1500 °C for extended periods in gas turbines in aerospace engines, and the Al_2O_3/YSZ system has demonstrated its potential. Engineering a bimodal microstructure in Al_2O_3/YSZ TBCs can toughen the material to tolerate damage in nanostructured regions while strengthening it in microstructured regions. Other potential La- and Sc-based Zr_2O_7 thermal barrier coatings and high-entropy ceramics may have insulation capabilities for applications exceeding 1500 °C. However, achieving columnar grains via plasma-enhanced chemical vapor deposition to enhance loading and the presence of strain-compliant vertical cracks remains a key challenge. This process must also restrict oxide ion diffusion to form TGO, and restrict growth strain (along the thickness and laterally) while encouraging TGO creep for damage tolerance without permitting gas permeation. In this case, a layered top coat of $GdAlO_3/Gd_2Zr_2O_7$ may be beneficial. Spallation of TBCs largely depends on compliance with TGO. Strict control of the thickness and distribution of growth stresses during the thermal oxidation of the bond coat results in the formation of TGO and the generation of an oxygen barrier as well as stable α-Al_2O_3 at the TGO, which provides relief.

Durable Anti-icing Coatings

Ali Dolatabadi, Julien Escobar, Xianghui Hou, André McDonald

Status of the Field

Ice accretion on surfaces, especially on airfoil structures, poses a significant challenge in industries such as aeronautics and wind energy, where it can cause disruption of boundary layers, increase drag, adversely affect aerodynamic or structural stability, and pose serious safety

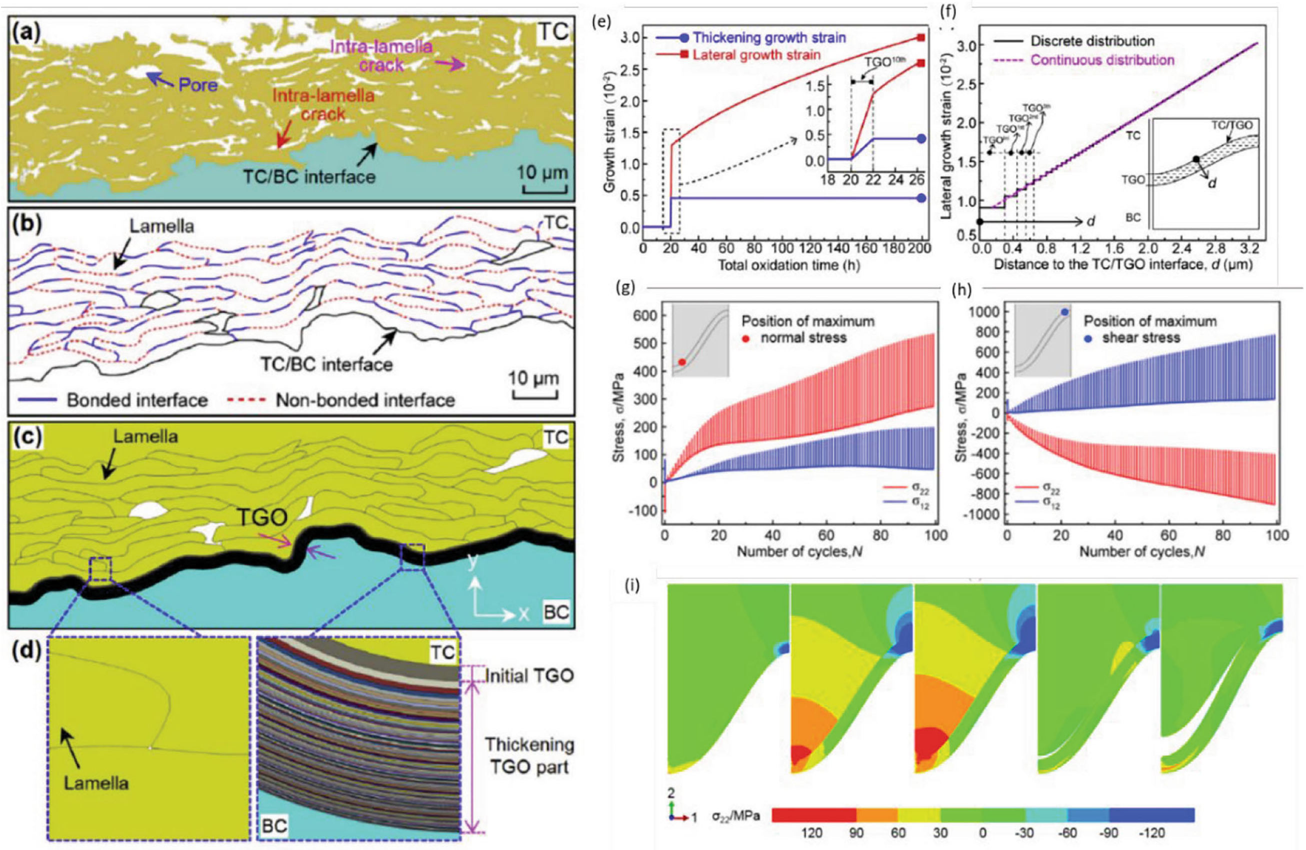

Fig. 24 (a-d) Schematic showing the thickening of TGO with thermal cycle due to oxide diffusion from atmosphere through defects/voids and microcracks in top-coating, (e) TGO thickening growth strain, and (f) lateral growth strain (Ref 130), leading to development of (g) normal stress, and (h) shear stress with (i) crack emanating at top-coat and TGO interface (Ref 132). (a-f) reprinted from *Ceramics International*, 46, Z.Y. Wei, H.N. Cai, "Comprehensive effects of TGO growth on the stress characteristic and delamination mechanism in lamellar structured thermal barrier coatings," 2220-2237, Copyright (2020), with permission from Elsevier. (g-i) reprinted from *Ceramics International*, 47, Ya-Ping Huang, Zhi-Yuan Wei, Hong-Neng Cai, Yang Liu, Xue-Cheng Han, "The effects of TGO growth stress and creep rate on TC/TGO interface cracking in APS thermal barrier coatings," 24760-24769, Copyright (2021), with permission from Elsevier

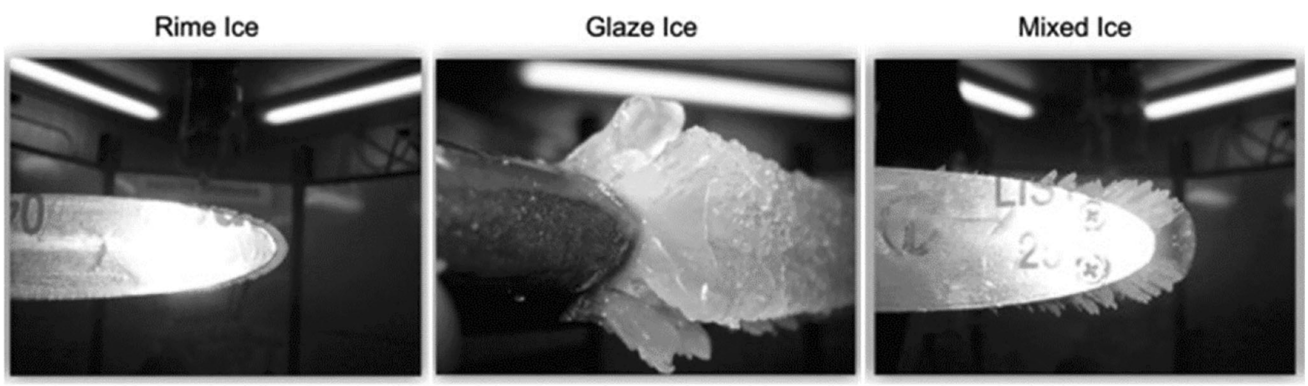

Fig. 25 Forms of ice: Rime, glaze, and mixed ice (Ref 133). Used with permission of SAE International, from "An experimental correlation between rotor test and wind tunnel ice shapes on NACA 0012 airfoils," Y. Han, J. Palacios, E. Smith, *Proceedings of the 2011-38-0092, SAE 2011 International Conference on Aircraft and Engine Icing and Ground Deicin, Chicago, 2011*; permission conveyed through Copyright Clearance Center, Inc

problems. Ice formation occurs when supercooled water droplets freeze upon contact with a surface, influenced by factors such as temperature, humidity, and wind speed. Different types of ice, including glaze ice (dense and adhesive), rime ice (brittle and opaque), and mixed ice, present unique challenges (Fig. 25).

In the aerospace sector, ice accumulation on aircraft wings, engines, and rotor blades can alter aerodynamics, increasing drag and reducing lift, potentially leading to dangerous failures. Previous studies (Ref 134) have shown that mass and aerodynamic imbalance of airfoil structures will occur due to ice accretion, even in the early stages of ice growth. These imbalances will cause higher fatigue and dynamic loads and increase the excitation of edgewise vibrations. Similarly, in wind energy, ice on turbine blades disrupts efficiency and increases mechanical stress, reducing power output and risking structural damage. Power lines and infrastructure are also susceptible to damage or other failure, where ice loading can cause mechanical failures and power outages.

To combat ice accretion, industries use both anti-icing and de-icing strategies. Anti-icing methods aim to prevent ice formation using hydrophobic and icephobic (or glaciophobic) coatings that repel water and reduce ice adhesion. Electro-thermal systems, such as embedded heating elements, maintain surfaces above freezing, while chemical agents like glycol-based fluids inhibit initial ice accumulation. Surface texturing, achieved through micro/nano-structured designs, minimizes ice adhesion and promotes shedding via Cassie state contact at the solid/ice interface.

When ice formation occurs, de-icing techniques become necessary. Thermal methods, including electric heating elements, hot air systems, and infrared heating, effectively melt ice on critical surfaces. Mechanical methods, such as vibration, pneumatic de-icing boots, and robotic systems, physically remove ice. Chemical de-icers, like glycol- and salt-based solutions, lower the freezing point of water, facilitating ice dissolution.

Hydrophobic and icephobic coatings play a crucial role in reducing ice adhesion, either by repelling water droplets or specifically minimizing ice adhesion forces. Their effectiveness depends on chemical composition and surface microstructure. Low surface energy materials, such as fluoropolymers (e.g., Polytetrafluoroethylene) and silicone-based coatings, prevent strong water adhesion. Lubricant-infused surfaces, like slippery liquid-infused porous surfaces (SLIPS), create a slippery barrier that hinders ice accumulation.

Current and Future Challenges

Active anti-icing systems, to prevent the initial accretion of ice on the surface, have been developed, and some include the use of electrical heating wires embedded within the blade, indirect heating with warm air inside the blade and heat conduction to the surface, and microwave heating. These methodologies have inherent problems, which include positioning of the heating wires in the blade to avoid potential structural issues, the generation of high dynamic loads, and the creation of concentrated localized “hot spots” on the surface, which leads to high-temperature degradation of airfoil structures. Also, microwave heating has never been successfully implemented.

Durability is considered a major barrier for the applications of icephobic coatings in the modern industries, especially due to the low erosion resistance of these coating treatments against solid particle, ice, and liquid water droplet impingement. Besides the weathering resistance to UV exposure, thermal aging and chemical exposure, icephobic coatings must remain functional under working environments. The latter implies that the long-term coating functionality needs to be verified, not only through the lens of material durability, but also through durability of its functionalities in relevant environmental conditions. To date, an ice protective surface is typically considered effective when its ice adhesion strength remains below 100 kPa. However, achieving and maintaining such performance over time remains challenging. Most reported coatings demonstrate durability over 10 to 15 icing/de-icing cycles, beyond which degradation in performance is frequently observed. Furthermore, the evaluation of long-term resistance is complicated by the variability in sand or water erosion test conditions across the literature (Ref 135), which limits direct comparability and highlights the need for standardized testing protocols.

The commercial maturity of icephobic coatings may also be limited by high material and processing costs, as well as challenges in achieving consistent repeatability. For example, producing specific superhydrophobic coatings or surfaces often requires dedicated techniques that can be difficult to scale for large structures, making them less practical for mass production. Furthermore, the effectiveness of these surfaces depends on delicate micro- or nanoscale features, such as textured peaks, which are vulnerable to degradation from erosion or repeated de-icing cycles.

Advances in Science and Technology to Address Challenges

Among fabrication techniques, thermal spraying has emerged as a versatile and scalable method for producing functional coatings with strong mechanical and environmental durability. Techniques such as HVOF, plasma spray, flame spray, and cold spray enable large-scale coating deposition with tunable properties. As an example, spray deposition of metal coatings onto polymer composite substrates has been employed by industry practitioners to address ice accretion in the aerospace field. Rooks (Ref 136) fabricated an electro-thermal icing protection system for polymer-matrix composite aircraft structures. In this real-world test case, plasma spraying was employed to produce embedded metallic layer heating elements for prevention of ice accumulation or de-icing activities.

One approach was to produce hard and robust metallic/ceramic coatings using thermal spraying, followed by subsequent surface functionalization with low surface-energy substances to obtain stable hydrophobicity and icephobicity (Ref 137). Reduced ice adhesion strength and energy consumption in the de-icing process had been demonstrated by such a two-step process. Recent studies have advanced the development of thermally sprayed anti-icing coatings made of hydrophobic plastic materials that demonstrated ice adhesion strength of only one-seventh of that on aluminum (Ref 138). Other approaches integrate embedded heating elements directly into the coating layers to enable active de-icing or anti-icing or use Joule heating energy generation by the coating, which can be triggered when needed, thereby reducing energy consumption (Ref 139, 140). For example, Lamarre et al. (Ref 141) have assessed and modeled the performance of FeCrAl wire-fed flame-sprayed coatings as heating elements on titanium substrates, obtaining temperatures above 450 °C when 5 W/cm^2 of power was applied.

In icing conditions, it was recently found that the interfacial toughness with ice dominates ice shedding at large scales (> 1 cm), which applies better to applications like rotary blades of helicopters or wind turbines. Recently, it has been shown that quasicrystalline-based composite coatings can be engineered via the high-velocity oxy-fuel (HVOF) spraying process to offer erosion resistance and promising anti-icing behavior due to their unique microstructure and interfacial properties (Ref 142, 143). They highlighted how surface engineering can produce coatings with extremely low ice adhesion even after multiple icing/de-icing cycles. In addition, icephobic composite coatings have been developed to resolve the inherent trade-off between surface icephobicity and mechanical durability, based on mechanical and chemical heterogeneity in the structures, including the strategies of multi-components (Ref 144), microporous metallic skeletons and fibrous construction, etc. Low ice adhesion strength could be well-maintained due to significantly amplified stress concentration at ice/solid interface.

Inspired by the lotus leaf effect, superhydrophobic surfaces exhibit water contact angles above 150° and low sliding angles by combining low-surface-energy chemistry with micro/nanostructured roughness. Suspension plasma-sprayed titania coatings functionalized with stearic acid exhibit excellent water repellency and maintain performance under environmental exposure (Ref 145). Despite these advances, long-term durability under abrasion, UV, and thermal fatigue remains a concern. Superhydrophobic coatings can lose function due to degradation of surface structures or chemistry. Current research focuses on improving adhesion between layers (e.g., through silica primers like TEOS) (Ref 146), enhancing mechanical robustness, and creating multifunctional coatings with anti-corrosion and self-healing capabilities (Ref 147). It is important to mention that studies report that superhydrophobic surfaces lose their anti-icing effect when ice forms by vapor frosting rather than liquid freezing, as ice nucleates in surface pores and firmly anchors to them, potentially damaging the asperities.

Concluding Remarks and Future Perspectives

Icephobic coatings can effectively reduce surface ice accumulation and lower ice adhesion strength under specific environmental conditions. However, their mechanical durability, environmental adaptability, and reliability still fail to meet the anti-icing/de-icing requirements in complex environments. Under extreme conditions such as ultra-low temperatures, high humidity, and erosion, these coatings struggle to maintain an ice-free surface. Therefore, to ensure timely and reliable anti-icing/de-icing performance, there has been growing attention from both academia and industry toward adopting hybrid ice protection strategies that combine passive icephobic coatings and active anti/de-icing approaches. Thermal spray offers an industrially viable route to develop next-generation anti-icing surfaces. As these coatings are developed further, they can be positioned to serve as replacements for heat tracers on liquid pipelines in ultra-cold environments or as energy generating surfaces to support high heat flux liquid boiling heat transfer. With applications in aircraft components, power lines, wind turbines, and cold-region infrastructure, these coatings align with sustainability goals and offer broad potential for commercialization.

Advanced Cold Spray Coatings for Aerospace Applications

Bertrand Jodoin, Rocco Lupoi, Aleksandra Nastic, Shuo Yin and Tianqi Zhu

Status of the Field

Cold Spray (CS) has emerged as a promising technology in aerospace, offering solid-state deposition that prevents melting and thereby minimizes thermal distortion while enabling the use of heat-sensitive materials. With the aviation sector increasingly focused on sustainability, CS contributes to greener manufacturing by reducing both energy input and material waste. Its capabilities have been demonstrated in lightweight structural applications, such as the fabrication of a topology-optimized GE jet engine bracket using Ti-6.1TiC feedstock (Ref 148) and in the on-site repair of aluminum-based stiffeners and fuselage ribs with high-strength alloys (Ref 149). Beyond structural builds, CS enables functional coatings crucial for aerospace operations: Cr_3C_2-NiCr coatings provide erosion and corrosion resistance for compressor components (Ref 150); anti-icing surfaces with hydrophobic and thermally conductive properties delay ice formation (Ref 151); and thermal barrier coatings are being explored to protect engine parts under extreme heat (Ref 149).

Current and Future Challenges

CS is an advanced solid-state deposition process that enables the deposition of metals, ceramics, and polymers at significantly lower temperatures than conventional thermal spray methods, preventing material degradation. While it has unique applications in aerospace, medical, and energy sectors, its large-scale industrial adoption still faces technical challenges.

Achieving strong adhesion between the cold-sprayed coating and the substrate remains a critical challenge, particularly in cases requiring the deposition of specialized materials or coatings on complex geometries (Ref 149). The flexibility of material selection is restricted due to the limited ability of CS to process certain materials, such as low-melting-point, brittle or highly deformable alloys, thereby reducing its compatibility with a broader range of materials (Ref 149). For low-melting-point or easily deformable substrates, the current CS technology still exhibits limitations and requires further process optimization. Deposition efficiency and thickness control in CS technology require further breakthroughs. Although significant progress has been made in deposition efficiency and thickness control, additional improvements are needed to meet future process requirements, especially in achieving uniform multi-material deposition. Another pressing issue is the need to improve the uniformity of multi-material deposition, which is limited by the differences in the physical properties of materials, such as thermal expansion coefficients. Advanced characterization and modeling techniques, including microstructural analysis and finite element simulations, contribute to optimizing material selection and deposition parameters (Ref 149). However, their application is hindered by the complexity of modeling and the high sensitivity of simulations to input parameters, including both intrinsic material properties (e.g., yield strength, thermal expansion) and critical factors such as powder quality, particle size and velocity (Ref 149). Thus, further advancements in predictive accuracy and computational efficiency are required.

Along with other additive manufacturing technologies such as Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS), CS faces common challenges in aerospace applications (Ref 152). Technically, cost, material properties and bonding remain a core constraint: DMLS relies on high-cost metal powders, FDM is limited by the properties of polymers, and CS faces interface delamination risks in multi-material deposition, particularly at the interfaces between deposited layers and between coating and substrate. Extensive post-processing is common: SLS and DMLS parts require sanding or chemical treatment to improve surface properties by reducing material defects, adding complexity to the process. Limited build volume and slower production rates further restrict large-scale adoption compared to subtractive manufacturing. Economically, the high cost of specialized equipment, working gas consumption and feedstock materials necessitates research efforts to enhance powder utilization, reduce material and gas consumption, and improve deposition efficiency, which makes additive manufacturing less competitive than conventional technologies for large-scale production. Scalability is another hurdle, particularly in achieving uniform coatings over large areas while simultaneously reducing production costs and enhancing process stability and repeatability to meet the stringent requirements of aerospace applications. Regulatory barriers are particularly rigorous in the aerospace industry, where both CS coatings and SLS/DMLS components require rigorous testing to ensure precision and reliability (Ref 152). Moreover, sustainable development demands minimizing material waste and reducing energy consumption to align with current and future global environmental goals (Ref 149). Addressing these economic, technical, and regulatory barriers will be critical for expanding the applications of

CS and additive manufacturing in high-performance industries.

Advances in Science and Technology to Address Challenges

These challenges currently hinder the broader adoption of CS in sectors such as the aerospace sector, where strict control over coating properties, refined process optimization, and a robust fundamental understanding of the deposition mechanisms are essential. Beyond these functional and technical requirements, CS—as with other additive manufacturing technologies—must evolve in alignment with the Industry 4.0 paradigm. Concurrently, the development and implementation of CS processes must also embrace the principles of the circular economy, emphasizing resource efficiency, material recyclability, and environmental sustainability to meet the demands of modern manufacturing ecosystems (Ref 153).

Data-driven approaches, including machine learning and advanced numerical modeling, are increasingly at the forefront of research aimed at improving geometry build-up accuracy, process control, and final product quality in CS manufacturing. Recent studies have demonstrated the potential of continuous toolpath planning and three-dimensional volume construction prediction to optimize CS deposition by forecasting effective manufacturing strategies and minimizing material waste (Ref 154). While precise toolpath definition is essential for producing near-net-shape components, current research is also focusing on the integration of non-destructive inspection and in situ monitoring systems to establish real-time feedback control loops. Such systems should enable dynamic adjustments to coating parameters, thereby ensuring consistent material properties throughout the build process. For instance, aeroacoustic measurements have shown promise in detecting deviations from nominal process conditions and identifying interfacial delamination or bonding anomalies (Ref 155). Additionally, laser ultrasonic techniques have been employed to detect subsurface flaws during coating build-up, offering a valuable tool for early defect detection and quality assurance in CS-based additive manufacturing.

In addition to the need for meticulous process control and the integration of CS into smart manufacturing frameworks aligned with Industry 4.0 objectives, recent studies have demonstrated that the performance and efficiency of CS can be significantly enhanced through the use of phase-changing propellant gases, such as steam, in place of conventional inert gases like nitrogen or compressed air (Ref 156). This novel approach introduces a more sustainable and cost-effective alternative, aligning with green manufacturing goals by reducing environmental impact and improving overall resource utilization. Furthermore, the inherent recyclability of steam enables its integration into a closed-loop system, wherein the vapor can be condensed, captured, and reused within the CS process—thereby supporting circular economy principles and further minimizing energy and material waste.

Beyond advances in single-material deposition, the application of functionally graded materials (FGMs) using CS has emerged as a promising strategy to address interfacial delamination arising from mismatched thermal expansion in multi-material systems (Ref 157). By tailoring the composition across the coating thickness, FGMs enable a gradual transition in material properties, thereby reducing thermal stresses and enhancing structural integrity. This can be achieved through the use of dual powder feeding systems, wherein two distinct feedstocks are introduced at controlled, time-dependent rates to produce a spatially varying composition. Such process control facilitates the optimization of the coating's final thermo-mechanical behavior, aligning it with specific performance requirements.

In addition to addressing delamination concerns, the need for extensive post-processing to improve adhesion strength and mechanical properties in CS coatings has also been the subject of recent investigation. Notably, the use of microwave heating has been proposed as an alternative to conventional electric furnace treatments or to costly post-processing techniques such as hot isostatic pressing and laser processing (Ref 158), offering a substantial reduction in processing time while achieving comparable or superior property enhancements.

These ongoing and effective research and development efforts underscore the adaptability and potential of CS technology to meet the evolving demands of advanced manufacturing, particularly in applications requiring customized material performance and efficient, sustainable processing solutions.

Concluding Remarks and Future Perspectives

Cold Spray (CS) is a robust solid-state AM technology aligned with advanced industry needs. For aerospace adoption, efficient nondestructive testing and integrated in-situ monitoring of coating and interface properties are essential for faster qualification and deployment. CS's unique ability to deposit a wide range of materials without melting enables the production of high-integrity coatings and components, particularly in applications where thermal degradation must be avoided.

The process is rapidly growing, led by aerospace, which makes up 28.2% of the USD 1.05 billion global market in 2024. Few key drivers include icephobic coatings that reduce energy-intensive de-icing and improved erosion resistance coatings for military rotor blades. Recent breakthroughs have further expanded the application space of CS, highlighting its potential in the fabrication of embedded smart structures and energy-harvesting devices (Ref 159), for in-situ monitoring of aerospace structural health.

Notably, CS has been successfully employed in the manufacturing of embedded, patterned structures capable of wireless crack detection in aerospace components. These integrated sensing systems represent a significant advancement in structural integrity monitoring, offering real-time, non-invasive diagnostics critical for maintaining safety and reducing maintenance costs in high-value assets (Ref 159). In parallel, the use of CS to fabricate tribo-electric nanogenerators (TENGs), devices that convert ambient mechanical energy into electrical energy, illustrates its potential in the emerging field of self-powered electronics (Ref 160). By enabling the direct deposition of functional materials onto complex geometries, CS facilitates the scalable production of energy-harvesting systems that leverage ubiquitous sources of dynamic motion.

These innovations underscore the untapped potential of CS as a next-generation manufacturing platform, uniquely positioned to support the development of intelligent, multifunctional systems in sectors such as aerospace, energy, and the Internet of Things (IoT). As research continues to push the boundaries of what CS can achieve, its role in enabling high-performance, sustainable, and smart manufacturing solutions becomes increasingly evident.

Perspectives for Vapor-Deposited Coatings

Marjorie Cavarroc-Weimer, Cédric Jaoul, Jolanta E. Klemberg-Sapieha, Ludvik Martinu, Uwe Schulz, Pascal Tristant

Status of the Field

Field Overview

This section focuses on Vapor-Deposited Coatings (VDC) obtained by the condensation of atoms and molecular fragments on the substrate surface, while their thickness typically ranges from just a few nanometers (nm) to several tens of micrometers (µm), and in selected cases a few hundred µm, depending on the deposition process and its intended application. The driving forces behind developing the VDC are primarily related to new functionality or to the performance enhancement of the components of aircraft. They are primarily meant to improve tribo-mechanical and electrochemical properties, especially wear-, abrasion-, erosion-, fretting-, fatigue-, and corrosion-resistance, reduce friction, and protect against chemicals, environment (oxidation, wet and hot corrosion), heat, high-temperature degradation and other effects of the frequently harsh environments (Ref 161).

Two primary types of fabrication technologies for the synthesis of VDC are considered, namely Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD), the latter one with a frequent emphasis on Plasma Enhanced CVD (PECVD). Particularly, PVD coatings prepared by electron beam evaporation (EB-PVD), cathodic arc deposition (CAD), magnetron sputtering (MS) or

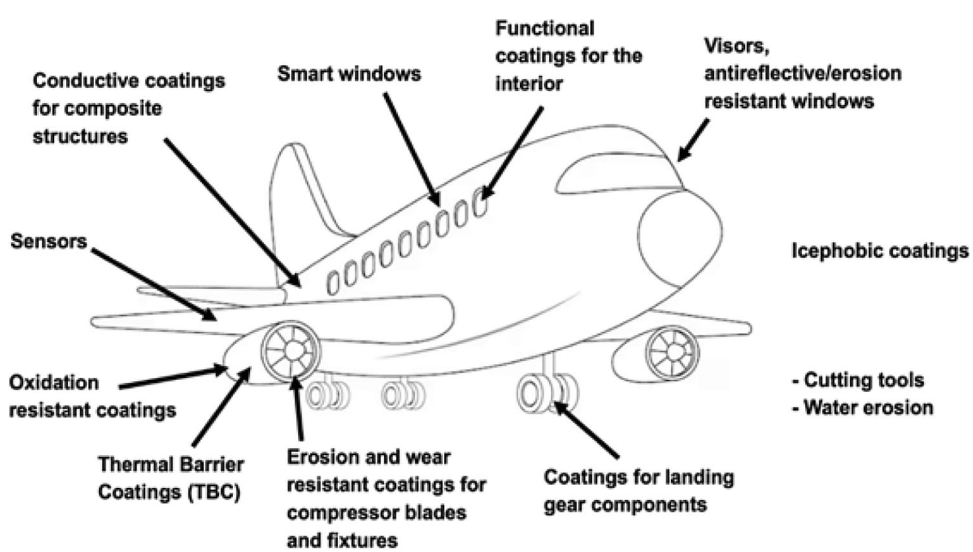

Fig. 26 Vapor-deposited coatings for different parts of aircraft and supporting technologies

Ion-assisted deposition (IAD), have emerged as an important technology in the aerospace industry that requires components to be lighter, withstand extreme conditions, while offering enhanced performance, durability, safety, and efficiency. This paper highlights clean (non-polluting) VDC methods and approaches, focusing on their applications in aerospace, challenges related to their implementation, and future directions. It emphasizes innovations, present and future trends in the development of coating materials, deposition processes, the multifunctional character of coatings, and the importance of understanding the materials' deterioration mechanisms, and ways how to mitigate them.

The main areas where VDC are applied in aircraft are schematically illustrated in Fig. 26. One can particularly distinguish those used in the engine, in the interior, on structural components (e.g., replacement of hard chrome), landing gears, and for tools suitable for the manufacturing steps. VDC with specific optical properties such as anti-reflective (AR) coatings on windows to minimize reflections, improve visibility (especially for the pilots to reduce glare from the sun), or VDC used for instrumentation, sensors (including microelectromechanical systems) and communication components will not be discussed at this point.

Examples of Applications

Examples of PVD protective coatings currently applied in different parts of aircraft and their manufacturers are as follows:

a) Structural Components (replacement of hard chrome): Chromium Nitride (CrN), Diamond-Like Carbon (DLC), and metal-doped DLC (a-C:H:Me is known as BALINIT C, namely WC/C ductile carbide) from Oerlikon Balzers, or Tribobond^{TM} coatings from IHI Ionbond provide high corrosion-, wear-, galling- and fretting-resistance for bearings, bushings, bolts, nuts, and screws, protecting the substrate materials such as steel, titanium, Inconel, and copper alloys.

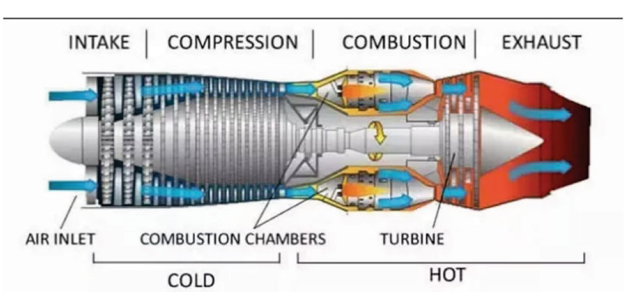

Fig. 27 Schematic of an aircraft engine indicating the main sections where VDC are used. Image courtesy of Jeff Dahl, available under CC BY-SA 4.0 license at Wikimedia Commons

b) Interior Components: decorative coatings are applied to the passenger cabin trim, door handles, fittings, fixtures, fasteners, and many different features to provide durable, corrosion-resistant finishes on exterior parts. Popular finishes include chrome, gold, bronze, black, and titanium, they are provided by companies such as IHI Hauzer Techno Coating B.V., IHI Ionbond, Saueressig Group, and others.

c) Landing Gear Components: TiN, AlTiN or DLC coatings with high hardness are essential for components such as bushings, bearings, pins, and shafts to improve durability and extend the service life of the land-riding surface of rolling bearings to provide enhanced reliability against fretting and severe damage in the case of bearing failure. Together with CrN and ZrN, they offer high wear- and corrosion-resistance and are suitable for sliders, actuators, and contact surfaces that require superior performance in harsh conditions. AlTiN is used for parts that face high temperatures and wear. Companies such as IHI Ionbond and Oerlikon Balzers are known for providing such coatings for the aerospace industry.

d) Aircraft Engine Components:Numerous protective coatings are already applied in different parts of the aircraft engine in both cold and hot parts (Fig. 27). This specifically includes the following components, materials, and suppliers:

Compressor blades: PVD coatings such as hard multilayer coatings based on Titanium Nitride (TiN) and Titanium Aluminum Nitride (TiAlN) offer high solid particle erosion (SPE) resistance of compressor blades against erosive and abrasive damage caused by solid particle impacts. This is particularly important in sandy conditions (Ref 162). BlackGold® combined with the MEERER^{TM} process provided by MDS Coating Technologies (MCT), Balinit® Turbine Pro from Oerlikon Balzers or ERCoat^{nt} from MTU aeroengines extend the service life of turbine components by up to 4 to 6 times, depending on the specific operating environment, and significantly reduce maintenance costs (Ref 163).

Turbine Blades: EB-PVD is well known for the fabrication of Thermal Barrier Coatings (TBCs) in the hot zone of aircraft engines. These coatings (complementary to the ones fabricated by atmospheric plasma spray – APS) are essential for protecting turbine blades made of nickel-based superalloys from extreme gas temperatures of $>$ 1,400 °C and oxidation. Most frequently, Yttria-Stabilized Zirconia (YSZ) is deposited over a bond coat of MCrAlY (M = Ni, Co, or a

combination) or PtAl. During deposition, the substrate temperature can be around 1000 °C, and the resulting microstructure features faceted conical columns with inter-columnar porosity. This microstructure significantly enhances strain tolerance and thermal expansion accommodation, which is mandatory for the durability of the rotating parts.
TBCs can provide heat resistance, crucial in high-temperature applications, while the bond coat acts as oxidation-resistant coating to prevent degradation of turbine blade materials caused by exposure to oxygen at high temperatures. EB-PVD TBCs are widely used in engine technology as part of advanced designs, such as the Pratt &Whitney 4000 family, General Electric /SAFRAN CFM56-7 version, and a great variety of other aero-engine types (Ref 164).

e) Indirectly Related Coatings - Cutting Tools: In the aerospace industry, PVD-coated drills, taps, and end mills are essential for machining high-performance materials such as titanium alloys, aluminum alloys, nickel-based superalloys, magnesium alloys, copper alloys, carbon fiber reinforced polymers (CFRP), and ceramic matrix composites (CMC). These tools are used for various operations, including threading, grooving, drilling, and high-speed machining. Coatings play a critical role in enhancing the durability of cutting tools by reducing wear and improving resistance to heat, corrosion, and oxidation. The diverse materials used in aerospace manufacturing pose unique challenges, such as heat buildup, wear, and degradation. PVD coatings such as SUBLIME®, CROSAL®-plus, DLC, and TiAlN/AlTiN are specifically designed to address these problems. Leading companies including Voestalpine Diamond Ltd., IHI Ionbond, Sandvik Coromant, APEX Cutting Tools, and Acree Technologies specialize in providing such coatings to meet the rigorous demands of the aerospace sector.

Current and Future Challenges

Main Barriers to the Adoption and Performance of the VDC Materials and Processes

PVD, CVD and PECVD coatings have gained high significance in the aerospace sector due to their capability and potential to reduce the environmental impact of transportation. Despite their benefits, widespread adoption is still limited by numerous performance and adoption challenges including coating adhesion reliability, application on complex geometries, issues with scalability, and materials compatibility. A major concern is ensuring strong and durable adhesion of VDC coatings under extreme operational conditions, including fluctuating pressures and high thermal loads. While progress has been made in improving coating performance, achieving long-term stability without delamination remains an ongoing area of research.

The geometrical complexity of many aerospace components makes it difficult to deposit a uniform coating. Current PVD processes struggle to achieve consistent coverage on parts such as turbine blades, bearings, and engine components, resulting in localized wear or erosion. To overcome this, it is essential to optimize deposition parameters and develop more adaptable PVD techniques such as, for example, the high-power impulse magnetron sputtering (HiPIMS) or the hollow-cathode PECVD

High-temperature performance: Advanced PVD coatings have enhanced the thermal stability of components, allowing engines to operate at higher temperatures while increasing their efficiency. In extreme environments such as in the turbine section of the engine, nitride-based formulations, such TiAlN, offer excellent resistance to oxidation and wear at elevated temperatures (Ref 165). However, thermal expansion mismatch between coatings and substrates can lead to microcracks and spallation. Advanced multilayer architecture and functionally graded coatings are promising solutions. The effectiveness of PVD coatings as diffusion barriers against oxidation and corrosive species remains a concern. Research on new materials, such as high-entropy alloys (HEAs) and refractory metal nitrides, can enhance long-term performance in extreme conditions.

Weight reduction: By enabling the use of lightweight materials such as titanium, aluminum and magnesium alloys, PVD coatings have contributed to significant weight savings, improving fuel efficiency and payload capacity. Due to their minimal thickness, PVD coatings contribute negligible additional weight to components. However, their compatibility with lightweight substrates must be ensured to avoid embrittlement or degradation under mechanical stress. The development of nanostructured coatings and optimization of deposition processes is essential to guarantee component integrity.

In the hot section of aeroengines lightweight SiC-CMCs have been used for a while with an advertised and expected growth in number of CMC parts in the next decade. This ceramic material relies on the protection by environmental barrier coatings (EBCs) that protect the CMC against degradation by water vapor in the fast gas stream, and from corrosive degradation by calcium-magnesium-alumino-silicates (CMAS). So far, mostly thermal spraying has been used for such EBCs, but VDC offers new opportunities to achieve dense and phase-pure protective layers. Some of the PVD methods such as MS suffer from low deposition rates, so increasing layer thickness is the key for successful application of VDCs to the EBC application.

High cost of deploying PVD on a large scale remains a significant barrier. Manufacturers need to carefully assess the cost-benefit ratio, by improving deposition rates, automation and use of hybrid solutions that combine different methods for VDC preparation.

Sustainability: PVD coatings have reduced the need to use hazardous materials such as chromium VI or cadmium for corrosion protection, aligning with environmental regulations and sustainability goals. Unlike electroplating, PVD is generally more environmentally friendly (Ref 166). However, its environmental footprint is still quite significant due to the reliance on energy-intensive vacuum-based processes and equipment and the use of scarce or energy-intensive raw materials, such as high-purity yttrium or hafnium targets. Innovations in low-temperature deposition and energy-efficient vacuum technologies can further support wider acceptance of the VDC processes.

The environmental impact of the presently used fuels in aircraft engines stimulates new developments of Sustainable Aviation Fuels (SAF). Different concepts are being studied including SAF derived from bio-based feedstocks, captured carbon, and green hydrogen. The fuels can thus have different chemical compositions, oxygen content, and lubricity compared with the conventional kerosene, necessitating material adaptations in aircraft systems, in particular materials compatibility, corrosion behavior, and wear in aerospace components.

Adopting the principles of circular economy also includes research on the recyclability of coated parts. Developing coatings that can be efficiently removed and re-applied without a significant loss of material and performance is a crucial step toward sustainable manufacturing. A current good practice of multiple re-coating cycles by repair processes is TBCs applied by EB-PVD. They can be re-coated at least a second time on a component, thereby utilizing the full lifetime of the Ni-based superalloys and avoiding early retirement of the turbine blades. This re-application of PVD coating should be implemented with an increasing number of components to improve sustainability.

Current and Future Challenges

Technical: Achieving uniform and defect-free coating remains a challenge, particularly for large or geometrically complex parts. Variability in deposition rates, non-uniform thickness and porosity can affect performance. For example, turbine blades require precise coatings to maintain efficiency and reliability, but achieving consistent adhesion across curved surfaces remains difficult.

Some materials, such as certain polymers and lightweight alloys with low thermal stability, are difficult to coat using conventional PVD methods. Advances in low-temperature deposition processes, such as IAD, could help mitigate these limitations.

While VDC provide superior wear resistance and oxidation protection, they may compromise other properties such as toughness, electrical conductivity, or thermal conductivity. For instance, some titanium nitride (TiN) coatings exhibit brittleness, which could be problematic in high-stress environments.

The vacuum- and vapor-based processes are rather complex since they are affected by numerous external and internal parameters with different levels of interdependence. Therefore, over the years, much of the progress evolved on the trial-and-error basis. In this context, development of new predictive tools allowing one to better optimize, control and enhance performance of the processes, materials and components is definitely required, an endeavor worth pursuing using the machine learning tools. In addition, VDC is highly reproducible once the processing parameters have been established since in most processes in the vacuum chamber all sub-steps can run automatically.

Economical: The relatively high cost of PVD or PECVD equipment (vacuum chambers, pumping and gas delivery systems, plasma generators, control units etc.) is a major barrier, especially for small and medium-sized enterprises (SMEs). A single system can cost well over $500,000, limiting accessibility to manufacturers. In addition, most deposition rates are lower than those of electroplating or CVD, resulting in longer production cycles that are not suitable for high-volume industries (such as automotive). Advanced coating materials including HEAs, DLC, and refractory nitrides can be expensive. Additionally, the need for periodic replacement of PVD targets or vapor/liquid precursors adds to operational costs. Research into cost-effective alternatives and recycling of spent targets and gases is needed.

The successful implementation of VDC requires expertise in vacuum technology, plasma physics, electrical engineering and materials science and engineering. The shortage of trained personnel in these specialized fields presents an economic challenge, as companies must invest in extensive training programs.

Regulatory

Stringent regulations, such as REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) in Europe, mandate the reduction of hazardous substances in industrial processes. While PVD is a cleaner alternative to electroplating, the use of certain precursor gases or coatings containing rare or toxic elements (such as in CVD) still poses regulatory hurdles.

Aerospace applications require rigorous testing and certification, such as those governed by the FAA (Federal Aviation Administration) and EASA (European Union Aviation Safety Agency). The extensive validation process for new VDC slows down their adoption, as meeting these standards requires long-term performance testing under extreme conditions.

Some VDC processes involve the use of high-energy plasma, reactive gases, or hazardous target/precursor materials, necessitating strict workplace safety protocols. Ensuring compliance with OSHA (Occupational Safety and Health Administration) or similar regulatory bodies adds complexity to implementation.

Despite many challenges, VDC represents a great potential to improve durability, reduce component weight and meet sustainability requirements in the aerospace, automotive and industrial sectors. However, to overcome technical, economic, and regulatory barriers, there is a need to continue research, collaboration between academia and industry, and policy incentives.

Advancements in high-performance coatings, process efficiency, and environmentally friendly technologies will be key drivers in expanding the adoption of VDC across various sectors. Given the challenges outlined above, extensive research and development efforts are directed toward advancing the understanding of high-performance coatings, such as solid particle erosion-resistant coatings, next-generation thermal barrier coatings (TBCs), environmental barrier coatings (EBCs), high-temperature oxidation-resistant coatings, and icephobic coatings, as well as the exploration of new materials, micro/nanostructures and processing technologies.

Advances in Science and Technology to Address Challenges

New Coating Systems and Related Breakthroughs

This section summarizes recent research and future perspectives focused on developing advanced coating systems with superior performance.

a) Nanostructured protective coatings against solid particle erosion – SPE: High-performance SPE-resistant coatings require high hardness, they need to be fully compatible with the underlying substrate, and they have to provide appropriate pathways for the dissipation of kinetic energy of the impinging solid particles. In this respect, the presence of internal interfaces in nanocomposite (nc) coatings provides very high hardness (even superhardness, H > 40 GPa, due to the inverse Hall-Petch effect) and toughness, and hence a high resistance to crack propagation. Figure 28 illustrates the effect of graded hard nc films on the improvement of SPE resistance of a Ti-6Al-4 V substrate when proceeding from surface nitriding to subsequently depositing TiN, ncTiSiN and ncTiSiCN layers prepared by PECVD. This allowed us to decrease erosion rate (ER) by a factor of 50 (tested according to the G76 standard using alumina particles, 50 µm in diameter, at a speed of 80 m/s) (Ref 167). Such behavior agrees with finite element modeling results used to predict the effect of the thickness (typically a minimum of 8-10 µm), and the advantage of incorporating a gradient in Young's modulus, *E*.

Similar observations have been made for ncTiAlN/Si_3N_4 systems that exhibited high H values (up to 40 GPa) and high thermal stability (up to 1000 °C). Related multilayer and gradient CrN/AlN coatings gave rise to improved toughness, and resistance to crack propagation. An

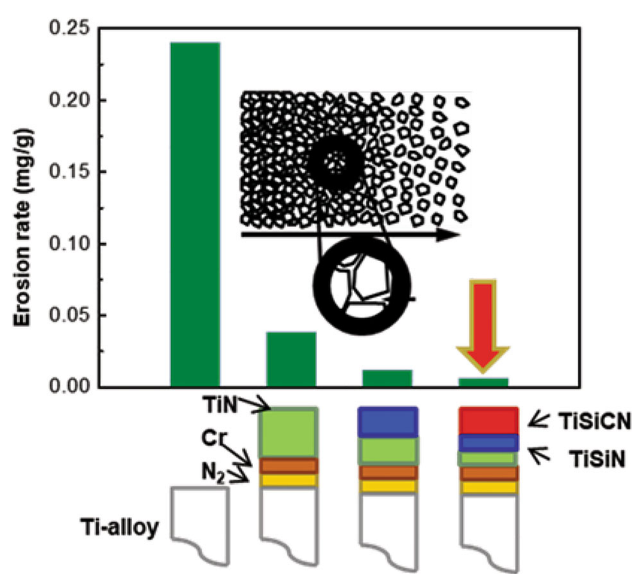

Fig. 28 Solid particle erosion rate of TiN, ncTiN/$SiN_{1.3}$ and ncTiCN/SiCN films deposited on Ti-6Al-4 V substrates and eroded by Al_2O_3 particles, 50 µm in diameter, at a speed of 80 m/s) (Ref 167). Reprinted from Ref 167, available under CC BY 4.0 license at IOPScience

interesting double-layer approach combining a highly elastic (or superelastic, with an elastic rebound > 80%) PECVD a-SiC films with a hard ncTiSiN topcoat has been shown to lead to a "trampoline" effect providing enhanced kinetic energy dissipation, ER improvement, as well as high corrosion resistance due to the presence of the amorphous layer (Ref 168).

When evaluating the SPE mechanisms (Ref 169), mechanical residual stress has been recognized as an important contributor to the coating behavior (Ref 170). Specifically, the role of stress and stress depth profile has been studied in CAD TiAlN hard ER coatings using x-ray diffraction. It is believed that further understanding of the mechanisms involved can significantly benefit from using machine learning tools applied to the ER assessment of the metal substrates (Ref 171), as well as of the coatings.

b) New-generation CMAS-resistant low-emissivity TBCs: There is an intense research on improving the performance of EB-PVD TBCs by exploring the control of microstructure and the use of novel materials (in complement to the most frequently applied YSZ and Gadolinium-zirconate, GZO) to reduce heat conductivity (or diffusivity), increase resistance to CMAS infiltration, and improve fuel efficiency by pushing the temperature limits higher, while reducing emissions and increasing resistance to hot corrosion. New EB-PVD coatings made of pyrochlore or perovskite phases, various zirconates, multi-component oxides or by co- or triple-doping rare-earth oxides into YSZ have recently been explored, and new microstructural features have been modeled and predicted (Ref 172). For instance, Ta-containing TBCs that offer unique phase stability (Ref 173) and provide low thermal conductivity have been obtained from powder mixtures and PVD coatings.

The recent trend toward higher fuel efficiency and reduced emissions leads to a continuing increase in the working temperature pushing the thermomechanical properties of the TBCs to their limit. In such a case, the radiative thermal load on the TBCs becomes increasingly important since it scales with the temperature as T^4 according to the Stefan-Boltzmann law. Therefore, new research is now devoted to the assessment of the optical reflectivity of the TBCs in the near-infrared region (typically corresponding to the wavelength range between 1.2 and 1.6 µm) in correlation with the TBC microstructure. This includes detailed optical reflectance and transmittance measurements of the diffusive media, determination of the scattering and absorption coefficients, and their correlation with the TBC's pore structure. In addition, attempts are being made to tune the light scattering and reflectance characteristics by coating the inner surfaces of the pores with vapor-based techniques such as atomic layer deposition, ALD (Ref 174); the latter approach is also expected to mitigate the effect of CMAS infiltration. Another approach is to sputter multilayer stacks consisting of Ti- and Al-oxide that are tuned to have multiple reflection peaks that can reflect over a wide range of the gas emission spectrum (Ref 175).

c) Environmental barrier coatings for SiC-SiC CMCs: The success of light-weight CMCs in aeroengines depends on the functionality of a reliable EBC. It must protect the parts against streaming water vapor, water vapor enhanced oxidation, CMAS degradation, and in some cases, it acts as an abradable surface. Commonly, a multilayer approach is used to fulfill the high number of requirements such as CTE (coefficient of thermal expansion) matching, phase stability, chemical matching with SiC, superior high-temperature behavior, and stability under water vapor and CMAS. So far, thermal spraying techniques have mostly been explored and used to fabricate EBCs. However, VDC offers unique possibilities to match those requirements, but they have not yet been fully explored. Early publications by NASA indicate that EB-PVD (in this case EB-directed vapor deposition) has a high potential to build multilayer EBCs made of rare-earth silicates on top of modified silicon bond coats. Later dual-source EB evaporation was explored to establish dense and stable Yb-disilicate and Y-mono- and -disilicate layers (Ref 176-178) of up to 70 µm in thickness.

MS can also be used to create the various layers of an EBC, for instance the silicon-based bond coat that can be modified by hafnia or in reactive mode deposition of yttrium silicate coatings (Ref 179), but only to thicknesses of approximately 30 to 40 µm. To address this limitation, a hybrid PVD/CVD process can be used to combine the advantages of both approaches. These processes are particularly useful for substrate complex geometries or engineering graded, multi-layer, or compositionally complex films. For example, CAD or MS is used for rapid deposition of dense bond coats (e.g., Si) while CVD or reactive evaporation follows for forming complex oxides like rare-earth silicates. This has been applied to produce Si + $Yb_2Si_2O_7$ EBCs with a large thickness and environmental resistance (Ref 178-180). Vapor-deposited EBCs have already demonstrated their excellent performance under water vapor and cyclic testing for 1000 h up to 1300 °C (Ref 181, 182).

d) Oxidation-Resistant Coatings: One of the key challenges in aerospace materials development is replacing heavy nickel-based alloys with lighter alloys such as γ-TiAl that provides an excellent combination of properties including high melting point (> 1400 °C), low density, and, in particular, high specific strength, elastic modulus, and creep resistance at elevated temperatures. However, the implementation of γ-TiAl is limited due to its susceptibility to severe oxidation and oxygen-induced embrittlement when exposed to temperatures exceeding 700 °C.

To address these limitations, various protective coating systems and surface engineering techniques have been developed to provide high-temperature protection of γ-TiAl alloys against environmental degradation. This includes application of well-adherent protective coatings that promote formation of dense, stable oxide scales (such as α-Al_2O_3, Cr_2O_3, SiO_2), acting as efficient barriers to oxygen (Ref 183). The coating systems can be categorized into three main types: (i) coatings produced using the halogen effect, where a halogen, such as chlorine or fluorine, is used to promote the growth of a protective alumina scale, (ii) diffusion barrier coatings, and (iii) overlay coatings.

Specifically, and as an example, surface treatment using the halogen effect involves enriching the surface of the TiAl alloy with halogens (F, Cl, Br, and I), which promotes the growth of a stable protective α-Al_2O_3 scale. A promising method is reactive magnetron sputtering of aluminum in an Ar, O_2, and CF_4 gas mixture to deposit AlOF, thereby promoting alumina formation at high temperatures. Another example is the use of highly thermally stable amorphous Si-B-C-N ceramics deposited via a PVD process (Ref 184). These coatings remain amorphous with excellent adhesion due to a thin Si bonding layer even after 1000 h at 800 °C. During high-temperature exposure, a thin SiO_2 protective layer forms on the surface, significantly reducing the oxidation rate by two orders of magnitude compared to unprotected γ-TiAl. Also, alumina forming and protective coatings based on Ti-Al-Cr doped either with Y, Zr or Si proved their potential to protect TiAl alloys up to 1000 h of cyclic testing at 850 °C (Ref 185). Those coatings can also be applied as bond coats with an EB-PVD YSZ TBC on top for future application of γ-TiAl in the hot section if cooling of those parts becomes available, for instance by additive manufacturing.

PVD methods are particularly suitable for the deposition of oxidation-resistant coatings on Ni-based alloys, either as stand-alone solutions or as bond coats with a TBC on top. While earlier attempts by using MS were restricted in terms of thickness (Ref 186) or have concentrated on NiAl phases, recent developments such as the BALORA™ PVD MCrAlY deposited by CAD by Oerlikon Balzers have achieved up to a 100 µm thickness. A significant advantage of all PVD-based oxidation-resistant coatings lies in the vacuum environment maintained within the deposition chambers. This vacuum minimizes the oxygen partial pressure, thereby limiting the oxygen content in the coating. Such conditions are particularly beneficial for rare-earth (RE) elements like yttrium (Y), as well as hafnium (Hf) or zirconium (Zr), which are able to remain in their metallic state within the coating. As a result, these elements contribute to enhanced oxidation resistance and improved oxide scale adhesion when compared to thermally sprayed MCrAlY coatings, where a substantial portion of the RE elements tends to oxidize during the fabrication process. This effect has been well understood and exploited in EB-PVD MCrAlY coatings for decades (Ref 187, 188). However, the relatively high cost of this technology has led to a decline in its market share over time.

e) Icephobic coatings: Icing in aerospace is primarily the result of supercooled water droplets suspended in clouds impacting the aircraft. Current systems for icing mitigation are mostly active (heating, pneumatic boots) or use chemical de-icing (glycerin spray). These add weight and complexity and are not environmentally friendly. Therefore, much research has focused on icephobic passive coating systems to decrease ice accretion (preventing ice buildup) or reduce ice adhesion.

Early icephobic coating approaches involved low-surface energy materials, which are more water-repellent than the base metals. While hydrophobicity may offer some reduction in ice adhesion strength, it is not sufficient for them to be considered "icephobic", which is associated with an ice adhesion strength of less than 100 kPa. Therefore, further work focused on superhydrophobic surfaces (SHS) and coatings, which combine hierarchical micro- and nano-scale roughness to achieve extreme water repellency, where droplets sit atop the surface features rather than wetting the area completely. This can reduce icing by causing impacting droplets to rebound rather than freeze at the surface (Ref 189). Formed ice which sits on top of the surface features is also less adherent due to a reduced contact area, and through air pockets acting as stress localizers, behaving similarly to defects in the ice itself.

Primary issues with SHS are durability and the potential for mechanical interlocking of ice. Because they rely on a specific combination of surface features and surface chemistry, a change to either of these can reduce their performance. Promising robust SHS have been developed through the combination of duplex thermal spray/PECVD coatings, where the thermal spray coating is used to achieve the desired morphology, and a PECVD coating provides a hydrophobic topcoat which is harder than the underlying layer (Ref 190).

An important issue is the interlocking of ice - this occurs when water penetrates the rough surface and fully wets it before freezing. One solution to avoid this is using SLIPS (Slippery Liquid-Infused Porous Surfaces), surfaces where the "empty" space is filled with liquid, generally an oil; such surfaces can again be prepared by thermal spray coating. This creates a composite solid-liquid surface which allows easy removal of ice or water. While surface porosity can be tuned to maximize liquid retention, the potential loss of impregnating liquid can limit the applicability of SLIPS in aerospace contexts (Ref 191).

The latest research has pivoted from limiting ice adhesion strength to limiting the toughness of the ice-surface interface. The reasoning is that while ice adhesion strength scales with surface area, interfacial toughness reaches a length threshold after which it plateaus, meaning no additional energy is required for removing a longer length of ice. Such low-interfacial toughness (LIT) coatings are particularly promising for airframe icing. Recently, quasi crystalline LIT coatings have been deposited by thermal spray, and a demonstrated relation between thinner coatings and decreased interfacial toughness (Ref 192) suggests that the nanoscale thickness regimes easily achieved by VDC methods may provide an attractive avenue for future solutions.

f) New materials - High-Entropy Alloys: HEAs, such as AlCoCrCuFeNi, have been explored for their unique combination of strength, oxidation resistance, and thermal stability, making them suitable for high-temperature aerospace applications (Ref 193). In addition, multi-component oxides have attracted interest in both TBC and EBC applications. They can offer reduced thermal conductivity, improved phase stability, better resistance against water vapor and CMAS, and in some cases can be more economic by saving costly elements. New material classes such as MAX- and MAB phases are currently under evaluation that can provide excellent property combinations for high-temperature applications. VDC provides great opportunities to both investigate and develop but also apply these novel coatings on parts since one can combine multiple targets to mix the elements, use compound targets consisting of an optimum mix of elements, as well as control the coating microstructure on the nanoscale.

Highly complementary to the HEAs are the self-lubricating coatings. Specifically, incorporating solid lubricants (e.g., MoS_2 or WS_2) into the functional and multifunctional PVD coatings leads to reduced friction and wear in moving parts, such as bearings and gears.

New VDC Processes and Related Breakthroughs

For aerospace engines, commercially available PVD processes include CAD for erosion and corrosion protection of the engine and its compressor gas path components, and EB evaporation for fabricating the TBCs. Considerable research is being devoted to the development of sputtering processes including planar or cylindrical magnetrons, as well as gas flow sputtering and closed hollow cathode deposition. The former technique is also being applied (together with CAD) for coating cutting tools.

Of particular importance in the PVD (as well as in all VDC) processes is the control of the evolution of the coating microstructure during the film growth in terms of temperature and the energy of particles (ions, atoms, molecular fragments) arriving at the growing surface (Ref 194). It has been accepted that the main film growth parameter is the energy per deposited atom expressed as $E_p \sim E_i / \varphi_i$, where E_i is the average ion energy and φ_i is the flux of impinging particles. Both E_i and φ_i can be determined experimentally using an electrostatic ion energy analyzer and techniques allowing one to obtain the deposition rate, r_D, and the film density, ρ. Specifically, $\varphi_i = r_D * \rho * N_A / m_A$, where N_A is the Avogadro number, and m_A is the atomic mass. The latest progress, and frequently a challenge for the PVD techniques, is related to the ways to optimize E_p (e.g., by selective control of E_i and φ_i) to obtain appropriate film microstructure and hence its properties. It also represents an opportunity to use this universal parameter when scaling up the PVD and PECVD processes.

The above statement is well illustrated by the progress in magnetron sputtering where φ_i and E_i can be controlled by plasma pulsing; this is particularly the case when a duty cycle is in the range between 1 and 10 % of the pulse period known as HiPIMS during which very dense plasma is formed in front of the target (ionization degree of 40 to 70% compared to standard < 1% in DC sputtering) giving rise to very high φ_i values (Ref 195). As such, HiPIMS enables the deposition of very dense, defect-free coatings with excellent adhesion (due to interface mixing), even on complex geometries. This technique has been particularly considered for coating critical aerospace components like landing gear and compressor blades (SPE-resistant coatings), as well as coatings for cutting tools for "difficult-to-cut materials". Present and future research focuses on controlled pulsing, target-substrate synchronization, stress and deposition rate optimization, and exploration of complementary characteristics including corrosion-, wear-, and fouling-resistance, and other functionalities.

The concept of controlling ion energy and ion flux is also exemplified by applying Ion Beam-Assisted Deposition (IBAD): IBAD has been used to enhance coating adhesion and density, particularly for coatings applied to lightweight alloys like titanium and aluminum.

Complementary to the PVD processes is CVD in which gaseous precursors arrive at the hot substrate surface where they get dissociated (chemical reaction initiation step), react between each other or with the surface (propagation step), while leaving behind a solid coating and removing the volatile products (termination step). Such thermally driven processes are used on hot end components (i.e., combustion and turbine areas) to protect against oxidation and hot corrosion. Such CVD coatings are sometimes referred to as "bond coats", as they serve a role of ensuring that the TBC adheres properly to the metallic substrate. One also benefits from the non-line-of-sight (NLOS) capabilities of CVD that are especially important for coating intricate geometrical areas such as internal cooling passages, shadowed areas on multiple vane segments, or other areas subjected to environmental attack.

PECVD can be considered an emerging technology in aerospace applications (unlike micro/optoelectronics, biomedical and other fields) that combines the benefits of both PVD and CVD worlds. It uses plasmas of electrical discharges (such as in the sputtering processes) for the initiation of chemical reactions in the gas phase by dissociating gaseous precursors, while their fragments (free radicals) arrive at the surface forming a coating at a significantly lower temperature than in CVD (Ref 167, Ref 194). Similar rules as in PVD apply when controlling the film microstructural characteristics in terms of the E_p parameter (see above). PECVD is suitable for the fabrication of hard and superhard (nc) protective coatings with a high SPE resistance (see Section "New coating systems and related breakthroughs"), corrosion resistance, icephobicity and other functionalities.

The CVD and PEVCD processes are suitable for coating inner surfaces such as tubes and concave 3D objects. Recently, an immersion hollow cathode PECVD process for coating inner surfaces has been developed to provide uniform SPE-resistant coatings in narrow tubes ($<$ 1 cm diameter) and cavities (Ref 196). The NLOS nature of the CVD and PECVD techniques appears particularly appropriate in the context of future alternative fuels to protect the exposed components against physical and chemical attacks. For example, when hydrogen is burned, reaction gases are composed of much more water vapor than when traditional jet fuel is burned. This can have an impact on gas path TBCs and silica-forming (SiC-SiC) CMC components, depending on the structural system used. Before burning, carrying hydrogen in fuel tubes and through other parts of the injection system might generate hydrogen embrittlement issues that need to be evaluated and mitigated. In addition, water-vapor enhanced oxidation is well known for many metallic alloys which call for new and adapted coatings that protect the underlying components. Synthetic aviation fuels may impose future requirements on coatings, but so far, they are cleaner and less aggressive than conventional fossil fuels, depending on the synthesis route.

Concluding Remarks and Future Perspectives

Vapor deposited coatings (VDC) play an important role on the way toward greener, more sustainable aviation by improving energy efficiency in aircraft engines, enhancing the performance and durability of components, lowering maintenance costs, and reducing fuel consumption through lower mass and better thermal management. Consequently, they help decrease the carbon footprint, while strongly contributing to a more environmentally friendly aviation industry.

Future research should prioritize the development of new, more sustainable materials that integrate multiple functionalities, including thermal protection, corrosion and hot corrosion resistance, and anti-icing capabilities. Active investigations are exploring self-healing coatings that repair damage, as well as adaptive PVD systems that prolong component life and minimize maintenance or replacement needs.

Ongoing efforts in materials science continue to target sustainable solutions for VDC, with a particular focus on multifunctional systems. These include next-generation TBCs designed to provide not only thermal insulation but also resistance to radiative heat loads, CMAS infiltration, mechanical degradation, and environmental corrosion.

A promising direction involves multi-process fabrication strategies combining thick thermal spray deposited layers with thin VDC to achieve layered architectures with enhanced performance.

To further advance the performance of these multifunctional systems, in-depth studies of the deterioration or aging mechanisms are of particular importance, possibly based on well-thought-through experiments in combination with machine learning approaches.

Present and future efforts aim to reduce equipment costs, improve process control, and explore automation techniques for scalability. Hybrid deposition methods, combining PVD, PECVD and other techniques (such as ALD) should also be explored to enhance coating properties and versatility. This can be particularly beneficial when coating complex 3D-printed components in the context of additive manufacturing.

The integration of AI, machine learning and modeling will play a significant role in optimizing the materials and coating designs and the deposition processes. These technologies can help reduce trial-and-error in development, speed up the innovation cycle, and improve predictive lifecycle management for coated components, ensuring better long-term performance.

As the aerospace sector moves toward more sustainable practices, VDC will continue to be a crucial technology in the aerospace industry's drive for a greener future.

Refurbishment and Lifetime Enhancement of Aircraft Components

Mettupalayam Balachander, Komal Laul

Status of the Field

Despite being a century-old process, thermal spray processes remain essential to the maintenance, repair, and overhaul (MRO) of aerospace and industrial gas turbines, finding applications in a multitude of components, from legacy to modern, futuristic engines. The ability to use a variety of feedstock materials to meet serviceability needs, such as dimensional restoration, abrasion resistance, wear resistance, and thermal protection on various substrate materials, makes thermal spray processes attractive for remanufacturing processes. This article provides an overview of thermal spray processes from the perspective of maintenance, repair, and overhaul organizations to promote improved sustainability practices.

Current and Future Challenges

The MRO market is transitioning from traditional labor-time-and-materials (T&M) pricing for legacy engines to power-by-hour (PBH) pricing for new-generation engines. Under PBH, airline operators pay a fixed cost per operating hour to the provider. The provider (OEM) assumes responsibility for providing maintenance, thereby offering operators predictable costs. Unplanned maintenance or breakdowns of gas turbine engines must be minimized, otherwise the PBH model will not be beneficial. Therefore, it is crucial for an MRO to be cost-efficient and have short turnaround times. A typical engine overhaul requires dismantling the engine into its component parts, cleaning and inspecting them, repairing them, assembling them, testing the engine, and shipping it. Among the many repair processes, thermal spray processes play an important role in renewing dimensional build-up and imparting wear protection, thermal protection, fretting resistance, and other important surface-engineered properties that extend the useful service life of these parts. (Ref 197).

The current engines used in commercial aviation belong to three generations: legacy (e.g., GE CF6 and PW JT8D), mature (e.g., CFM56 and V2500), and new generation (e.g., PW GTF, RR Trent, and CFM Leap). Airline operators seek the new generation of engines for their efficiency and performance. However, mature and legacy engines still power many aircraft due to supply chain constraints, financial issues (capital and operating costs), and regulatory issues. This results in an extended transition to newer engines. (Ref 198).

A typical coating repair qualification and approval process for a piece part involves the following:

- Repair design and documentation (OEM)
- Tool and fixture development (MRO)
- Application method development (MRO)
- Repair qualification document development (MRO)
- Non-destructive and destructive evaluation (OEM)
- OEM repair approval.

The first part to qualify the repair is documented as a FAIR (First Article Inspection Report). Then, qualified MROs perform industrial or serialized repairs. However, when it comes to maintaining mature and legacy engine repairs, MROs must continuously maintain previously qualified repairs developed decades ago. The airline MRO perspective is challenging because they must maintain the expertise, materials, methods, tools, equipment, and technologies necessary to perform previously qualified repairs and keep pace with newer repair approvals to support the repair and overhaul of all three generations of gas turbine engines (mature, legacy, and newer generation). This requires the ability to perform repairs using various processes, maintain and calibrate equipment, maintain a variety of tools and fixtures, train highly qualified personnel (HQP), maintain a wide range of repair approvals, and manage the logistics of sourcing various materials while meeting compliance requirements. A large MRO that caters to multiple engine models and multiple OEMs can face very complicated challenges and opportunities. It is similar to a large car repair shop that is fully licensed and qualified by OEMs such as GM, Ford, and Toyota to perform repairs and overhauls on various generations of car engines.

Some of the above-detailed challenges from a thermal spray coating processes perspective are illustrated in Fig. 29.

Example (All Factors, Operational Complexity, Financial)

This fictional example, as shown in Table 3, illustrates the complexity of an MRO repairing multiple engine parts with various thermal spray coating processes and materials while fulfilling repair, compliance, and quality requirements.

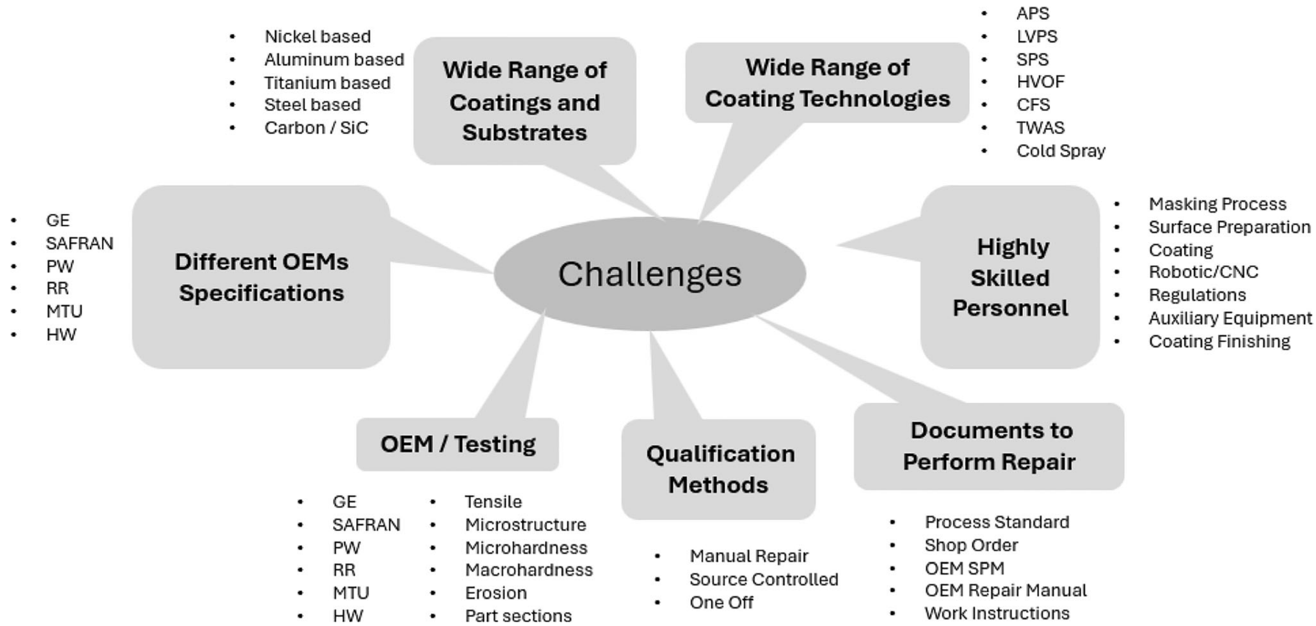

Fig. 29 Challenges in Thermal Spray repairs in MRO Industry

Table 3 Example of MRO operational complexity due to multi-factors

Number of different unique repairs offered per engine model	Number of different coatings	Number of coating booths	Number of skilled technicians	Number of OEM / Number of engine types	Number of specifications(Repair requirements, testing requirements)	Turn time (Days)
50 +	20 +	5 +	15 +	10 +	10 +	< 20

When we overlay the examples, the complexity becomes multidimensional. Important factors such as coating equipment, torch types and manipulation methods (robot and gantry), surface preparation methods, finished coating requirements, testing requirements, part geometry, masking types, substrate material types, and turn time requirements could make this extremely complicated. At the same time, large MROs that cater to multiple engine models involving multiple OEMs have multiple opportunities. Some of these opportunities include:

1) Standardized procedures, where common repairs can be aggregated using standardized procedures
2) Workforce flexibility: Highly qualified personnel can be cross-skilled to work on similar repairs across engine models.
3) Quality and compliance optimization: The same ISO 9000 and repair station compliance requirements (FAA) can be addressed across engine models.

Digital integration: Workflows, data capture, and digital integration can be optimized to implement version control that addresses repair processes across the board.

An optimized qualification process allows for an accelerated repair development process, enabling repairs to be developed, qualified, and industrialized at an accelerated pace. Process efficiency: Due to economies of scale (workforce, equipment, materials, etc.), process efficiency can increase.

Advances in Science and Technology to Address Challenges

Many of these challenges can be addressed using solutions provided by recent advances in science and technology, here are some examples detailing the opportunities.

Coating Material Standardization

It is quite common to find specifications to call out limits on a certain powder, for example gas atomized Nickel-5% wt. Aluminum pre-alloyed powder. The same Ni-Al material is available in different forms such as water atomized, mechanically clad, chemically clad and variants like Ni-Cr-Al and Ni-Mo-Al with similar coating properties. There is tremendous potential for the turbine Engine

OEMs to standardize these mature coating material options. Standardizing or allowing other coating material as optional repair materials provide logistics, cost and aggregation benefits. In the current situation, parts within the same engine model for the same application requirements will have varying coating material requirements that might be easy during new manufacturing due to larger batch manufacturing that might not be the case during the repair or remanufacturing process. The majority of the widely varying repair requirements by different OEMs are based on proprietary reasons (segmentation and differentiation), some changes without impacting business practices for mature legacy coatings could help in standardization and improve sustainable practices due to the recent advances in science and technology. This is akin to having various charging cable connectors for different brands of cellular phones although the battery charging requirements are like a single standardized connector would be very helpful.

Coating Testing / Evaluation Standardization

Standardize coating testing requirements for industry, as often one OEM's testing requirements could specify Microstructure, Tensile Bond Strength, while the other OEM's testing requirements for the same coating would specify Microstructure and Rockwell Hardness test. Rockwell hardness testing often typically requires greater than 1 mm thick coating for accurate testing which might not be representative of the coating on the part, where the coating thickness requirement could be 0.5 mm. The use of microhardness testing method instead of Rockwell hardness testing in this case could be more representative and sustainable. There are also opportunities to use AI/ML enabled microscopes for evaluation of coating microstructure to bring more consistency and speed for high volume coating precise evaluation that typically consists of evaluating porosity, coating phases, interface contamination and oxides. This will need substantial participation from industry partners, researchers, OEM and MRO shops to standardize these methods. The abradable hardness testing (R15Y) method used in abradable coating testing requires over 2 mm coating thickness, also the availability of standard calibration hardness blocks for this hardness testing method is very selective instead of covering the entire range of actual harness testing range.

Need for Faster, Accurate and Precise Coating Evaluation

The primary challenge lies in metallographic evaluation, where slight changes to the preparation method can lead to scratches, cracks, pullouts, and microstructures that obscure true coating properties. Small changes to the metallographic routines can cause microhardness variations exceeding 100 HV0.3 (Ref 199). Majority of the repair specifications are based on new manufacturing coating process methods which are different within the population due to varying service exposure that can include varying coating thicknesses requirements. The coating testing frequency is lot easier for newly manufactured parts due to larger batch sizes whereas, the frequency of testing is much higher in the repair industry due to frequent set-up changes. Testing and evaluation requirements for the same coating by different OEMs can vary widely, there is an opportunity for standardization to make the testing criteria standardized with the input from coating manufacturers. The current coating evaluation methods take several hours to test which are expensive and labor intensive. There are opportunities to simplify testing requirements by using better in situ coating property measurement sensors or developing easier and faster coating test methods in partnership with the OEMs and industry stakeholders.

Coating Technology Advancements

Majority of the repair specifications are based on new manufacturing methods which are different when it comes to repair as a batch consists of one to few parts requiring frequent set-up changes. There are only a handful of equipment manufacturers with one larger company and several smaller companies with most of the equipment are tailor or custom made compared to standardized equipment. The coating material wastage and power lost to heat removal in APS process is an opportunity that needs improvement. It is important to develop more integrated multi-process capable thermal spray equipment with the ability to quickly change equipment set-up that is machine learning capable with the ability to optimize spray parameters, ability to switch powders quickly, generate automated robot tool path based on part condition like 3D scanning, perform in process measurements, and inspection.

Introduction of New Repairs

There are multiple unrealized repair opportunities within the aircraft engines and components where currently OEM repair specifications or authorization is not available. Thermal spray and other coating processes like cold spray process offer immense benefits that can be used to repair parts rather than using a newly manufactured replacement part with an immense amount of cost and environmental benefits. Advances in Thermal and Cold spray processes and coating materials have opened potentially expanding prospects for repairing components that could not be repaired previously.

Coating Material Improvements / Deposition Efficiency Improvements

Sensitive coating powder materials vary from one lot to the next lot resulting in material inconsistency issues. Particle size distribution influences multiple aspects of the coating process, including fluidization, charging, transportation from feeder to torch, spray trajectories, layer build-up, coating microstructure, deposition efficiency and bond strength. Let us say due to powder size distribution (PSD) where the ratio between the large and small particles are over two, the mass difference would be over eight thus affecting the spray trajectory by increased divergence as shown by Vardelle et al (Ref 200). It is important for materials suppliers to have better control in order to reduce variation from one material lot to another. Today, there is access to much better advanced technologies and techniques for manufacturing and classifying powder materials (Ref 201), which can be put to good use.

Advanced Process Monitoring

Process monitoring is becoming an essential requirement for a deeper understanding of the coating process before depositing the coating on test pieces. This includes understanding the average particle velocity, temperature, and trajectory. Advancements in diagnostic methods, sensors, and process maps have improved our understanding of thermal spray process control, yielding greater reliability and robustness.

Industrialization of New Repairs

The repair qualification process for OEM-licensed repairs, often called source-controlled repairs, uses a gated approval process. Tooling, fixtures, coatings, and repair qualification procedures must meet the OEM's stringent requirements. Advances in 3D modeling, reusable masking, robotic toolpath automation in virtual settings, process mapping, advanced thermal spray equipment with intelligent control systems, and the availability of skilled personnel can help repair shops accelerate the industrialization of new repairs.

Training

The availability of skilled labor and labor costs are problematic because the thermal spray and repair domain of the aerospace industry involves a steep learning curve, and few structured training programs are offered outside of potential employers. There is a need for better training programs for spray technicians and operators, similar to welding programs offered in technical colleges, to industrialize new repairs in a shorter time.

Advancements of Coating Finishing Processes

The repair instructions detail the coating materials, application, and evaluation requirements. The finishing requirements, especially for interrupted surfaces with brittle coatings, can be challenging. There are few published materials available on finishing coatings (turning, machining, and grinding). Coating failures are common during finishing operations in the thermal industry because coatings are often considered substrate materials rather than mechanically bonded materials with their own characteristic properties, which can differ greatly from those of the substrate. For example, when turning in a lathe, the tool material, tool geometry, work speed (RPM), feed rate, depth of cut, and blending any overspray material are all important factors. Substantial participation from industry partners, researchers, OEMs, and MRO shops is needed to standardize these methods. This is an area of interest for the entire thermal spray industry, not just the MRO industry.

Concluding Remarks and Future Perspectives

This section points out the challenges and possible solutions due to recent advances in science and technology. There are tremendous opportunities for all stakeholders, including OEMs, MRO coating shops, coating providers, equipment manufacturers, and researchers, to contribute to a vibrant, growing MRO industry. Compared to new manufacturing, MRO has a positive impact by reducing the use of natural resources, carbon emissions, and waste generation, thereby improving the vision for a greener future and positively impacting sustainability. Resolving critical challenges will allow the MRO industry to contribute significantly to the global transition toward a sustainable, circular economy in the aerospace industry.

Cutting-edge Thermal Spray Technologies

Liquid Feedstock Thermal Spray Opportunities and Challenges for Aerospace Applications

Nicholas Curry, Mohit Gupta, and Filofteia-Laura Toma

Status of the Field

Liquid feedstock spraying at its most basic level, utilizes suspensions of solid particles in a liquid transport media (suspension thermal spraying) or solution precursors made of mixed chemical constituent at the molecular level (solution precursor thermal spraying). The suspension spray process was developed as a way to enable the feeding of fine particles below 10 µm in size that cannot be conventionally sprayed. In practice, this has involved nano, submicron or micrometric powders in a liquid carrier based on water or an organic solvent. The solution precursor process takes this a step further by utilizing only metallic or organometallic salts (e.g., zirconium acetate) in solution with the coating material forming in-flight before depositing on the surface. This essentially moves the complex process of powder/particle formation from the powder manufacturer to the spray process itself.

Suspension plasma spray (SPS), in particular, became an important processing technique for the aerospace industry with the discovery of columnar coating formation. The ability to produce a strain tolerant coating similar to thermal barrier coatings (TBCs) produced by electron beam – physical vapor deposition (EB-PVD), spurred on further research in the field due to the attractiveness of a more flexible and lower cost, atmospheric process. Over the past 15 years, the capability of the process has advanced intensely. This can be illustrated in the solid load (weight percent of coating material to carrier solvent) of suspensions increasing from 5-10 wt. % initially to commercial suspensions now available at 70-80 wt%.

In these intervening years, TBCs produced by SPS are known to have been flight qualified for use in aeroengines and the suspension manufacturing process has been certified for use in the aviation industry. Solution precursor plasma spraying (SPPS) and suspension high velocity oxy fuel spraying (SHVOF) are still in early stages of development when considering aerospace applications. On the equipment side, there are currently at least two fully commercialized equipment for processing of liquid feedstocks with plasma and one provider of commercial SHVOF equipment. This demonstrates the need for specific equipment designed to enable liquid feedstock spraying. The state of the field can be considered to be at the early stages of commercialization.

Current and Future Challenges

Current Challenges

From a technical perspective, one of the main challenges is preparing suspensions and solutions. As Toma et al. (Ref 202) pointed out, using suspensions as feedstock requires certain properties: good homogeneity, good flowability, low viscosity, high particle stability against agglomeration and sedimentation, fast re-dispersability, compatibility with hardware components, and long-term process stability. Developing stable and reliable suspensions that can be tailored to the specific requirements of each application can be challenging because finding suitable feedstock materials that perform consistently is difficult. Currently, there is a limited number of commercially available suspensions tailored for specific applications. Developing new suspensions with different feedstock sizes is still a tedious process. In developing liquid feedstock, water and various organic solvents, mainly alcohols, are used as liquid media. Ethanol-based feedstocks are preferred for creating columnar microstructures but require careful handling, storage, and transport due to their volatility, demanding stringent safety measures. Stricter environmental regulations regarding waste disposal and emissions could increase operational costs. The handling of fine particles in suspensions could also be a concern.

Spraying liquid feedstocks requires specific feeding systems, adequate injectors, and spray torches. The initial investment in advanced liquid feedstock thermal spraying equipment and technology can be significant. The need for high-power torches increases operational and energy costs, which could limit the implementation of this technology for many companies. Uncertainty regarding return on investment (ROI) and competition from alternative technologies or established EB-PVD, which could offer better performance, present ongoing challenges to the acceptance of liquid thermal spraying in aerospace applications.

Effectively coating complex geometries remains challenging because coating coverage and adherence may not follow the same trends as traditional powder spraying techniques, which compromises the durability and performance of the coatings. The currently available diagnostic tools and models are insufficient because they provide a limited understanding of droplet interaction with plasma/flame and coating formation. Additionally, the lack of extensive research and understanding of non-thermal barrier coating applications limits the acceptance of liquid feedstock spraying for broader applications.

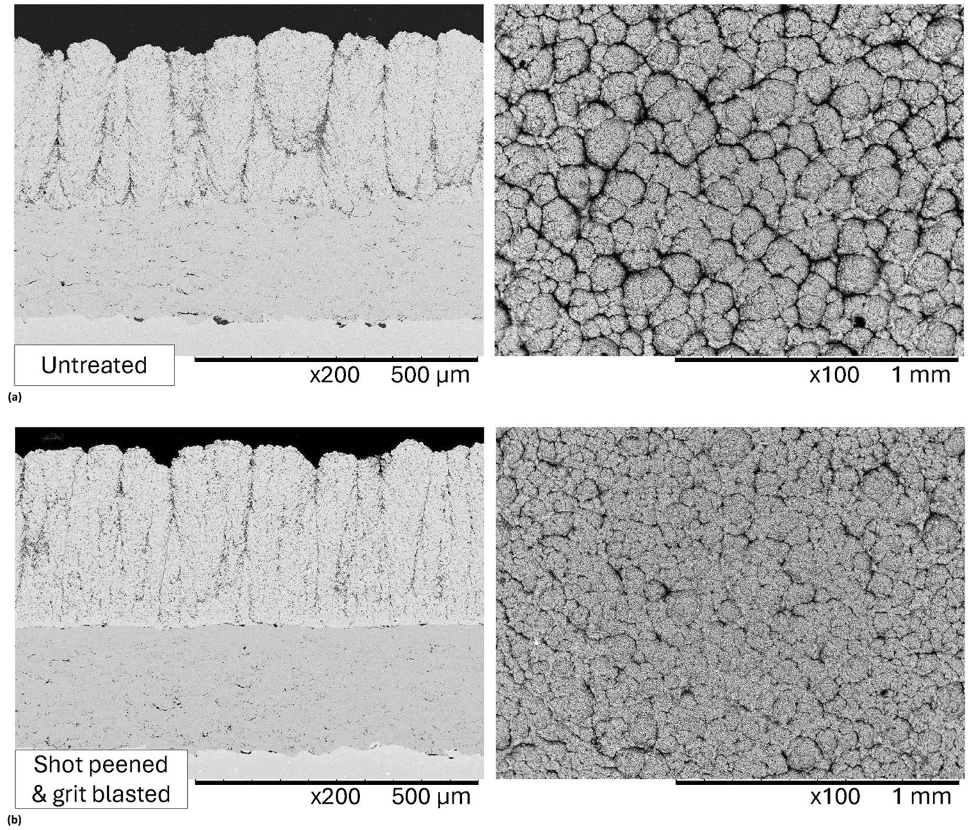

Fig. 30 Cross-section (left) and top view (right) images showing columnar YSZ TBCs produced by SPS with HVAF sprayed bondcoats: (a) untreated bondcoat and (b) with shot peened and grit-blasted bondcoats.

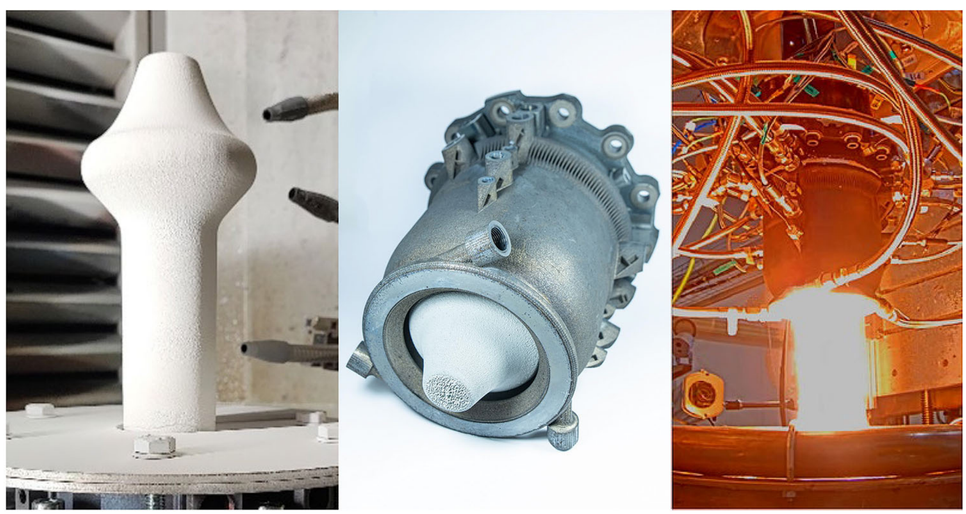

Fig. 31 Aerospike component (length about 265 mm and maximum diameter 240 mm) coated by SPS (left), aerospace engine demonstrator with coated spike (middle), and bipropellant hot-fire test run of the ASPIRER aerospike engine (right)

Future Challenges

As aerospace manufacturers develop next-generation engines, there will be a need for advanced thermal barrier coatings (TBCs) and environmental barrier coatings (EBCs) with superior corrosion- and wear-protection properties. These coatings must be able to withstand higher temperatures and more severe operating conditions in order to protect components from extreme environments. This will require continuous research in terms of material selection and efficient processing methods.

Addressing these challenges requires intensive research, collaboration among industry stakeholders, and innovative solutions to improve the performance and acceptance of liquid thermal spraying technologies.

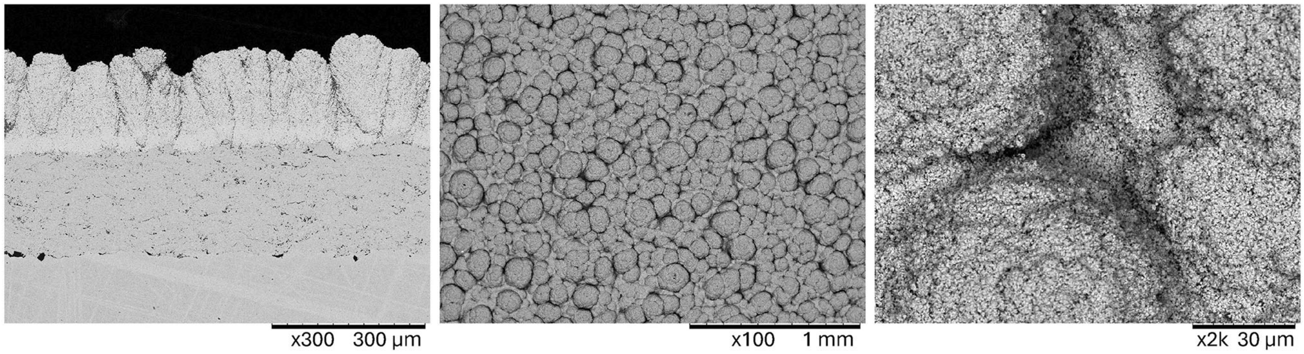

Fig. 32 Cross-section (left) and topview (middle and right) images showing columnar YSZ TBCs produced by SPPS

Advances in Science and Technology to Address Challenges

In recent years, significant advancements and breakthroughs have been made in the field of liquid feedstock thermal spraying for aerospace applications. Several studies have focused on the durability of YSZ TBCs produced by SPS. One approach has been to modify the topcoat-bondcoat interface to produce a favorable columnar microstructure. Using high-velocity air-fuel (HVAF) spraying has been shown to create a dense bond coat with minimal in-flight oxidation and low surface roughness, which is necessary for producing high-column-density SPS top coats. Gupta et al. compared various bondcoat deposition processes, demonstrating that shot peening the bondcoat, followed by light grit blasting, creates small-scale roughness features on the bondcoat surface. This results in a strain-tolerant topcoat microstructure with high column density (Fig. 30) and a cyclic lifetime nearly twice that of untreated samples (Ref 203).

A deeper understanding has been gained of how column formation and the microstructure of coatings are affected by spraying liquid feedstock onto complex geometries. Uczak de Goes et al. systematically studied how spray angle influences the microstructure, thermal conductivity, erosion resistance, and lifetime of SPS TBCs. They concluded that spray angles lower than 70° could significantly deteriorate the performance of the coatings (Ref 204). Bellippady et al. deposited SPS TBCs on additively manufactured (AM) superalloy substrates, which can have very high surface roughness. They observed that the microstructure and lifetime of the SPS TBCs were not significantly affected by the initial high roughness of the AM substrates (Ref 205). Toma et al. studied the evolution of the SPS TBC microstructure on the AM spike contour of an engine demonstrator (Fig. 31) and observed different columnar microstructures in various regions of the spike's complex shape (Ref 206). Engine testing successfully demonstrated stable operation in different hot-fire test runs powered by a combination of sustainable hydrogen peroxide and kerosene propellant (Ref 207).

There are continuous efforts to find alternatives to ethanol as a solvent for producing columnar TBCs. Xu et al. modified a water-based suspension by adding surfactants to reduce its viscosity and surface tension. They demonstrated that producing columnar TBCs with a water-based suspension is possible using this method (Ref 208). Nonflammable organic solvents have also been developed that produce columnar microstructures (Ref 209). Hervy et al. used an aqueous precursor salt solution as the feedstock instead of a suspension. They utilized a high-power axial injection plasma spray gun to deposit SPPS TBCs (Ref 210). Earlier works employing radial injection plasma spray guns encountered challenges with the incomplete pyrolysis of the solution precursor due to the inefficient transfer of thermal energy from the plasma plume to the feedstock. However, this study successfully produced columnar TBCs (Fig. 32) because the solution precursor could be injected directly into the plasma core. Furthermore, this was achieved at similar deposition rates and stand-off distances as state-of-the-art axial SPS TBCs.

Using SPS to produce Ytterbium Disilicate (EBCs) is of great interest and has been investigated in detail in recent years. Although SPS has the potential to deposit denser, higher-crystallinity layers than APS, the formation of segmentation cracks remains a challenge (Ref 211). Furthermore, SPS is being investigated for depositing superhydrophobic titania coatings for anti-icing applications in the aviation industry since SPS can produce a microstructure with dual-scale (also known as hierarchical) surface roughness. Farahani et al. demonstrated that SPS titania coatings with a polymeric topcoat significantly reduce ice adhesion (Ref 212).

Concluding Remarks and Future Perspectives

Combining liquid feedstock thermal spraying with the new generation of high-power spray torches can create unique coating microstructures with enhanced features and improved performance. Microstructures and chemistries that are impossible to create with conventional powder feedstock can easily be formed with liquid feedstock, providing much greater potential for a variety of aerospace applications. These advanced coatings can lead to higher engine efficiency, the use of more corrosive alternative fuels, and a longer component lifetime.

Future research could focus on fundamental studies of coating formation on complex geometries to facilitate the technology's transition to industrial components. The development of diagnostic tools to investigate in-flight droplets and particles is also necessary. Advanced models of liquid feedstock spraying could provide a fundamental understanding of droplet interaction with plasma/flame and coating formation. Promising new chemistries, such as high-entropy oxides (HEOs), could be explored using solution-precursor feedstocks, eliminating the need to produce expensive feedstock powders.

Cord Plasma Spray: A Possible Alternative to Suspension Plasma Spray?

Dominique Billières, Shrikant Joshi

Status of the Field

In the growing field of advanced ceramic coatings, which have applications in diverse industrial segments ranging from gas turbines to semiconductors, the microstructure of the coating is often as important as the intrinsic properties of the coating material. Only a few of the available coating methods allow for the deposition of a consolidated ceramic layer without post-sintering, with thermal spray and PVD technologies being the most notable exceptions. Each of these techniques has a "signature" microstructure — columnar for PVD and lamellar for thermal spray — as well as a typical thickness domain: 0.1 to 5 µm for PVD and 30 to 1,000 µm for thermal spray. PVD has expanded its thickness domain to include thick coatings (a few hundred µm) thanks to EB-PVD technology. Thermal spray technology has also evolved significantly in the past 25 years. The Cord Plasma Spray (CPS) technique is the most recent development in the thermal spray processing portfolio. It is based on a new type of feedstock that delivers fine particles into the plasma stream while eliminating the need for a liquid carrier. Apart from its versatility in conveniently combining desired coating materials, CPS has the potential to provide considerable microstructure control and process robustness, overcoming some of the key challenges associated with the use of suspensions as thermal spray feedstock.

Prior to the introduction of SPS technology in November 2024, the most significant developments in thermal spray technology over the past two to three decades were (i) the use of liquid feedstock, particularly in the form of suspension plasma spray (SPS), which enables the spraying of much finer particles than is conventionally possible, and (ii) the development of axial-feed capable plasma spray systems that allow for the reliable feeding of starting materials and the more effective utilization of the thermal energy available in the plasma plume. The SPS method enables the deposition of coatings as thin as ~ 10 µm and produces microstructures that cannot be achieved with conventional powder-based thermal spraying. These microstructures include very dense layers and deposits with fine, controlled porosity and columnar structures.

These microstructures are relevant in the demanding fields of advanced thermal barrier coatings (TBCs) and environmental barrier coatings (EBCs) for gas turbines and aeroengines. Progress in TBCs has enabled higher combustion temperatures, enhancing turbine efficiency, extending lifetime, and reducing maintenance frequency. EBCs promise to facilitate the use of CMCs, which are crucial for significantly reducing the weight of turbines. Apart from assessing the prospects of deploying new materials (Ref 50, 213-217) and evaluating new coating configurations (Ref 218-221), considerable emphasis has recently been placed on developing approaches to exercise requisite microstructural control. Such control is desirable to optimize the performance and longevity of TBCs and EBCs and to tailor ceramic coatings for other applications depending on the operating environment.

For example, dense coatings are desirable for EBC (Ref 70, 222) and semiconductor (Ref 223) applications, while columnar or dense vertically cracked microstructures are preferred to impart superior strain tolerance to TBCs (Ref 224).

In the above context, the SPS route has generated strong interest in particular for delivering the following:

- Very dense layers in a wider thickness range of the order of 10-300 µm
- Finely structured or nano-structured ceramic coatings offering potentially higher toughness and/or lower thermal conductivity
- Columnar coatings, with some potential advantages over EB-PVD technique including ability to coat larger or more complex components, lower operating costs,

lower capex requirement, reduced overall environmental impact, and higher industrial flexibility for more efficient MRO operations due to relative ease of adding more capacity in order to reduce lead-times.

In tandem with the development of SPS technology, the availability of axial-feed capable plasma torches has led to substantially higher throughputs being demonstrated to prompt the transition of SPS from merely being academic to becoming relevant for actual industrial applications. However, a few significant challenges associated with the SPS route, briefly discussed below, have hampered its adoption on the shop floors. The CPS technology presents an elegant approach to overcome the extant hurdles for SPS implementation and offers an attractive alternative while retaining all benefits of the latter.

The primary motivation behind the CPS innovation was the desire to eliminate the use of a liquid carrier to introduce the fine powder particles into the plasma spray process, and to devise a more industry-friendly strategy. A similar incentive has previously prompted use of a filament, highly filled with a fine powder with a solid polymer carrier, as a feedstock material for thermal spraying (Ref 225). As a reminder, the concept of SPS was developed with the goal of overcoming the feeding problems traditionally associated with fine powders by utilizing a liquid carrier (the solvent) to facilitate transport of powders from the feeder to the injection point as well as providing enough momentum to the powder particles enveloped in a solvent droplet to penetrate the plasma stream upon radial injection. The recent availability of a tri-cathode gun with axial material feeding has demonstrated an interesting capability of permitting more reliable introduction of the suspension into the core of the plasma plume while ensuring superior plasma stability. Apart from suppressing all the challenges and drawbacks of radial feeding, axial injection has also been shown to address concerns regarding narrow process windows and also enables better deposition rates, higher particle speed than with radial feeding. Notwithstanding the above, a significant barrier to adoption of SPS technology are a couple of factors related to the use of suspensions: (a) handling of a flammable solvent such as ethanol in storage and transportation; and (b) stability of the suspensions during storage and spraying process, since settling or agglomeration of particles in the suspension drastically influences the process results. While most of the previous studies aimed at obtaining columnar microstructures have involved alcohol-based suspensions, we must mention that there have also been some rare prior reports on achievement of columnar TBC microstructures using, for example, surfactant-modified water-based suspensions (Ref 208).

In the CPS process, a completely different approach is taken to introduce the fine particles into the plasma stream compared to the SPS. A solid carrier is designed in the form of a “flexicord”, which is an extruded cord constituted of fine particles and a suitable binder capable of being easily pyrolyzed, such that the particles are released into the plasma stream almost instantaneously as the binder burns off. Combining the above idea with a suitable axial feed capable plasma gun presents a facile pathway to reliably inject the flexicord into the plasma plume. Figure 33 schematically illustrates the CPS set-up.

Interesting initial results have been demonstrated with the CPS approach utilizing YSZ (Yttria-Stabilized Zirconia) material as a case study, representing a first proof-of-concept validation. This preliminary study has already led to promising results not only in terms of establishing wide-ranging control over coating microstructures but also with respect to process attributes. Four distinct types of YSZ coating microstructures, namely very dense, segmented (dense with vertical cracks), finely porous and columnar/feathery coatings have been achieved by CPS as shown in Fig. 34, with the last two being of particular relevance to TBC applications.

These microstructures were achieved with the use of an Axial 3 + plasma gun (from Northwest Mettech Corp. Canada), using ternary gas mixtures (Ar, N_2, H_2), at powers ranging from 107 to 140 kW and stand-off distances from

Fig. 33 Schematic view of the set-up for CPS (Cord Plasma Spray) process.

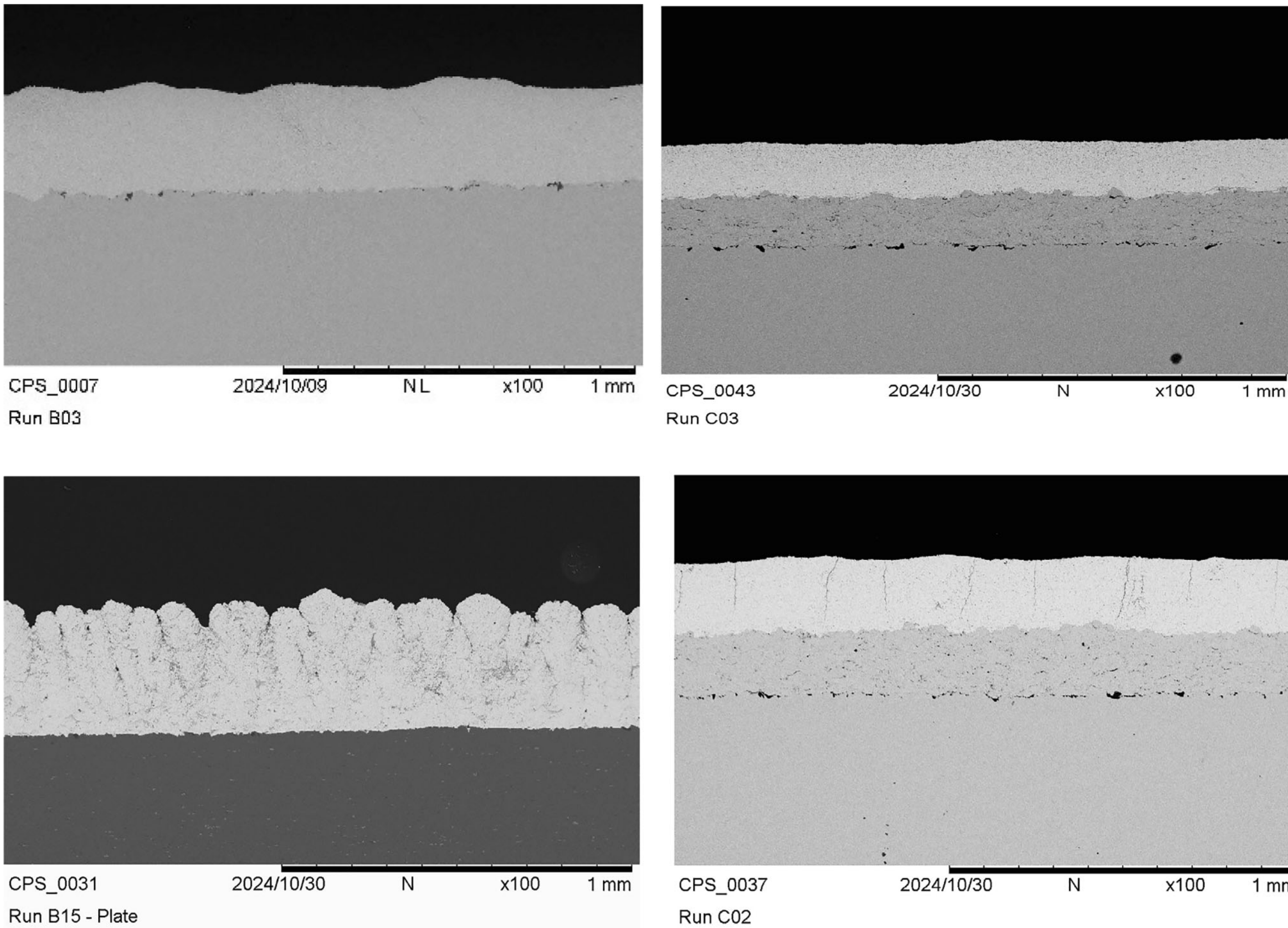

Fig. 34 Cross-section images by Secondary Electron SEM of YSZ coatings obtained by CPS demonstrating 4 main types of microstructures (Dense, finely porous, Columnar, and segmented)

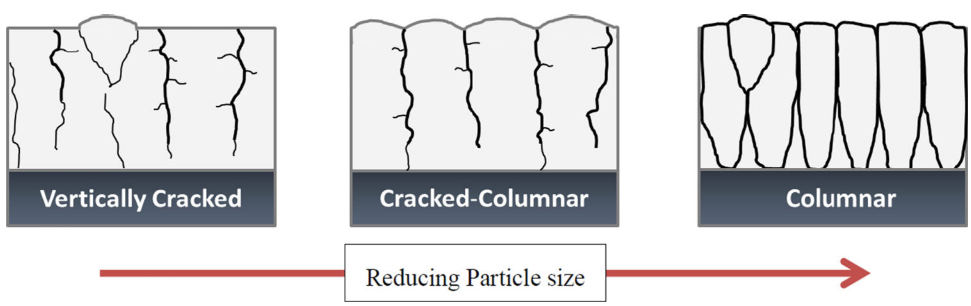

Fig. 35 Schematic illustrating different coatings microstructures obtained as a function of particle size in SPS process (Ref 226). Reprinted from (Ref 226), available under CC BY 4.0 license at MDPI

70 to 90 mm. The feed-rates were varied between 25 and 35 g/min and the resulting deposition efficiencies ranged from 25 to 45%. Compared to other thermal spray processes involving such fine particles, these values represent a promising start in terms of productivity and applicability but shall be considered as a preliminary status and further work will likely lead to further improvement in these values.

This development was made possible due to the considerable prior research conducted with SPS, which provided a sound foundation of process understanding. In many respects, this understanding is translatable to CPS. Consequently, appropriate particle size control during fabrication of the flexicord results in different microstructures that have been previously achieved by SPS (Ref 226) (Fig. 35). Thus, the link between the particle size utilized when manufacturing YSZ-based flexicords and the obtained microstructures is very consistent with prior learnings associated with research on SPS: the columnar microstructure was achieved with a sub-micron powder used in the flexicord while the 2 other microstructures were obtained with a powder exhibiting an average particle size

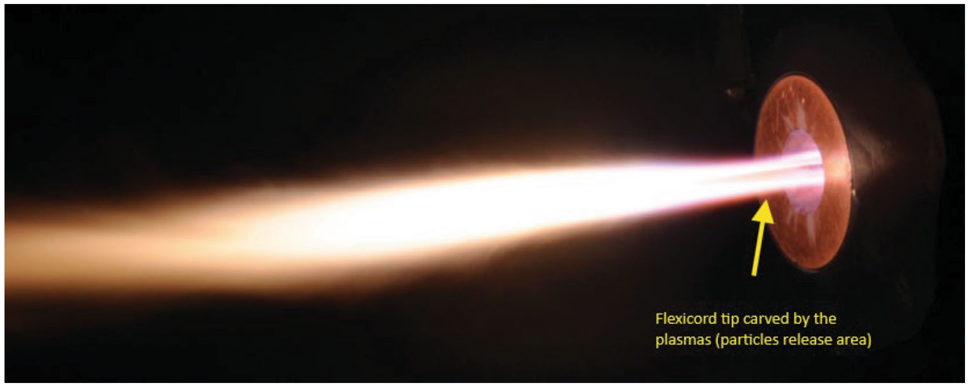

Fig. 36 View of the CPS in operation revealing the tip of the flexicord carved at the exit of the nozzle, indicating the location where the particles are released into the plasma stream

of 5 µm. This consistency of the above microstructures with past research on SPS demonstrates that the CPS process also allows a good release of fine particles from the flexicord in a controlled manner into the plasma stream, just like when using a volatile solvent like ethanol in SPS. It can be envisioned that particle momentum and/or trajectory linked mechanisms responsible for different coating microstructures in SPS also hold true in case of CPS coatings (Ref 227).

The CPS process has revealed some interesting attributes that seem promising for its reliable operation in production and, therefore, for implementation. These include:

- The spray stream was surprisingly stable (visual observation), which we believe is due to the higher stability of the multi-cathode plasma stream, the symmetric axial injection of material, and the fact that mechanical feeding of the cord is perfectly stable without any pressure fluctuations as in pneumatic feeding.
- No clogging inside the gun was observed, even after a prolonged session of spraying; the release area of the particles (corresponding to the region where the flexicord is carved by the plasma, i.e., where pyrolysis of the binder occurs) can be positioned just downstream of the gun nozzle exit as shown in Fig. 36.
- No solvent and no handling of fine powder associated with the process.
- The process can be started and stopped quickly, easily and reliably. It is stabilized and ready to spray on the component after a few seconds (< 5 seconds) and can also be stopped rapidly.

Current and Future Challenges

Despite its short development phase so far, CPS appears capable of delivering the wide range of microstructures that can be produced by suspension thermal spray. Furthermore, the ability to achieve such microstructure control without encountering the stability issues associated with suspensions, or the flammability issues associated with use of alcohol as a solvent, makes it attractive for industrial implementation. However, several further steps remain yet to be taken to convert the considerable early promise of CPS into widespread industrial acceptance. The more prominent among these are:

Feedstock Related

The composition of the flexicord is a key factor in the CPS process as it embeds several parameters such as the particle size distribution of the coating material, the useful solid content, and its design contributes to the quality and consistency of particles release in the plasma stream. Therefore, the manufacturing of the flexicord will be at the heart of each new coating development with the CPS process. Among the most prominent tasks will be the following:

- Design and development of flexicords for each class of application to achieve targeted microstructures.
- Optimization of flexicord composition for enhanced deposition efficiency and other process KPIs as deemed relevant
- Development and fabrication of flexicord for a wide range of materials and their combinations to ensure versatility of CPS.
- Scaling-up of flexicord manufacture to support industrial adoption of CPS
- Assessment of shelf-life and definition of recommended storage conditions (can be composition-specific)

Hardware Related

Successful and easy implementation of CPS also requires a specific device, the feeding unit, that must be suitably integrated with the plasma gun, leading to an increased overall size and weight of the spraying system. With the proof-of-concept results now demonstrating considerable promise, further developments are expected to be focused on shrinking the size and weight of the device, as well as potentially developing an integrated gun design to address the size constraint of CPS. An interesting feature that can also be implemented is a closed-loop control of the actual flexicord advance speed to reliably regulate the feed rate and detect any deviation versus nominal value.

Process Related

In order to build a robust process understanding, many aspects of CPS process need to be further studied and documented. These include:

- Collection and characterization of sprayed particles for each CPS coating developed, in order to further document the link between sprayed particles size distribution and coating microstructure
- Investigation of influence of feed-rate and location of particle release in the plasma stream on the coating microstructure and deposition efficiency
- Establishment of process-maps defining process parameter - coating microstructure relationship, including the role of substrate surface attributes wherever relevant.
- Demonstration of ability to realize varied function-specific coating architectures such as multi-layered, composite etc.

The above aspects can be topics of future academic research related to the CPS process and bear some similarities with the road map followed for development of SPS through collective efforts by thermal spray groups worldwide.

Performance Related

As with any emerging coating technology, the performance of CPS-derived coatings will need to be comprehensively assessed for each envisioned application and compared with alternative thermal spray approaches. For example, in the case of TBCs this could imply evaluating the thermal cyclic fatigue, burner rig and erosion behavior of the coatings as well as the associated failure mechanisms through in-depth post-mortem analysis. From the standpoint of existing OEM users of TBCs, a comparison of the CPS coatings' performance with appropriate coatings obtained from competing technologies (viz. EB-PVD and SPS for columnar TBCs; APS for segmented TBCs) will be key. Other functional coatings targeted by the CPS technology would similarly have corresponding performance tests and process comparison requirements.

Advances in Science and Technology to Address Challenges

As mentioned in the previous sections, the vast body of prior research conducted on SPS coatings is educative and has established an important foundation for further technological progress with CPS. Research activities related to SPS have provided a good understanding of what drives the different types of microstructures obtained. For example: (a) deposition of very dense layers requires a few µm-size (1-5 µm) powder particles; (b) realization of columnar layers is facilitated by very fine particles (typically < 1 µm). The column formation is also known to rely on particles with low Stokes number following the gas stream in the vicinity of the substrate surface and leading to coating build-up on the sides of asperities/roughness present on the surface.

Advancements in sensors allowing in-flight particle diagnostics to be applied to very fine particles (µm or sub-micron size) will be of particular interest for further understanding and optimization of the CPS process. The fact that the particles in this process are "dry" allows such developments to be implemented more efficiently than processes involving liquid droplets in the spray stream. By analogy and comparison between SPS and CPS processes, the advances in particles metrology realized using CPS can also enhance the understanding of SPS considering that the mechanisms of coating formation (and the dependence on particle size, velocity and stokes number) would be similar in the two cases once the powder particles are 'released' in the spray plume.

Concluding Remarks and Future Perspectives

The recent introduction of CPS (Cord Plasma Spray) has demonstrated very interesting potential as it can deliver the same range of microstructures as SPS but with added interesting attributes from the perspective of industrial implementation: simpler process, no solvent or fine powder handling, as well as options for process control.

The first available CPS results provide ample incentive to conduct further research in the following directions:

- Further optimization of the process and the cord design with YSZ model material to explore the boundaries of the CPS process in terms of productivity and achievable microstructures.
- Evaluate the performance of TBCs deposited by CPS process and compare with best-in-class TBCs
- Expand CPS process to other chemistries for TBCs and EBCs as well as other applications

- Explore flexicord manufacturing and CPS interest for different material combinations that are challenging or difficult to achieve in the form of traditional thermal spray powder feedstock and difficult to apply by regular thermal spray (e.g., wear resistant + solid lubricant material combinations).

In conclusion, the CPS technology shows promise to accelerate the implementation of innovative coatings on industrial components, as it seems well suited for the deposition of high-performance coatings with promising attributes for good process robustness. Some cross-fertilization of knowledge from research carried out on SPS and CPS could also benefit these technologies to address wider fields of application and accelerating their acceptance in market segments.

Thermal and Cold Spray Deposition onto Polymer-based Substrates

Andreas Killinger, Andre C. Liberati, Christian Semmler, Sophie Senani-de Monredon, Stephen Yue

Status of the Field

The aerospace industry has transitioned to polymeric or fiber-reinforced composite structures to reduce weight and increase formability, thereby achieving lower fuel consumption and CO_2 emissions. The downsides of these materials, such as poor tribological behavior and low heat resistance, can be offset by coatings applied through thermal and cold spraying. These mature solutions offer great flexibility, are automated in industrial settings, and provide potential for rapid scaling up on parts with complex geometries. While the 2016 Thermal Spray Roadmap barely addressed the topic, growing efforts from academic and industrial actors have since aimed to develop novel "coating-substrate-thermal spray process" combinations, clarify deposition mechanisms, improve adhesion, and explore relevant applications.

Some of the first applications were functional graded polyimide + WC-Co coatings on polyimide fiber-reinforced substrates, which NASA developed in the early 2000 s for erosion and oxidation resistance (Ref 228). Then, Airbus and Boeing published patents on the topic in 2013 (DE 102008001468) and 2014 (US 10060019B2), respectively. Meanwhile, GKN Aerospace (Redditch, UK) developed the proprietary "Spraymat," which includes flame-sprayed, fiber-reinforced, epoxy heating elements (GB 2477336A), for deicing Boeing 787 Dreamliner carbon fiber-reinforced polymer (CFRP) wing parts (Ref 229).

Most thermal spray studies have focused on thermosetting (TS) glass- or 2D/3D-CFRP, while cold spraying has concentrated on thermoplastic (TP) polymers and carbon- or glass-FRP. 2D/3D TS-CFRPs are typically used for structural applications due to their superior mechanical properties compared to TPs, which are used for nonstructural and interior parts.

TS polymers are obtained by irreversibly curing a resin, such as epoxy. However, studies increasingly include TPs substrates such as polyetheretherketone (PEEK), which demonstrate plastic deformation above a glass transition temperature. Although the manufacturing process is more expensive, TPs are rapidly emerging in aerospace applications due to their durability and reformability.

Current and Future Challenges

Direct cold spraying onto CFRP is generally limited to low melting point or relatively soft materials (Sn, Al or Cu), while harder materials (e.g., Fe, 316L, Ti) only bounce or weakly embed at the substrate surface. Coating mechanistics can be attributed to differing deposition windows for concurring metal-on-polymer or metal-on-metal deposition. Suitable deposition conditions appear to rely on having 1) comparable hardness between the metal and the substrate, to enhance co-deformation and avoid substrate erosion, and 2) adequate impact energy, which imposes conditions on the particle size, relatable to the particle's critical velocity (Ref 230). In parallel, direct deposition of ceramics or high melting point metals (316L, NiCr) *via* thermal spray often burns or degrades the substrate, whereas lower melting point metals can be deposited by plasma spraying (Zn, Al, AlSi6, CuAl10, Cu) or wire arc spraying (Cu, Ni-Cr). These materials have lower density, higher thermal conductivity and store less heat, which may facilitate deposition compared to thermally resistant ceramics. For both techniques, direct deposition relies on the erosion of near-surface polymeric layers with low adhesion, generally between 4 and 10 MPa, occurring around the relatively harder fiber sections, acting as anchoring points for the coating.

Improving the coating deposition, or adhesion, often relies on the use of interlayers or substrate surfacing agents, to improve material compatibility or mechanical interlocking. Typically, thin plasma sprayed Al bondcoats have allowed deposition of Al_2O_3, YSZ, Mullite or Cordierite coatings (Ref 231). Polymer-garnet-sand interlayers have also improved the flame spraying of Al-12Si coatings, or pull-off strength for cold sprayed Sn coatings. Adding polymer-copper powder or embedding wire-mesh in the top layer has improved the deposition and adhesion of various coating materials (Zn, Al_2O_3-TiO_2, WC-Co, Stainless steel) (Ref 232, 233). Other solutions include the use of electroplated interlayers, surface laser ablation (SLA) (Ref 234) and plasma treatments to induce roughness or chemical changes that improve adhesion ($\sim$ 20 MPa for the SLA samples), yet these approaches complicate the development of coatings, without providing significant cost reduction or manufacturing improvements. While the technology is somewhat mature for coating deposition, assessing properties, performance and possible applications requires further investigation.

Unlike aluminum structures, which naturally provide a Faraday cage effect, additional lightning strike protection (LSP) on CFRP parts is mandatory. Lightning strikes aircraft numerous times in-flight and on average once per year, the strike intensity may severely affect structural parts, avionics, communication systems and fly-by-wire controls through electromagnetic interference (EMI). Growing adoption of electric propulsion systems in future aircraft also increases the need to develop new LSP solutions. Wire mesh and metal foils have been proposed, but these tend to be costly or labor-intensive, whereas near fully dense Cu coatings have been achieved *via* cold spraying thus providing promise for TP-CFRP LSP (Ref 235).

CFRP components have entered the turbine cold-sections of the CFM International LEAP ("Leading Edge Aviation Propulsion") engine, but bird strike protection remains a priority for the fan blades' leading edge. These are currently protected by sharp-edged, forged Ti parts that must be bonded to complex CFRP fan geometries, with high precision to maintain aerodynamics. As thermal spray should provide faster, larger deposition and critical quality improvements with high precision robotic controls , it should also benefit open-fan turbine designs requiring bird strike and erosion protection, on larger, more complex blades. To answer these new challenges, Safran has been working to introduce such functionalities into engines and equipment via thermal spray coated parts since 2018 (patents FR 3141965A1 & FR 3100139A1), with specific bond coats directly thermal-/cold-spayed.

For the next-generation's turbine parts, coated CFRP outlet guide vanes (OGV) should also become relevant, just behind the fans, where erosive particles (e.g., water droplets, sand) may reach up to 200-400 m/s. While less constrained by the bird strike protection, the replacement of metallic OGVs by CFRP would require erosion and icing-resistant coatings to mitigate impacting particle damage or catastrophic engine issues.

Thermal spray coating solutions also strongly align with industrial interests as shown by recent patents published by Airbus Helicopters Deutschland on the cold spraying of electrically conductive layers on polymeric foil FRP assemblies (EP 3401419B1) or by Boeing on the cold spraying of erosion protective coatings on airfoils (US 11167864B2).

Advances in Science and Technology to Address Challenges

"Coating transplantation" was recently introduced to coat the internal surfaces of CFRP tubes and housings (Ref 236). It relies on applying a coating onto a mandrel, then manufacturing the CFRP component onto the coated mandrel, which is subsequently removed after curing. Advantages include the limited direct contact between metal and carbon fibers, improved adhesion strength and low surface roughness without the need for post-processing, thus significantly improving industrial scalability. This may even be used in combination with water dissolvable polymers to produce more complex, coated parts.

Other applications concern the transition toward novel aircraft fuels (e.g., H_2, N_2O), with interest in replacing 2 mm-thick tank liners (Al or stainless steel) with thinner, lighter, impermeable and corrosion resistant coatings (Cu, Ni), though the permeation of cold- or thermal-sprayed coatings needs to be investigated to prove their lower permeability. Recent patents have also been published on the deposition of transparent polymeric thin films on polymeric substrates *via* plasma spray – to provide lighter acrylic replacements to glass panels in aircraft (US 10118195B2) – or thermal/cold sprayed electrically conductive TP coatings on fuel tank fasteners for LSP, EMI shielding, or for high-performance sealing (US 11767436B2).

With electrical engines becoming more widespread, thermally sprayed polymers could have a future in electric vertical take-off and landing (eVTOL) aircraft, drones, air taxis or blended wing aircraft designs. Novel aerospace applications may also be sought from solutions in other industries, such as flame-sprayed piezoresistive coatings (NiCoCrAlTaY and TiO_2) on CFRP for wind turbine sensor applications, or thermally resistive, low thermal expansion ceramic coatings adapted to CFRP (e.g., mullite or corderite) used in the automotive industry to help reduce the thermal load on the CFRP. Zircotec (Oxfordshire, UK) offers such solutions with their zirconia-based ceramic blend ThermoHold, a Formula one (F1) thermal barrier coating for CFRPs. High hardness coatings (Cr_2O_3, Al_2O_3, TiO_2) on CFRP rollers, applied by Inometa (Herford, Germany) in the printing industry for electrical insulation or tribological properties could also serve in aircraft.

Nevertheless, some concerns are worth mentioning for these technologies. Galvanic corrosion of metal coatings on a carbon fiber composite, in the presence of an electrolyte (e.g., water or a humid environment) is generally a concern, but should be avoided with fully dense or impermeable coatings reinforced by polymeric sealers or glass-fiber insulating meshes. The sustainability of coated CFRPs may also be a concern as well-adhered coatings could complicate recycling. In parallel, processing gas, powder and energy consumption reductions are required to demonstrate environmental benefits compared to other coating processes or forged part assemblies. Some cases-study assessing the life cycle of coatings sprayed on CFRP substrates have been conducted, notably on thermal sprayed Al_2O_3-NiCr coatings for pipe freeze protection in Canada (Ref 237). However, more studies including the use-phase and end-of-life of the coated CFRP (i.e., cradle-to-grave studies) would be required to identify which specific use cases these technical solutions could benefits.

Concluding Remarks and Future Perspectives

Thermal or cold spray coatings on polymeric substrates have reached a level of maturity, with emerging applications in de-icing, erosion resistance, and EMI shielding. There is still potential to assess the properties and functional performance of these systems, particularly their cycling behavior throughout an aircraft's lifecycle. The advantage of this approach is its ability to adapt and modify coating materials, substrates (e.g., polymer nature, fiber reinforcements), and applications. The latter would benefit from greater industry-university collaboration. One notable problem is the effect of coatings on CFRP, which requires discussions about testing standards or key metrics that could improve the maturity of the technology. Certification is another issue, but ultimately, it relies on industry's drive to develop and implement these solutions.

Looking ahead, aircraft projects span 10-15 years before reaching the market. While the current approach has focused on replacing metallic parts with lighter CFRP counterparts, most of the low-hanging fruit has already been picked, as evidenced by the Boeing 787 Dreamliner and the Airbus A350 and A320, whose fuselages contain 45-55 wt.% composite materials. Therefore, future projects may search for marginal, application-specific weight gains (e.g., replacing bronze meshes with LSP) and rely on cost or cycle-time optimizations. Thermal- and cold-sprayed coatings may provide key solutions for these optimizations. Future aircraft designs may differ significantly from current designs, with gas turbine engines evolving toward open-fan engines and requiring new materials and applications.

However, surface functionalization of carbon fiber reinforced plastics (CFRPs) by thermal spraying remains a major challenge for engine manufacturers, helicopter makers, landing gear and nacelle equipment suppliers, and cabin interior suppliers, as well as for space applications. The development potential relating to many functionalities, such as thermal protection, erosion protection, icing protection, and fire protection, opens the way to numerous business cases that have been largely unexplored by academics and industry thus far. The first barrier lifted by industry is understanding the anchoring mechanisms according to different types of CFRPs, paving the way for developing a functional layer adapted to each usage environment. This work is necessary to achieve applications that will be used in the next generation of aircraft, engines, and space launchers. Therefore, while it may be tempting to think in terms of bulk materials (metal or composite) during the selection and design process, it is crucial to integrate coatings as part of the solution rather than as an add-on.

Advances and Challenges of the Aerosol Deposition Method in Aeronautical Applications

Frank Gärtner, Makoto Hasegawa, Óscar Rojas, Pierre Sallot, Kentaro Shinoda

Status of the Field

Among coating techniques, aerosol deposition (AD) bridges the gap between thin-film techniques for electronic devices and the production of medium-thickness protective layers for harsh environments. It enables deposit buildup ranging from less than one micrometer to hundreds of micrometers (Ref 238, 239). Relying on high-velocity particle deposition in the solid state of the material allows one to maintain the crystallographic structure, and thus the properties, of the feedstock, thereby retaining its well-designed attributes (Ref 240). Although AD is especially suited for ceramic materials, the process can also, in principle, be used to deposit metals (Ref 241). The main industrial application of AD is currently plasma-resistant coatings for semiconductor manufacturing components. Due to their excellent erosion resistance, nanocrystalline, dense Y_2O_3 coatings on the inner walls of process chambers reduce particle generation by fluorine plasma (Ref 242). Similarly, aerospace industries could also benefit from the unique properties of AD coatings in harsh environments.

At first glance, using AD as a kinetic spraying method for ceramics appears contradictory since any pottery would shatter under high mechanical loads. In AD, however, fine particles, typically ranging from 0.1 to 5 µm, impact and adhere to the substrate to form dense ceramic coatings. The associated mechanisms are usually described in the

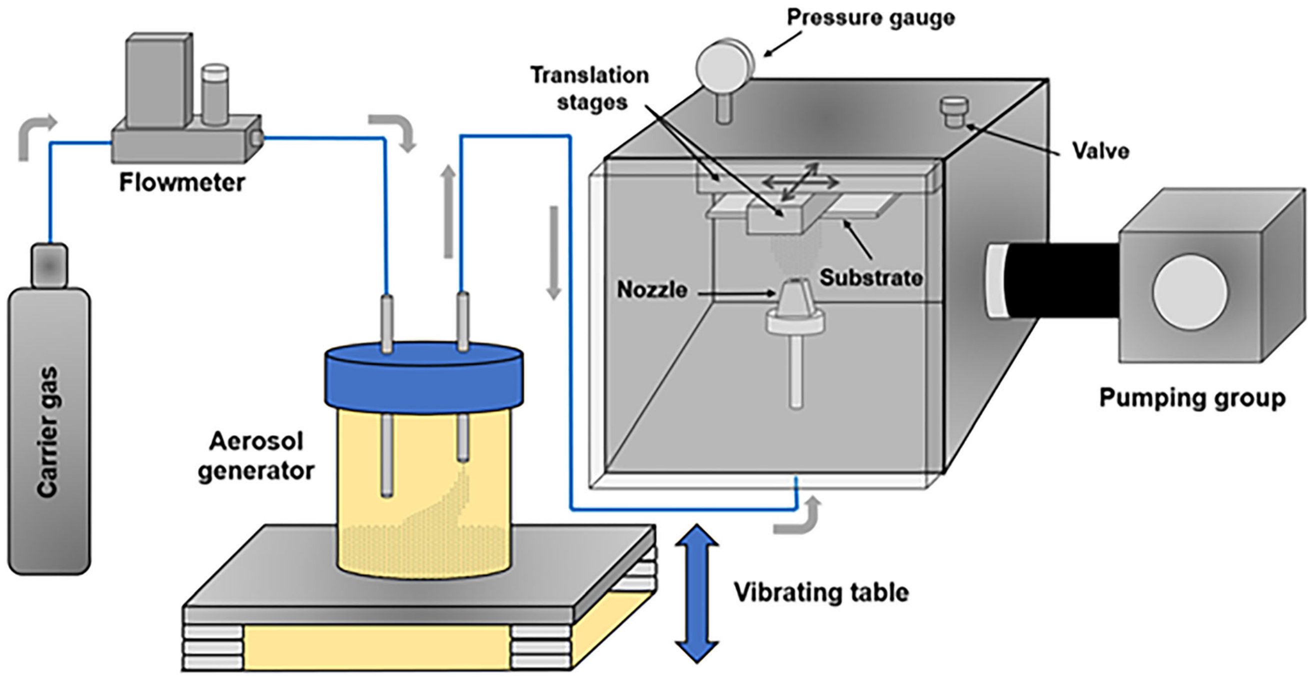

Fig. 37 Schematic illustration of the principle of the aerosol deposition method

literature as room temperature impact consolidation (RTIC) (Ref 238). These mechanisms support successful deposition by transforming brittle fracture into ductile deformation at dimensions in the micrometer range or below. Thus, AD of ceramics requires much smaller particle sizes than cold spray deposition of ductile metals. Fine ceramic particles must be accelerated to high velocities (100-600 m/s) to induce pseudoplastic deformation and dynamic fragmentation, thereby causing them to adhere to the substrate. Enabling subsonic to supersonic impact velocities of micro- to sub-micrometer-size particles defines the technical layout for AD, as shown in Fig. 37. An aerosol generator fluidizes and transports the fine powder into the main process gas stream. Due to their small momentum, the fine particles can be efficiently accelerated. The acceleration needed for particles sized about one micrometer can be ensured by flowing them through a slit-type nozzle at gas pressures of less than three bars. However, the particles' small momentum could lead them to diverge by following the gas stream in the free jet. To minimize interactions between the aerosol particles and the surrounding gas, which would otherwise deflect and decelerate the particles, especially in the bow shock region in front of the substrate, the deposition process is performed under vacuum conditions. This environment ensures the particles reach the substrate surface with sufficient velocity for effective coating formation.

Under optimized conditions, AD can provide a coating density of over 95% and an adhesion strength of up to 50 MPa. These properties are ideal for the thin-film processing of functional applications (Ref 243).

AD offers exceptional versatility in terms of materials and substrate selection. Since AD is a low-temperature deposition process, it retains the properties of the original feedstock material and can offer further benefits by resulting in nanocrystalline microstructures. AD also enables the deposition of different microstructures and materials by avoiding thermal mismatch stress during deposition. For instance, a dense sealing coating can be applied to porous materials.

Regarding commercial combustion engines used in aerospace applications, AD's capabilities could offer advantages through the deposition of high-hardness, thermally stable ceramics such as Al_2O_3, ZrO_2, Y_2O_3, and mullite (including stabilized variants and mixtures) for use in thermal barrier coatings (TBCs) and for high-temperature corrosion and environmental protection (Ref 244). Beyond high-temperature applications, AD's versatility extends to a wide range of aerospace applications, including structural protection and functionalized surfaces. This is thanks to its compatibility with various substrate materials, such as metals, ceramics, glasses, and polymers, in thin and thick configurations and with rigid or flexible properties. For example, corrosion-resistant coatings could be used for aluminum parts, as well as self-lubricating coatings for space applications. Transparent, adaptive, hydrophobic alumina coatings enhanced with poly-tetra-fluoro-ethylene (PTFE) have been developed for the potential optical protection of cameras and radar systems in aerospace applications (Ref 245).

The versatility of depositing ceramic materials by AD also offers the potential to produce state-of-the-art sensors (Ref 239), which could be essential for developing processes and monitoring services with new technologies that enable a green future. Examples thus far include gas sensors for oxygen ($BaTi0._7TaO_{3-\delta}$, BFT, etc.), humidity ($BaTiO_3$ or n-type CuO), and carbon monoxide (SnO_2), as well as temperature sensors. Other examples include coatings for new all-solid-state battery designs ($TiNb_2O_7$, among others) and fuel cells (YSZ with $Sm_{0.2}Ce_{0.8}O_2$ as a diffusion barrier). Additional developments could be tuned by respective material design.

Current and Future Challenges

In order to reach net-zero emissions by 2050, the aerospace and transportation industries must develop innovative technologies to produce and utilize alternative fuels (Ref 9). For short and possibly mid-distance flights, electrical propulsion powered by batteries, fuel cells, or stored hydrogen is a viable solution. However, long-distance flights will require the direct use of high-energy-density synthetic fuels. Electrical propulsion and the production and use of synthetic fuels will require new energy storage technologies, green fuel production, and all associated infrastructure, particularly for hydrogen. Thus, technological breakthroughs are needed in new propulsion designs, energy storage, and efficient green production techniques for electricity, hydrogen, and associated e-fuels, including ammonia as an energy carrier. These global requirements call for novel solutions and consequently present challenges for coating technologies, ranging from thin films for new functional applications to thick coatings that can withstand newly defined harsh environmental conditions. Additionally, to ensure longer lifetimes, coating or deposition techniques could benefit the production or repair of aerospace parts using additive manufacturing techniques.

Following this roadmap, the AD process's applicability to the aerospace industry to achieve a greener sky must address the following challenges:

With respect to current and future applications, AD offers the advantage of being able to deposit dense ceramic coatings, such as alumina, onto various substrate materials without any phase changes. This could be particularly beneficial in harsh environments involving E-fuels, wear conditions, and thermal or electrical insulation. Additionally, maintaining the original properties of the feedstock offers opportunities to develop new concepts for energy harvesting and sensors for monitoring.

To apply the AD process to large-scale production, however, process stability and reliability must be improved. A major challenge of AD, especially from an economic standpoint, is the low deposition efficiency of less than 10%. This efficiency is sufficient for thin film processing, but it must be improved for larger scales and thicker coatings. Process reliability also requires a better specification of powder properties and processing designs. Despite the low deposition efficiency, AD offers advantages in energy and operational efficiency because it operates under moderate vacuum conditions (approximately 1 mbar) and requires low gas pressures (less than 2.5 bar) and flow rates (5-30 l/min). This results in comparatively low energy and resource consumption, as well as low operational costs.

One primary technical barrier remains, however: the preparation, adaptation, and control of feedstock powder characteristics. The process efficiency and coating quality heavily depend on particle size distribution, morphology, composition, agglomeration state, and the nature of the process gas. Greater standardization of these parameters would lead to more consistent coating density and adhesion, thereby strengthening the reproducibility and overall reliability of the process (Ref 239).

An improved understanding of the mechanisms that ensure material bonding under high-velocity particle impact could support the definition of powder characteristics and process parameters. Knowledge of the complex interplay between plastic deformation, cracking, fragmentation, and erosion, as well as consolidation and densification, could enable better process optimization. Although theoretical models and partial experimental validations have been proposed, technological challenges related to phenomena occurring on the nanometric to submicrometric scale within timescales of pico- to nanoseconds limit complete experimental validation and delay the development of standardized guidelines for material selection and process parameters (Ref 246). Additionally, the performance of deposits after heat treatments or at high service temperatures needs to be investigated. The high defect density caused by low temperatures and the nanocrystalline microstructure caused by solid-state deposition will certainly change at higher temperatures.

Apart from understanding, optimizing, and possibly standardizing AD coatings, major challenges concern exploring new material systems for functional applications, covering everything from sensors and electronic components to sunlight harvesting.

Advances in Science and Technology to Address these Challenges

To overcome the technical challenges, further research is essential to optimize feedstock powder properties and to enhance the understanding of process parameters for improving compatibility, performance, and reproducibility across various spray and substrate materials. The fundamental understanding of AD phenomena must be supported by advancements in automated process control, leveraging technological innovations from thermal spray techniques, with which AD shares phenomenological similarities. However, with small, about micrometer sized particles, about one to two orders of magnitude smaller than that of thermal spray, AD faces challenges in supplying controlled feed rates and avoiding agglomeration.

The adhesion mechanisms and particle-substrate or particle-deposit interactions in AD remain a subject of extensive research. Adhesion has been primarily attributed to mechanical anchoring and deformation, occurring without thermal activation. While localized temperature increases (500-1000 °C) during impact dissipate rapidly, as suggested by numerical simulations (Ref 247, 248), the generated thermal energy may contribute to surface activation and/or plastic deformation, enhancing particle-substrate and interparticle bonding. Furthermore, chemical compatibility has been proposed as a factor influencing coating adhesion, suggesting that fragmentation and erosion processes generate reactive surfaces that promote interfacial bonding (Ref 249). However, limited understanding and control over these simultaneous mechanisms, coupled with variability in feedstock powder characteristics and deposition parameters, complicate the elimination of interfacial defects. Nonetheless, further investigation is required to establish multi-property particle-substrate correlations and to develop optimized surface modifications as well as deposit designs, leading to standardized processing conditions and enhanced reproducibility.

Transmission electron microscopy is needed to observe the details of coating microstructures and faces difficulties to visualize such small particle directly. Alternative way to explore particle deformation behavior is given by the utilization of quasi-static nanoindentation test. Recent study suggests that a transition from tensile cracking to shear deformation is the key for pseudo-plastic deformation of AD particles (Ref 250).

Recent study also suggests the texture formation in AD process (Ref 251) and support observations that plastic deformation occurs during room-temperature impact consolidation. Generally, texture (crystal orientation) forms in metal and ceramic polycrystalline materials through plastic deformation associated with the activation of slip and twin systems. Based on this, it is believed that even in coatings formed by the AD method, lattice rotation occurs due to plastic deformation from the collision of particles with the substrate, leading to texture formation. Further understanding of the texture formation in AD process may not only support the understanding of the AD process but also the control of crystal orientation, providing additional tools for utilizing anisotropies of ceramic materials.

With respect to process stability and a significantly improved deposition efficiency, major advantages are expected by hybrid deposition approaches incorporating lasers or plasmas. One possible solution is given by AD under assistance by a radio frequency-inductively coupled plasma (RF-ICP) - termed as hybrid aerosol deposition (HAD) (Ref 252). This hybrid process offers significant advantages, including an order-of-magnitude increase of the deposition efficiency, improved density and homogeneity, and enhanced flexibility for applications on complex 3D components. At the same time, it retains the benefits of high adhesion and low-energy consumption, operating at up to 80% less energy input compared to plasma-based deposition processes. Such advancements get particularly relevant for aerospace applications, where high-density ceramic coatings are essential for long-term durability in extreme environments.

Additionally, a comprehensive evaluation of the environmental impact of AD must also account for the energy involved in producing the required fine powders, the so far typically low deposition efficiency, and the energy consumption of the vacuum systems. These factors must be balanced when considering AD as a potentially disruptive technology for aerospace applications.

However, AD should not be seen in competition to classical thermal spray processes. With the given versality to maintain the structures and designed features of ceramic feedstock, it could pave the way for new material developments and, respectively, adopted functional coating designs. Within that context, apart from traditional ceramics, one example is given by the application of AD for depositing so called MAX phases, in which "M" stands for an early transition metal, "A" for a group IIIA or IVA element, and "X" for carbon or nitrogen. With covalent bonded units and metal layers in their complex crystallographic structure, they combine ceramic and metallic properties, as thermal shock resistances and electrical and thermal conductivity alongside with excellent oxidation resistance by thermally grown oxides. AD is particularly interesting in that case considering that such materials are highly oxidized when deposited using other high-temperature deposition processes. Studies demonstrated the successful deposition of Ti_3SiC_2 (a representative MAX phase) coatings using AD, achieving dense and adherent layers even from particle sizes as large as D50 $\sim$ 7 μm (which is atypical for AD), thanks to their higher plasticity. These coatings offer

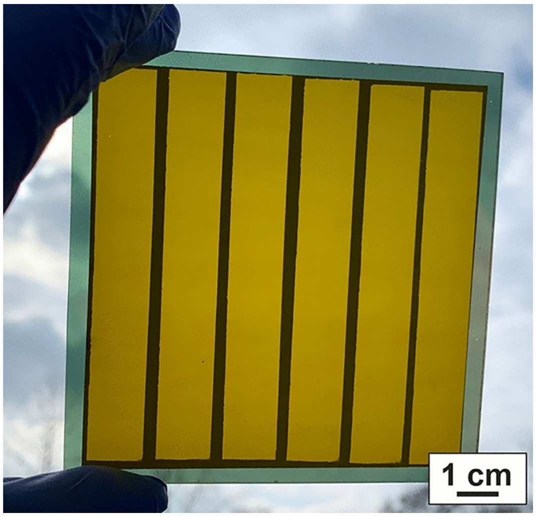

Fig. 38 Macrograph showing a homogeneous semitransparent $BiVO_4$ coating on an FTO glass substrate plate under illumination by sunlight (Ref 255). Reproduced from (Ref 255), available under CC BY 4.0 license at SpringerLink

significant potential for high-temperature aerospace components, such as engine parts exposed to oxidative and corrosive environments (Ref 253, 254). Envisaging a wider range of applications, the given versality in deposition of ceramic materials by AD already demonstrated capabilities for producing gas sensors, soft or hard magnetic films as well as examples for solid-state battery designs or fuel cells (Ref 239). With respect to new technologies enabling a green sky, particularly new generations of sensors could be essential for process development and in service monitoring.

All such new developments however should be tuned with respect to material design. However, with respect to the zero emission goal by 2050, the main focus should be on energy and fuel production. In the context of engineering artificial leaves, AD offers opportunities for material design and layer deposition with the necessary integrity and thickness to avoid charge recombination losses when harvesting hydrogen in direct sunlight. Laboratory examples demonstrate that AD-processed $BiVO_4$ as a photoanode coating in an electrolyte can already reach H_2 production efficiencies that are competitive with the most recent solar cells and electrolysis. Figure 38 shows an example of such a coating (Ref 255). Additionally, AD enables the processing of more efficient photocathodes using a specially synthesized $CuFeO_2$ feedstock powder (Ref 240). More sophisticated material design is expected to improve the efficiency of solar energy harvesting and carbon capture.

Concluding Remarks and Future Perspectives

AD is a unique process for the solid-state deposition of ceramics. It has the potential to be a disruptive technological alternative that could bring significant changes to the aerospace industry, ranging from new concepts for using synthetic fuels to harvesting solar energy (Ref 255). However, despite its novelty and versatility, AD's application is still limited. Therefore, its adoption by the aerospace industry, which requires very high safety and environmental standards, will take time and require fundamental research and development (R&D) activities. This concerns the optimization of feedstock powder characteristics and the development of a deeper phenomenological understanding of bonding phenomena, as well as the standardization and reproducibility of coatings. These are key aspects for large-scale implementation and include increased deposition efficiencies. Future research should focus on improving coating properties by gaining a better understanding of the underlying mechanisms of AD and improving control over feedstock materials.

As with other research fields, integrating advanced digital approaches, such as computational modeling, artificial intelligence, and digital twins, may enable predictive analysis and real-time process adjustments. Furthermore, exploring new materials, multi-material coatings, and possibly derived hierarchical structures, as well as leveraging technological combinations or hybrid approaches, such as HAD, will expand AD's applicability and provide more tailored solutions, particularly in the aerospace industry. This progress will require greater synergy between academia, technology centers, industry, public research institutes, and regulatory agencies to establish a clear pathway for AD to become standard technology for manufacturing and maintaining structural and functional components across small- and large-scale aerospace applications.

In the long term, the deposition principle of AD, which is completely different from that of thermal spray, can pave the way for exploring material systems and their necessary functional applications from a design level. This offers numerous opportunities for significant progress in the development of powders, equipment, and services in AD research and business, particularly for aerospace applications, to help achieve a greener sky.

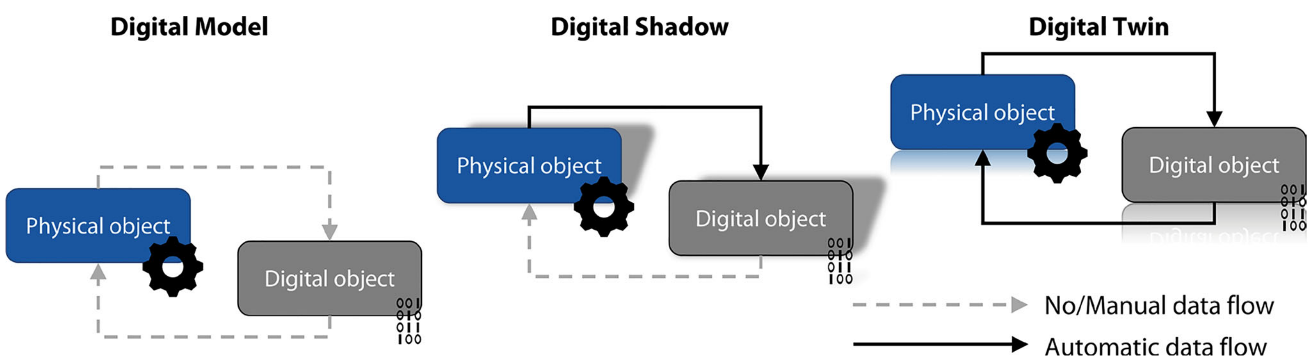

Fig. 39 Differentiation between Digital Model (DM), Digital Shadow (DS) and Digital Twin (DT)

Digital Integration

Use of Digital Twins to Simulate and Optimize Coating Processes

Hendrik Heinemann, Mehdi Jadidi, Gilles Mariaux, Majid Nabavi, Vincent Rat

Status of the Field

The digital transformation of manufacturing and industries stems from the concept of smart manufacturing of the Industry 4.0. It leverages innovative, intelligent and adaptive technologies based on the Industrial Internet of Things (IIoT), Machine Learning (ML) and Big Data (BD) encompassing automation and high connectivity between systems, real-time data analysis and control for decision making. It gives rise to material and energy savings and to the reduction of waste throughout the product life cycle.

Introduction to Digital Twin

The American Institute of Aeronautics and Astronautics released a position paper wherein a Digital Twin (DT) is defined as “a set of virtual information constructs that mimics the structure, context and behavior of an individual/unique physical asset or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value” (Ref 256). The Aerospace and Defense Product Lifecycle Management (PLM) Action Group stressed the different stages of product life cycle, design phase, production, operation and end-of-life, including the dynamic supply chain (Ref 257). A DT can be applied at different levels including component, asset, system, unit that must be defined by means of specific taxonomies of those entities along with the ontology of data dynamically generated in the process and must be coordinated by means of standardized methods. In general, a DT can be distinguished from a digital shadow (DS) and a digital model (DM) as displayed in Fig. 39. While there is no data flow in case of a DM, it is only one-directional from the physical object to the digital object in case of the DS. The DT, however, enables an automatic data flow between the physical and the digital object. It leads to a constant interaction of the digital and physical space for every work piece. Using this definition there can only be one individual DT for every physical object (Ref 258). The corresponding DT may represent an individual workpiece - such as a turbine blade prepared for coating - or a complete thermal spray production facility.

Digital Twin for Thermal Spray

Thermal spray is a complex technology comprising of numerous process components, including peripherals, handling and core components, and physical phenomena covering a large span of space and time scales that make the deposition difficult to control. Critical is the powders treatment that depends on the operating parameters having nonlinear coupled effects upon materials trajectories, temperature and velocities particles at very short-time scales.

The application of DT in a thermal spray production environment is illustrated in Fig. 40. All machine data, production data, sensor data, and test data are transferred to the DT in real time. The model previously developed in the DT simulates the coating and production process, predicts the coating quality, and optimizes the production sequence. The results are transferred back to the physical space to simultaneously adjust the production process and possibly modify the coating recipe achieving optimal coating quality, productivity, and machine utilization.

A robust DT for thermal spray integrates various interconnected physics-based, reduced-order, and data-driven models that are continuously trained and updated. These models predict coating formation and performance under real-world conditions, enhancing DTs’ predictive

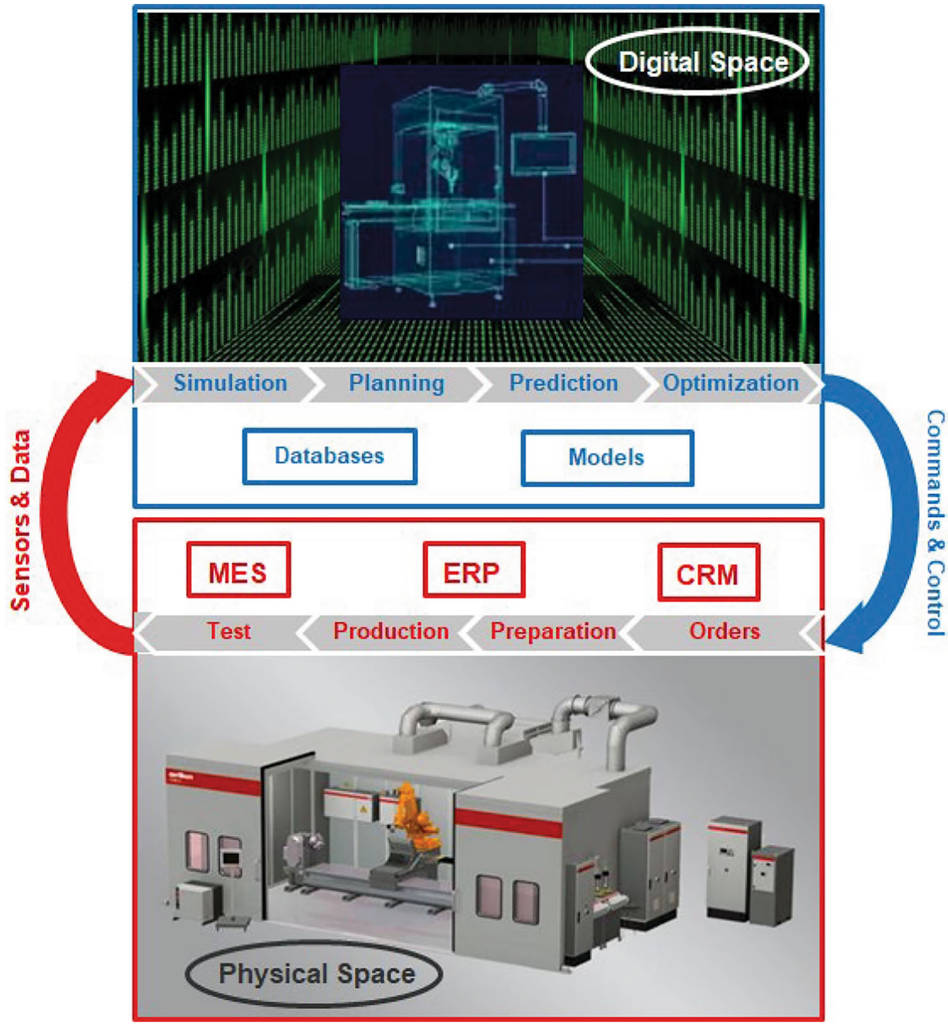

Fig. 40 Conceptual representation of application of DT in a thermal spray production environment (MES: Manufacturing Execution System, ERP: Enterprise Resource Planning, CRM: Costumer-Relationship-Management). Two main components in this configuration that are essential to the operation of DT are sensors and models. (Figure courtesy of Oerlikon-Metco)

capabilities while helping manufacturers refine processes, minimize trial-and-error, and improve product longevity. They are essential for simulating the underlying physical phenomena involved in thermal spray processes, such as multiphase flow dynamics, particle impact, and coating build-up. Specifically, mechanistic models, including high-fidelity computational fluid dynamics (CFD), magnetohydrodynamics (MHD), finite element analysis (FEA), and molecular dynamics (MD) simulations, capture the complexities of these processes across different length scales. These models are already in use to predict key parameters such as plasma arc reattachment, particle velocity and temperature distributions, liquid jet atomization and evaporation, turbulence, splat morphology, residual stress, microstructure evolution, and dislocation activities (Ref 259).

To improve predictions and manage uncertainties, data-driven techniques are being integrated into thermal spray modeling. Black-box, gray-box, and physics-informed neural networks (PINNs) trained on large simulation and experimental datasets provide faster predictions with acceptable error margins. First examples for combining both physics and data-based models on the path toward a DT exhibited in the recent works of a DS to predict the deposition efficiency in plasma spraying (Ref 260). Additionally, reduced-order models like Proper Orthogonal Decomposition (POD) and Dynamic Mode Decomposition (DMD) were used to extract dominant spatial and temporal features from high-fidelity simulations and experimental data, allowing rapid approximation of complex flows (Ref 261). For example, DMD was used to analyze key flow features from high-speed imaging of liquid jets in crossflow (Ref 262), offering a simplified framework that can be expanded for more complex processes such as suspension and solution precursor plasma spray.

Reliability of deposition process is a major concern to ensure repeatability and reproducibility of coating performance. It relies on sensing and control developed for several decades, while real online control is acknowledged to be a huge challenge (Ref 263). Prior expert knowledge of the deposition should be required to determine the window of operating parameters for a specific application and to cover all process variables of the system. Multi-stage plasma spray process is suggested bringing out the relationships between the extrinsic parameters (gun, feed-stock, …), hardware-independent intrinsic variables like in-flight particles properties-related and explicit coating properties (Ref 264). These intrinsic and extrinsic categories containing numerous parameters and variables also refer to sub-systems or process nodes (gun, jet/particles, coating) that must be sensed. Plasma spectroscopy provides qualitative and quantitative valuable information to monitor electrode wear or particles evaporation. Several commercial systems of in-flight particles monitoring for single particles detection and ensemble measurement are ready to-use and relies on time-of-flight method and two-color pyrometry. Particle Image Velocimetry (PIV) and shadowgraphy are powerful and mainly research-dedicated techniques to measure complex fluid flows embedding condensed phases (droplets and micrometer-sized particles). The data produced by this set of techniques completed with heat flux measurements upon substrate can reflect the major process nodes but they have to tackle their integration into a DT framework where the hierarchical information flows must be set up (Ref 264).

Current and Future Challenges

The adoption and effective performance of DT technology in thermal spray coating production face several barriers:

- *Complexity of the process:* Thermal spray processes involve a multitude of complex physical phenomena, including turbulent compressible reactive gas/plasma flow, liquid atomization and evaporation, particle impact, splat formation, and microstructural evolution. Modeling these processes with high accuracy requires advanced computational techniques. The difficulty lies in ensuring these models can realistically replicate real-world behavior, especially when it comes to interactions at the micro- and nanoscales. Data capturing the processes and feeding the models must be representative of real phenomena meaning that a digital mapping relying on a reciprocal relationship between coating properties and the numerous process variables should be established. The understanding of the ontology of data generated by thermal spray systems is essential for accurately defining the hierarchical relationships among process variables and for choosing relevant sensors for the intended application.
- *Model accuracy and validation*: The accuracy of the models is highly dependent on factors such as the quality of input data and the availability of accurate thermophysical properties for different materials. Simplifying assumptions in the models also contribute to uncertainties. Additionally, validating these models can be difficult, as experimental data may be sparse, and physical instabilities often affect model performance. Sensors are also limited in terms of noise/signal ratio that may be challenged with the injection of complex mixture particles exhibiting different melting points, sizes and temperatures, and in terms of accuracy due to calibration challenges and interference from non-thermal radiation caused by plasma and particle evaporation (Ref 263).
- Careful attention should be paid to the sensor accuracy and then to data trust, or similarly to the assumptions posed in data post-treatment affecting measurement accuracy, in order to assess its propagation into models.
- *Computational expense*: The numerical simulations are computationally expensive, often taking hours or days to run. This limits their practical application, especially when multiple simulations are required to explore various operating conditions and make real-time adjustments.
- *Model generalization*: Ensuring that the computational models can generalize across a wide range of operating conditions is essential. Sensors range, complementarity, and redundancy are critical for the model generalization and the introduction of skewness in the results.
- *Real-time data integration and modeling:* Successful implementation of DT requires integrating data from multiple sources, such as sensors and models. However, ensuring seamless data acquisition and synchronization remains a challenge, particularly when dealing with heterogeneous data formats, varying sampling rates, and high-dimensional datasets. Low and high-bandwidth sensors must co-exist to account for the chronology and the time scales of physical phenomena. Electric arc reattachment affecting the torch stability needs a few microseconds to occur while particles' time of flight is several hundred times higher. Additionally, achieving real-time monitoring and simulation demands high-speed data processing, which is constrained by computational power, data transmission latency, and storage limitations. This imposes significant constraints on SPS and SPPS processes, which rely on complex diagnostics such as PIV or shadowgraphy, while effective techniques for characterizing submicron-sized particles remain lacking. Moreover, integrating physics-based and data-driven models into real-time industrial frameworks poses challenges related to model adaptability to respond system changes ensuring model robustness backed by some knowledge-based

rules (Ref 265), predictive reliability, and computational efficiency.

- *Data Availability and Storage*: Capturing the entire coating process generates massive data volumes, demanding significant computational resources and energy for storage and management. Moreover, no universally accepted standards currently exist for the structured storage and annotation of data acquired in thermal spray processes.
- *Connectivity to adjacent manufacturing processes*: Thermal spraying is typically embedded within broader production chains, including machining, surface preparation, inspection, and post-treatment. Developing digital twins as isolated solutions for thermal spraying lacks practical value. Instead, integration into end-to-end manufacturing frameworks is essential to ensure data continuity, process interoperability, and system-level optimization.
- *Cybersecurity concerns*: DTs often rely on cloud computing, raising concerns about data security and potential vulnerabilities to cyber-attacks.
- *High initial investment and Return on Investment (ROI) uncertainty*: Developing and implementing a DT require substantial upfront investment in technology, software, training, and infrastructure, which may be a barrier for smaller companies. Additionally, the benefits of adopting a DT may not be immediately evident, leading to uncertainty about the ROI.
- *Skill gaps*: A shortage of skilled personnel who understand both the thermal spray process and DT technology limit current implementation.

Advances in Science and Technology to Address Challenges

The thermal spray community can expect significant improvements from the DT implementation in several key areas far surpassing the capabilities of traditional methods. In error prediction area, by collecting and analyzing vast amounts of real-time data from sensors, DT allows for the immediate detection of subtle deviations. In the area of optimization, DTs can simultaneously optimize multiple, often conflicting, objectives such as coating quality, deposition rate, material usage, energy consumption, and cost. The validation of the optimization can be achieved by means of experimental comparisons, testing the model generalization with unseen data, performing a sensitivity analysis of the input parameters to detect their meaningful influences and to assess the robustness of the model. In the area of coating variability, by predicting how slight variations in input parameters or environmental factors will affect the coating, DTs can proactively adjust other parameters to compensate, thereby minimizing variability in real-time. DTs also offer a transformative shift from reactive or prescriptive control to predictive, adaptive, and holistic process management. Unlike PID loops or expert systems, which are mainly constrained by fixed logic, DTs integrate high-fidelity simulations, machine learning models, and live sensor feedback to achieve greater precision, process stability, and reproducibility. As such, DTs represent the most comprehensive and future-proof solution for controlling thermal spray processes, especially under increasingly stringent performance and sustainability demands.

Some of the advances in science and technology that are helping to address the above-mentioned barriers are discussed below:

- *Improved computational models:* Efforts to enhance the accuracy and efficiency of CFD, FEA, and MD simulations are focused on developing more efficient algorithms and improving physical representations within models. Current research is exploring advanced solvers, parallel computing techniques, and adaptive meshing methods to accelerate simulations and reduce computational overhead. Additionally, work is being done to incorporate more detailed models of physical phenomena, such as turbulence and combustion, to create simulations that better reflect real-world conditions. To improve these models, future research will need to refine algorithms to address more complex physical phenomena, such as suspension atomization, and particle nucleation and shell formation in SPPS. Furthermore, developing multi-scale modeling approaches that link microscopic particle behavior to macroscopic outcomes will provide a more holistic understanding of the spray process. As simulation accuracy and efficiency improve, parallel computing and cloud-based simulations will play an increasingly vital role in enabling real-time applications. Future work should also prioritize validating these models with additional experimental data to ensure they remain accurate and reliable in practical applications.
- Developing ML, PINN, and reduced-order models enhance thermal spray simulations by lowering computational costs while maintaining accuracy, enabling real-time optimization and adaptive control in DTs. Looking ahead, it is essential to expand and improve the integration of ML and AI, focusing on collecting larger, more diverse datasets, particularly real-time sensor data on particle velocity, temperature, and coating properties. Future research should also work on improving the interpretability of these models to enhance their adoption in industry.

- For DTs to function reliably under varying conditions, it is essential to incorporate systematic parameter identification strategies that leverage experimental and in-flight data for model calibration. Moreover, accounting for model uncertainties through ensemble simulations, sensitivity analyses, or Bayesian inference will strengthen the robustness of DT-based control systems and support safer, more autonomous thermal spray operations.
- *Real-time data integration and modeling:* The development of real-time non-contact, non-destructive and in-situ methods for coating monitoring is essential. Optical methods are under study based on confocal distance sensors (Ref 265) or on Terahertz (THz) propagation in coatings. THz spectroscopy applied to TBC is promising for the prediction of coating thickness or the characterization of thermally grown oxide (TGO). Acoustics emission due to the impact of plasma sprayed particles is also expected to be sensitive to some extrinsic parameters. Advances in high-performance computing (HPC), edge computing, and cloud-based architectures are enabling faster data processing and scalable storage, facilitating the integration of data from various models and sensors. Standardized data acquisition protocols as well as machine learning and big data algorithms improve data fusion, enabling real-time synchronization across multiple sources. Real-time analysis of multiple sensing modalities requires careful synchronization and time-stamping of sensor signals, extraction of relevant features from each data stream, and, when necessary, dimensionality reduction before input into ML models. To support sim-to-reality implementation, this process must be optimized to minimize latency across all steps, including signal acquisition, data processing, and software integration.
- For these initiatives to succeed, cross-industry collaboration, particularly between aerospace and academic institutions, will be crucial in driving innovation across modeling techniques, data collection, machine learning integration, experimental setups, and computational resources. These collaborative efforts will accelerate the widespread adoption of real-time, data-driven thermal spray technologies, leading to significant improvements in manufacturing efficiency and product performance.
- *Cybersecurity concerns*: Advances in robust cybersecurity measures are helping to protect sensitive data and systems from threats, aiding businesses in adopting DT technologies confidently.
- *High initial investment and Return on Investment (ROI) uncertainty*: More initiatives fostering collaboration between manufacturers, software developers, and researchers can lead to the sharing of best practices, tools, and frameworks that can reduce the initial investment and ensure faster ROI.
- *Skill gaps*: Advances in Augmented Reality (AR) and Virtual Reality (VR) will help in training operators by providing immersive experiences that demonstrate the thermal spray coating process and the function of DTs, bridging the knowledge gap and enhancing adoption.
- *Open data initiatives*: The lack of large, high-quality, and openly accessible datasets for thermal spray remains a major bottleneck for data-driven model development. Establishing shared, standardized, and open-access databases could accelerate the training and validation of ML and hybrid models, facilitate benchmarking, and promote cross-institutional collaboration. Such an initiative would require consensus on data formats, metadata standards, and intellectual property frameworks, but offers substantial long-term benefits for the entire field.

Concluding Remarks and Future Perspectives

DT technology plays a crucial role in advancing thermal spray processes, contributing to greener aviation by optimizing material performance and coating quality improvement. By creating precise virtual models of components, engineers can simulate and analyze how various spray parameters impact the coating durability under real-world conditions. This data-driven approach allows for the identification of more efficient processes that reduce waste and energy consumption. Additionally, DT facilitates predictive maintenance, ensuring that parts maintain optimal performance throughout their life cycle, which ultimately leads to lower emissions and increased fuel efficiency in aircraft operations.

To fully realize these benefits, it is essential to develop industry standards for data exchange, ensure interoperability of DT platforms, and establish best practices for implementing DTs in thermal spray applications. By fostering strong collaborations across the aviation, thermal spray communities, and universities, the transformative potential of DTs can be unlocked, not only for operational efficiency and error reduction for the improvement of the aircraft performance but also as a powerful enabler for achieving ambitious sustainability goals in the aerospace sector.

Acknowledgments

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Thermal Spray Coatings on Complex Parts

William Duarte, Guillaume Fradet, Thibaut Van Hoof

Status of the Field

Since the 1960 s, the thermal spray industry has experienced significant growth, primarily driven by aerospace applications, particularly aircraft engines (Ref 91). This growth is largely due to the democratization of plasma spraying, HVOF, etc. Thermal spraying has developed an extensive range of coatings that cover all parts of an aircraft engine. Consequently, there are coatings with various functionalities, such as abrasion resistance, fretting resistance, and wear resistance in low-pressure areas (where operating temperatures range from approximately 100 to 450 °C), as well as thermal barrier coatings in high-pressure areas where temperatures approach 1000 °C.

The current state of thermal spraying in the aerospace industry from an engine manufacturer's perspective is threefold: (i) ensuring an increase in production rates and significant new industrializations, (ii) improving the durability of parts by applying thermal spray coatings to less accessible areas, and (iii) developing new technologies to meet greenhouse gas emission reduction targets by 2030. These targets include a reduction of at least 55% for the EU compared to 1990 levels (Ref 266) and a reduction of 50-52% for the USA (target established in 2021) compared to 2005 levels (Ref 267).

The impacts on thermal spray job shops are numerous, but successfully applying a coating while adhering to best practices in the field is the major difficulty. The shapes of the areas to be coated are often complex and beyond the experience of thermal spray job shops. These areas often have irregular shapes and/or are difficult to access due to obstructions caused by the part itself or the tools. This may require the use of projection angles of less than 45°. This leads to increasingly complex phases of product industrialization and technological demonstration where traditional methods reach their limits.

This requires interdisciplinary collaboration to develop innovative, applicable solutions in thermal spray job shops.

Currently, many parts must be sectioned off to verify compliance with technical requirements regarding microstructure and thickness distribution. This requires a lengthy and costly iterative trial-and-error methodology. Several approaches are used to limit these costs. These include rapidly developing tooling through polymer or metal additive manufacturing. Other approaches are more exploratory and have yet to be proven. One such approach is the use of new protective materials for parts whose physical properties may positively or negatively impact particle kinetics. Other approaches include using numerical simulations to predict microstructure. Using diagnostic tools for particles in flight is essential for this. Additionally,

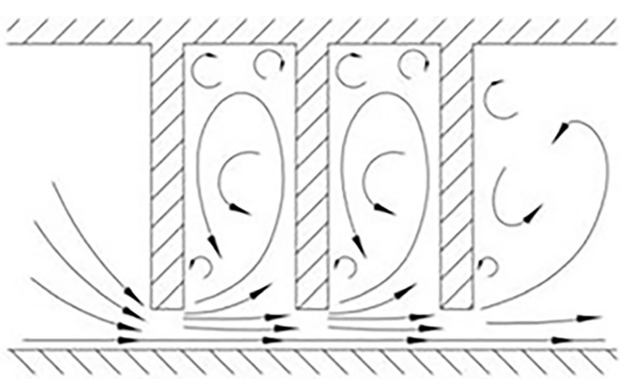

Fig. 41 Schematic of gas flow through a labyrinth seal teeth (Ref 268)

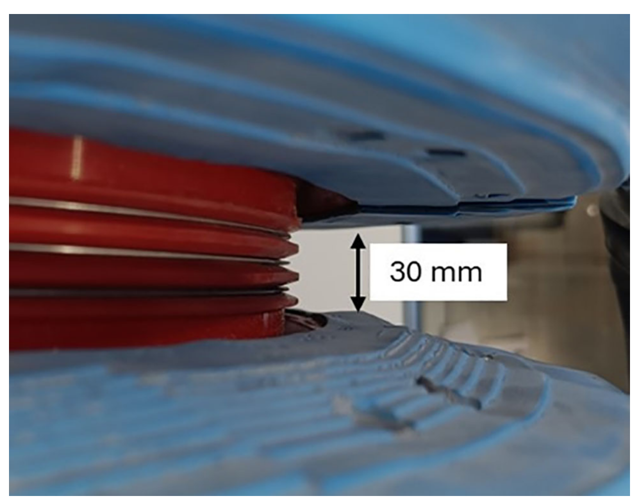

Fig. 42 Illustration of masking tools on a complex seal teeth part Used with permission, Safran property

numerical simulations help understand the thickness distribution of the coating on the part.

Current and Future Challenges

The increase in the geometric complexity of aerospace parts poses obstacles to the application of processes, mainly due to the desire of original equipment manufacturers (OEMs) to lighten parts to reduce fuel consumption and greenhouse gas emissions, which are major issues for the entire aeronautics industry.

Currently, seal teeth parts are the most complex parts of an aircraft engine to coat. These parts ensure a seal between different compression stages by limiting secondary airflow, which improves engine efficiency by increasing the proportion of primary flow. Seal teeth are rotating parts with blade-shaped appendages that extend close to the rotor surface. Seal teeth reduce gas flow through a series of restrictions and expansions (Fig. 41) (Ref 268).

The seal teeth must be protected from possible shock from the stator that may occur during engine operation due to thermal expansion, vibration, etc. (Ref 269).

To limit wear on the rotor parts, a two-layer coating is deposited by plasma spraying. This coating includes a metallic bond coat, which ensures mechanical adhesion, and a ceramic topcoat (Al_2O_3-TiO_2) that acts as an abrasive at high temperatures. The bond coat is made of either NiAl or NiCrAlY, depending on the operating temperatures (Ref 270).

Optimizing engine performance has led to complex part geometries that require masking tools to limit the coating to only the functional areas of the part. These special requirements severely restrict accessibility to the surfaces to be coated (see Fig. 42).

These constraints result in angles of incidence of the molten particles of less than 20° relative to the surface to be coated, which is far from optimal for thermal spraying. Additionally, meeting the coating quality requirements is difficult: achieving homogeneous thickness and distribution of the coating and addressing metallographic defects (porosity, lack of material, unmelted particles, low oxidation, etc.).

Industrial constraints must also be considered, such as the high cost and limited availability of scrap parts for destructive testing and the significant production load on thermal projection booths, which limits their availability for developing robust solutions.

These constraints lead to the conclusion that modeling studies must be conducted prior to the industrialization step through numerical simulations. This allows for testing of different spraying configurations (e.g., deposition angle, standoff distance), different masking tool designs, and different plasma torch trajectories, as well as evaluation of their impact on the coating, including coverage, thickness distribution, and metallographic quality. This would significantly reduce costs and development time by enabling precise parameter targeting during industrialization on scrap parts.

Designing a coating process for a complex part is challenging due to the intricate interplay between the part's 3D geometry and the imposed kinetics (i.e., trajectories and velocities) of the part and the thermal spray beam ("source"). The transient footprint growth process can be described as a succession of nearly instantaneous "spots" with growth rate distributions that depend on local variables.

- Nozzle-to-surface distance: The complex physical interaction between the projected particle and the torch results in variations in particle state and flux distribution along the projection beam. Depending on the nature of the projected material and the projection method, the optimal coating properties are achieved at a specific distance between the nozzle and the target surface. This ensures the optimal kinetic and thermal state of the impacting particles. For complex parts, fine-tuned trajectories may be needed to maintain this distance within tolerance throughout the process.
- Deposition angle: The spot area and thickness depend on the local angle (α) between the projected particle beam and the outgoing normal of the surface. The spot has maximal thickness and minimal area when the beam is aligned with the surface normal ($\alpha = 180°$); no deposition occurs when $\alpha \leq 90°$. This angular dependency is especially crucial for complex 3D parts, where the surface normal varies significantly with position.
- Spot velocity: Increasing the transverse velocity of the spot on the surface leads to an increase in spot area and a decrease in spot thickness (Ref 271).
- In practice, this effect is offset by increasing the number of passes to achieve the desired coating thickness. The spot growth rate is also affected by the relative velocity between the surface and the projected particles along the beam direction. Surfaces moving toward the gun collect more particles than surfaces moving away from the gun. This leads to an increase or decrease in the effective material deposition rate.
- Shadowing: Shadows appear in regions of the part hidden by other objects or by regions of the same object located in the beam's path. No deposition occurs in shadowed regions, which has a strong impact on the final footprint uniformity. During the coating of a complex part, shadows vary according to the part's and beam's trajectories. Additionally, growth of a thick

coating can deform the free surface of the part significantly, which can affect subsequent shadows. In industrial applications, protective materials (masks) are used to prevent material deposition in specific regions of the part.

- Deposition efficiency: Deposition efficiency is defined as the ratio of the total mass of impacting particles to the mass of material deposited on the surface. Experimental studies show that particle adhesion depends on mechanical and chemical interactions between the partially melted particles and the surface. More precisely, deposition efficiency is a function of the particle impact angle and velocity, particle and surface temperatures, and surface nature and roughness. Additionally, reflected particles may impact another surface in their path, potentially creating a secondary coating spot.
- During the coating process, these variables evolve over time according to the operational parameters imposed. The projection source parameters: the particle beam is mainly characterized by the mass (or volume) flux distributions (shape, intensity, radius, ...). Depending on the equipment, different operating parameters can be tuned to control the flux distribution: carrier gas velocity, temperature, material feed rate, etc. Their values typically depend on the type of coating material and substrate used, and remain constant throughout the coating process. However, fine-tuning and/or adjusting the source parameter values over time could improve the quality and/or efficiency of the process for complex parts.
- The trajectories of both the part and the source: Motion equipment, such as robotic arms or rotating devices, is used to move the part and source in a controlled manner during the coating process. The degrees of freedom of the motion equipment impose constraints that must be considered when defining the trajectories. Because geometrical and kinematic effects strongly influence the final footprint, optimizing the part and source trajectories is critical to designing a coating process for a complex 3D part.

Advances in Science and Technology to Address Challenges

Numerical simulations are a promising approach for designing efficient, high-quality thermal spray coating processes for complex parts. High-fidelity computational fluid dynamics (CFD) simulations have been proposed to model thermal spray flows and particle impact on parts. However, these simulations require expensive, complex, multi-physics approaches, which limits their use in designing industrial complex part coating processes.

Therefore, more pragmatic approaches have been proposed that are based on analytical source models adjusted using simple experiments. The resulting source model can be projected onto any three-dimensional (3D) part surface and integrated over time along predefined trajectories to simulate footprint growth.

The source model describes the distribution of material flux in a plane perpendicular to the source direction. The model's free parameters (e.g., the intensity and width of the two-dimensional Gaussian distribution) are adjusted to reproduce the thickness distributions of footprints obtained from simple coating experiments on flat surfaces with controlled source velocity and impact angle.

Recently, efficient transient and 3D methods have been proposed to simulate the coating of complex parts. The

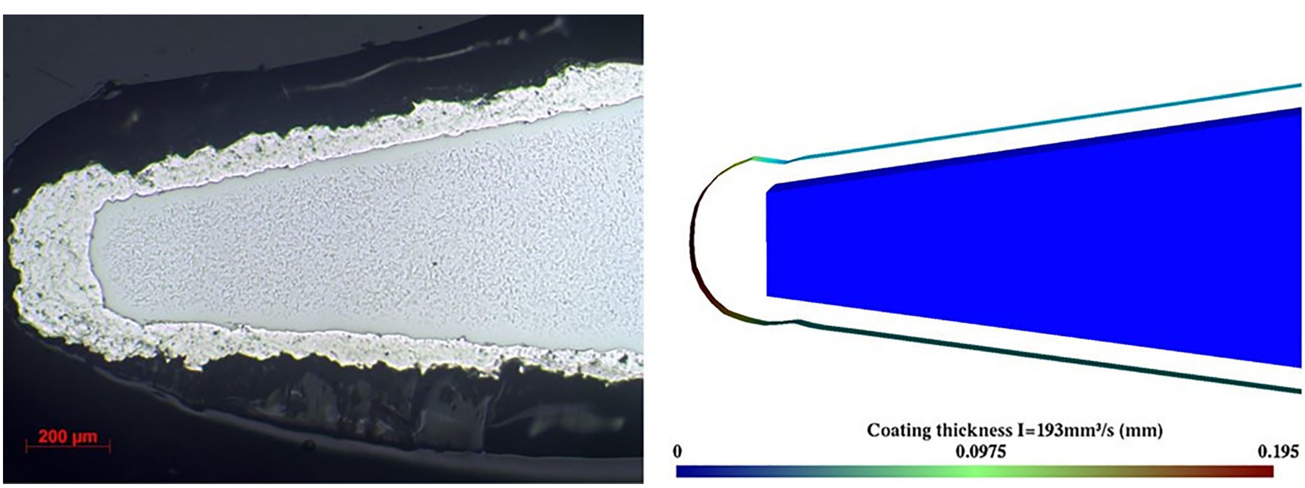

Fig. 43 Cross section of the coating on an aircraft engine seal teeth as measured experimentally (left) and simulated using the method from (Ref 271) (right)

trajectories are discretized in time according to a user-imposed time resolution, Δt. At each time step, the source model is projected onto the triangulated surface, which leads to an almost instantaneous deposited spot. The footprint is integrated step by step by adding the successive spot contributions. This method takes into account the effects of local angle, distance to the source, spot velocity, and shadowing, enabling the simulation of the coating process of complex 3D parts.

Van Hoof et al. (Ref 272) introduced a method for simulating the coating of complex parts. This method relies on a level set (LS) approach to track the evolution of the coating layer geometry and solves the LS equations on an unstructured mesh using the standard finite elements method (FEM). The source model describes the deposition rate distribution and is translated into an LS advection velocity field. This field is then integrated over time to capture the evolution of the footprint geometry. Shadows, including self-shadows and masking, are simulated using an efficient beam-eye-view projection method. This method has been successfully applied to an aeronautical test case and has provided accurate predictions of coating thickness distribution for HVOF coatings on aircraft engine seal teeth, as shown in Fig. 43. This method has been adapted into a voxel-based formulation using the lattice Boltzmann method (LBM), a computational fluid dynamics (CFD) method based on the kinetic theory of gases, which has been modified to solve the level set equation. The triangulated surface of the part is immersed in a Cartesian grid (voxels), eliminating the need for costly 3D conformal mesh pretreatments. The part moves independently of the source using a change of reference frame. Time-varying source parameters are also available. The LBM implementation eases the setup of the simulation and allows users to freely define the space resolution (grid size Δx). The LBM coating solver substantially reduces computational costs while preserving the same functionalities and accuracy as the FEM solver.

Meanwhile, Tzinava et al. (Ref 272) proposed a similar method that included a shadowing algorithm. However, their approach does not simulate the deformation of the part's surface during coating growth. The source model in Ref 272 is based on the deposition rate distribution, whereas the source model in Ref 273 is based directly on an imposed thickness distribution. Adjusting such a thickness-based source model requires more experiments to account for factors such as the influence of the spot transverse velocity.

Concluding Remarks and future perspectives

The social climate and political commitments of the EU and the US (as of 2021) are prompting the aerospace industry, especially aircraft engine manufacturers, to reduce their greenhouse gas emissions significantly. Thermal spraying is widely used in this industry; therefore, it is necessary to incorporate new digital tools to facilitate and reinforce the application of thermal spray coatings on increasingly complex parts.

Current numerical simulation tools focus on predicting coating thickness while taking into account the main driving phenomena. Further improvements are needed to increase the reliability and capabilities of the simulations, especially for complex parts with highly constrained coating trajectories.

First, improve the source model with a finer description of the particle flux distribution. Second, improve the footprint growth predictions in critical configurations (e.g., low impact angle, high velocity) using advanced deposition efficiency models. Third, extend the prediction capabilities to other coating properties (e.g., metallographic properties, hardness) using specific models or AI. Finally, add the simulation or modeling of other relevant physical phenomena (e.g., heat treatment, residual stresses). Finally, substantially reducing the high cost of the design phase requires coupling coating simulations with numerical optimization tools to identify the optimal set of operational parameters for each new application.

Predicting Coating Performance using AI-driven Modeling

Andrew Ang and Moussa Tembely

Status of the Field

The aerospace industry's push for greener aero-propulsion demands "right-first-time" coatings to reduce material waste, energy consumption, and development time. Thermal and cold spray technologies are well-established techniques used in this field, (i) providing crucial thermal/ environmental barrier coatings (TBCs/ EBCs) and abradable coatings that enhance the performance of aero-turbines, (ii) hard chrome replacements for aircraft landing gear hydraulic components, and (iii) dimensional restoration or functional coatings for aircraft skins. Although these coating technologies have benefited from advancements in numerical modeling, sensor data, and fast processing of recorded information to advance coating

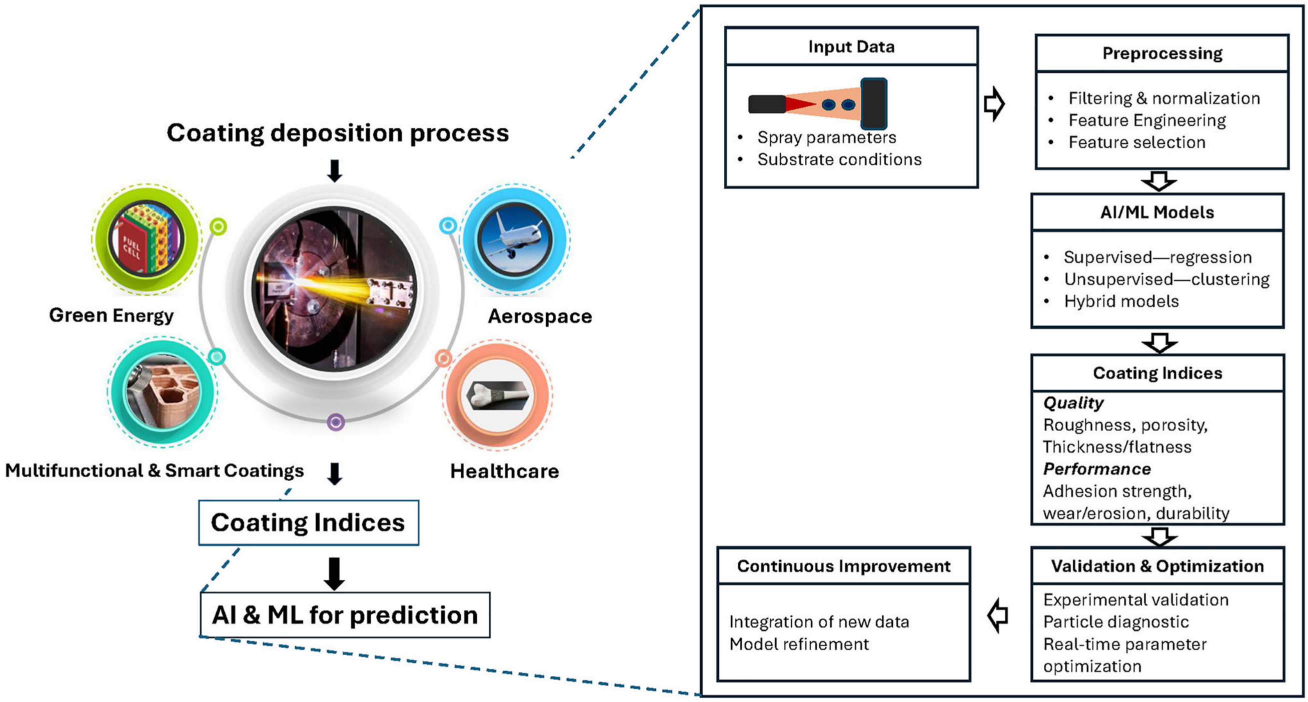

Fig. 44 AI/ML-integrated framework for optimizing coating deposition, from input data processing to performance prediction, validation, and continuous improvement across multiple application areas

performance predictions, a major challenge remains: the lack of comprehensive physics-based models that fully capture the complex, stochastic nature of the coating buildup process (Ref 27). This gap makes it difficult to accurately predict the real-world coating performance. To address this, there has been a growing use of Artificial Intelligence (AI) in thermal and cold spray processes to identify patterns within complex processing conditions and make more precise predictions about coating performance, ultimately improving the efficiency and reliability of surface engineering processes (Ref 273-278).

The emergence of AI, and in particular the use of traditional AI approaches such as machine learning (ML) and deep learning (DL), has introduced new possibilities for predicting coating performance and optimizing thermal spray/ cold spray manufacturing processes (Ref 275, 277, 278) . These traditional AI-based approaches take advantage of experimental data to predict key coating features such as surface roughness, grain size, adhesion strength, thickness, residual stress distribution, porosity, tribological behavior, and resistance to wear or corrosion (Ref 273-282). By capturing complex nonlinear interactions between coating features and the desired functional coating property performances, AI techniques complement traditional empirical and analytical models, providing enhanced predictive capabilities and enabling more effective optimization of the desired coating performance (Ref 275, 278).

In addition to coating performance evaluation, AI has strong potential to be deployed as an intelligent manufacturing process optimization tool. AI models can digitally correlate complex spray parameters with tool path planning for certain coating geometrical features (i.e., thickness) and control/maintain certain microstructural characteristics of the coatings. This capability opens up opportunities for AI-driven process optimization, where the model becomes a prescriptive tool for recommending parameter adjustments for desired coating outcomes. This includes the pre-processing steps before coating (i.e., substrate grit-blasting) and post-processing coating treatments (i.e., heat curing and finishing) can also be incorporated, although current studies in this area remain preliminary. Malamousi et al. (2022) highlight that such AI integration is pivotal in the digital transformation of thermal/cold spray processes, linking processing conditions directly to coating performance (Ref 277).

Within the open literature, the majority of AI-themed research on thermal/cold spray coatings can be grouped into three main categories: (i) using AI to predict coating quality and enable monitoring/control of the coating process, (ii) prediction of coating performance, such as functional properties and lifetime, using AI-driven models, and (iii) using AI for tool path planning to achieve geometrical accuracy, process efficiency, and reliability.

Predicting Coating Quality and Enabling Monitoring/Control of Coating Process

Figure 44 presents an AI/ML-driven framework for optimizing coating deposition across diverse applications, including energy, aerospace, healthcare, and smart coating fields. In this ML approach, input data from spray parameters and substrate conditions are pre-processed and analyzed using supervised, unsupervised, or hybrid machine learning models to predict key coating performance metrics. In this framework, it is useful to distinguish intermediate quality indices (i.e., roughness, porosity, and thickness) from final performance indices (i.e., wear rate and erosion resistance) to clarify how process inputs are translated into both immediate coating quality and ultimate functional performance outcomes. Furthermore, continuous validation, iterative optimization, and feedback loops support ongoing improvements in coating quality and processing efficiency.

AI-driven modeling has already begun to influence thermal and plasma spray technologies by enabling early stage predictions of coating properties and performance. Various ML techniques, such as artificial neural networks (ANNs), support vector machines (SVMs), random forests, convolutional neural networks (CNNs), and generative models, have been explored to predict both in-flight particle conditions and post-deposition coating characteristics, including porosity, hardness, and bond strength, based on process parameters (Ref 273, 274, 276, 279-282). There has also been an increase in the use of computer image recognition and deep learning models, such as CNN, to automate microstructure characterization from SEM or optical micrographs (Ref 277, 281). These approaches reduce the subjective bias in image analysis and provide quantitative features for performance modeling. Methods such as U-Net have been used to automatically segment deformed particle micrographs, enabling objective measurements of splat flattening and compactness that correlate with the mechanical response. Tu et al. (Ref 281)

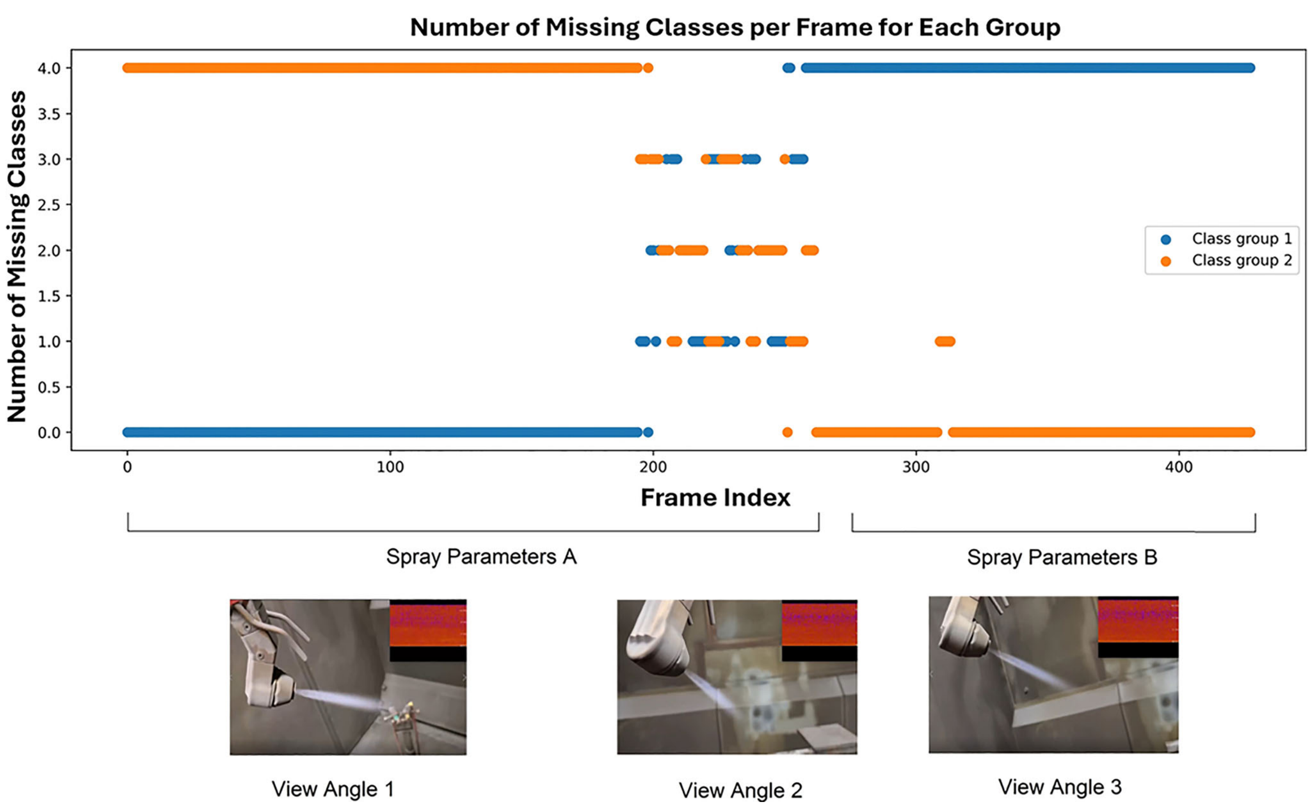

Fig. 45 Real-time monitoring of thermal spray process using deep learning-based computer vision. The plot (top) tracks an anomaly classification metric ("Number of Missing Classes") frame-by-frame for two different spray parameter sets (blue: Class Group 1, orange: Class Group 2). The images (bottom) show the thermal spray torch from three camera viewpoints under each parameter set (Spray Parameters A vs. B). A convolutional neural network model (using a YOLO architecture) processes the torch images and acoustic signals to detect deviations in the plume shape or brightness that indicate off-nominal conditions. This AI approach enables the rapid detection of issues such as nozzle wear, clogging, or flame instabilities, allowing for real-time adjustments in the spray process (Ref 284). Reproduced with permission from K. Malamousi, K. Delibasis, and S. Kamnis, "Real-Time Thermal Spray Process Monitoring Using Convolution Neural Network Deep Learning Architectures," *J. Therm. Spray Technol.*, 33, p 17-32, 2024, Springer Nature

demonstrated that such image segmentation can replace subjective manual stereology for characterizing cold-sprayed Al-alloy deposits.

Other ML principles and algorithms have also been used to predict TBCs properties, such as thermal conductivity. Researchers now prefer ensemble methods (i.e., XGBoost, and Gradient Boosting) for their robustness in small experimental datasets typical of thermal spray studies. One study (Ref 275) collected a large dataset of experimental thermal conductivity data for YSZ TBCs to train various ML models and found that ANN with Bayesian regularization and Gradient Boosting Regression exhibited better predictive capabilities than polynomial regression, offering a more accurate and efficient method for predicting TBC properties. Separately, a method for diagnosing the quality of TBCs was developed using machine learning algorithms, which used PCA and KNN algorithms on reconstructed 3D coating morphology data, achieved a high accuracy of 94.7% in classifying process quality, and provided a framework for rapid feedback and process control (Ref 283). These examples illustrate how AI can ingest heterogeneous sensor data and images to provide insights and control capabilities that were previously unattainable using traditional models.

Figure 45 shows an example of real-time thermal spray process monitoring using a deep learning approach (Ref 284) . In this study, a CNN-based model was used to analyze the spray plume and acoustic emissions under two different sets of spray parameters (i.e., Spray Parameter A and B). The model classifies the torch operating condition in real time, and the plot indicates the number of detection anomalies ("missing classes") per frame over time for the two defined condition groups. Such AI-driven in-situ monitoring systems can enable real-time process control, reduce defects and enhance efficiency in manufacturing. As shown in the figure, the system monitored the spray process from multiple camera angles by comparing two sets of spray parameters. This demonstrates how deep learning can identify subtle changes in the spray plume that correlate with process drift or hardware issues, providing a basis for automated adjustments during coating deposition.

Predicting Coating Functional Properties and Lifetime Using AI-Driven Models

In the field of TBCs applications, researchers have developed multiscale models integrating ANNs to predict coating failure and lifetime (Ref 280, 282). Liu et al (Ref 280) showed that model accuracy improved by considering both microscale failure mechanisms and macroscale operating conditions, with a key finding that damage accumulation is initially dominated by thermal mismatch but is later controlled by oxidation. Another probabilistic lifetime prediction model (Ref 282) also addressed the complex chemo-thermo-mechanical failure and parameter uncertainties in TBCs, achieving excellent prediction accuracy with an error of just 14%. Other recent research has successfully applied ANN modeling combined with aero-acoustic emission analysis to monitor and optimize High-Velocity Oxy-Fuel (HVOF) spray processes, ensuring coating quality control for hard chrome replacement for hydraulic components (Ref 274). Similarly, Arkhipov et al. (Ref 279) integrated digital twin technology with aero-acoustic monitoring in cold spray, significantly improving the reliability of coating deposition. Focusing on cold spray that can be used for the dimensional restoration of aerospace components, Huaraca Aparco et al. (Ref 285) developed an Expectation-Maximization (EM) machine learning model to predict the residual stress distributions in cold spray coatings. Their approach provided insights into complex property-process relationships, demonstrating that while selected processing parameters drive tensile stress formation, intrinsic material properties such as thermal conductivity and strength predominantly control compressive stresses. The incorporation of additional cold spray parameters, such as particle morphology, substrate surface conditions, and spray distance, as well as verification with real-world data, will further improve the model.

Collectively, these studies also enable process optimization: once a model maps the process to quality/performance, it can be used (directly or via search/optimization) to recommend parameter sets that maximize functional performance targets (i.e., lifetime and wear resistance) while meeting the coating's quality constraints (i.e., porosity and thickness).

Use of AI for Tool Path Planning to Achieve Coating Geometrical Accuracy, Process Efficiency and Reliability

Recent AI-enabled approaches have also addressed coating shape, especially thickness distribution and geometric control (i.e., track profile, uniformity/flatness), which are critical for dimensional restoration and spray-based additive manufacturing. For example, neural network models have been used to predict cold spray track/profile geometries under different processing conditions, supporting improved geometric control and process planning for additive builds (Ref 286). Recently, Falco et al. (Ref 287) introduced a deep neural network (DNN) framework that integrates adaptive slicing algorithms with automated toolpath planning. Their model can accurately predict 3D deposit shapes and dynamically adjust the layer thickness based on the local curvature, significantly minimizing material waste and improving geometrical fidelity (Ref 287).

Current capabilities have advanced and moved beyond simple symmetric Gaussian distributions to account for shadow effects and the evolution of track shapes from Gaussian to triangular profiles, which are essential for building sharp edges and vertical walls without significant “edge loss.” This includes the works by Ikeuchi et al. (Ref 286, 288) that utilized Gaussian Process Regression (GPR) to model overlapping track profiles in cold spray additive manufacturing. By explicitly incorporating surface topology features, such as the profile of the previous track, their data-driven model outperformed traditional Gaussian superposition methods, providing consistent predictions across varying overlap ratios.

These models (Ref 287, 288) also account for the complexity of multi-layer build-ups, and can simulate how successive layers interact, allowing for the fabrication of near-net-shape parts with high dimensional accuracy. These models can often be integrated into offline programming (OLP) environments, where optimization algorithms such as the Nelder-Mead simplex method (Ref 289) have been demonstrated to be capable of planning robot trajectories that ensure uniform thickness on complex spherical or free-form surfaces. The reliability of these tool paths can be further bolstered by in situ laser profilometry, which provides real-time measurement of the track shape during the spray process (Ref 263, 286). This closed-loop approach allows for immediate adjustments, ensuring that the final geometry meets strict industrial tolerances and reduces reliance on costly post-process destructive testing.

Current and Future Challenges

Although AI is pivotal in advancing thermal spray technologies, its full potential is constrained by several current and future challenges. The dominant issues range from data acquisition and model complexity to practical industrial implementation.

Data-related issues are among the most significant (Ref 276, 277, 283). ML models, especially deep learning architectures, require extensive high-quality data for effective training; however, generating these data through physical experiments is expensive and time-consuming. The limited availability of diverse data or reliance on simulated datasets can lead to models that overfit, meaning they perform well on the training data but fail to generalize to new, unseen conditions. The reliance on simulated data in these studies is often due to the lack of abundant real experimental data, and training with excessively small datasets increases the risk of overfitting, as this can cause the model to fit too closely to noise and random fluctuations, leading to suboptimal performance. This issue is compounded by existing monitoring equipment, which is often static and cannot capture dynamic process data while the spray torch is in motion, which is a critical element for building robust, real-time models.

Complexity of thermal/ cold spray processes: Another significant challenge is the inherent complexity of thermal spray processes that involve numerous interdependent parameters, and capturing their nonlinear interactions requires advanced models that consider the underlying physics (Ref 27, 283, 290-292). While models such as ANN have shown success in predicting specific properties, they struggle to holistically capture the intricate interactions between all variables. For example, an AI/ ML model trained on one set of materials or spray conditions may not generalize reliably to new materials or extreme conditions.

The “black box” nature of many ML models, where the reasoning behind a prediction is not transparent, presents a barrier to industrial adoption. A further practical barrier is ***data fragmentation***: studies often use different experimental conditions, equipment configurations, parameter definitions, and reporting conventions, which limits the ability to merge datasets across laboratories and slows the creation of robust benchmarks (Ref 263, 277).

Looking ahead, a key challenge will be developing sophisticated and integrated AI frameworks. Future systems must move beyond predicting single or limited number of coating properties to providing a comprehensive understanding of the entire coating process and the associated coating properties. This involves creating multiscale models that can accurately link microstructural features to macroscopic performance, which is a task that require bridging significant gaps in both data availability and modeling techniques (Ref 280) . The successful integration of various data sources, such as acoustic emissions, real-time video, and equipment sensor readings, into a single, cohesive model is a major hurdle (Ref 263). The ultimate goal is to create a “digital twin” of the thermal spray process that can simulate outcomes and optimize parameters, but this demands substantial advancements in all aspects including, data handling, simulation and ML algorithms.

Practical industrial implementation: Finally, the practical implementation of these advanced AI systems in industrial settings poses its own set of challenges. For AI-driven process control to be widely adopted, especially by small and medium-sized enterprises, the technology must be robust, user-friendly, and cost-effective (Ref 284) . This requires better integration of sensors into spray systems and standardized data interfaces. Without a clear short-term return on investment, it can be difficult for industry players to justify the expense of data collection campaigns and ML model development. Furthermore, the transferability of models remains a concern; a model trained for a specific torch and material may not work for another without significant recalibration, highlighting the need for more adaptable and generalizable AI solutions. There is also the issue of reluctance to share proprietary data and the absence of standardized models and validation methods, which impedes collaboration and regulatory acceptance. Overcoming these issues, along with challenges in data quality, model interpretability, and the stringent certification requirements for safety-critical applications, is crucial for transitioning AI from academic research to routine industrial practice.

Advances in Science and Technology to Address Challenges

One promising avenue is the development of hybrid modeling approaches that combine data-driven AI with physics-based understanding to reduce the reliance on large experimental datasets, which are often costly and time-consuming to generate. Physics-Informed Neural Networks (PINNs) embed governing physical laws (i.e., conservation equations, constitutive models) directly into the training of neural networks (Ref 275, 292). Raissi et al. (Ref 292) demonstrated that PINN frameworks could solve fluid and solid mechanics problems by embedding physics into the loss function of a neural network. By constraining the model with known physics variables, PINNs can achieve accurate predictions even with limited data and inherently respect physical principles like mass or energy balance. This approach helps to open the "black box" of traditional AI models, providing a degree of interpretability that is crucial for industrial adoption. In thermal spray, Bobzin et al. (Ref 290) applied PINNs to plasma spraying, showing improved prediction of in-flight particle velocity based on CFD-generated data, though temperature remained more challenging to model effectively.

To further address data scarcity, generative AI methods, such as generative adversarial networks (GANs), can also be coupled with simulations to produce realistic synthetic datasets of microstructures or splat morphologies, augmenting experimental data for training (Ref 5). For example, GANs have been successfully employed to generate realistic scanning electron microscope (SEM) images of suspension plasma spray coatings with specific sliding angles (Ref 276). In this approach, *K*-means clustering is first used to analyze the microstructural features and group existing images into distinct classes based on their properties; the GAN is then trained on these classes to generate new, high-fidelity images that are visually and qualitatively satisfactory. The quality of these generated images can be quantitatively assessed using metrics such as the Fréchet Inception Distance (FID), which measures the similarity between the distribution of generated images and real images (Ref 276, 293).

The integration of digital twin technology with AI is a significant advancement for coatings manufacturing. A digital twin is a virtual replica of the coating process that runs in parallel with the actual process and is continuously updated with sensor data. While modern control systems can reproduce primary input parameters, they cannot monitor variations in coating quality resulting from hardware degradation like nozzle wear or clogging (Ref 277) . For example, Arkhipov et al. (Ref 279) developed a digital twin for cold spray that ingested live acoustic emission data to predict deposition quality and detect anomalies during the build. This approach enabled immediate identification of events such as nozzle clogging or irregular powder feed, allowing operators (or an automated control system) to take corrective action. Digital twins can also be used to perform virtual experiments; exploring the effect of parameter changes on the coating outcome in a simulation, which reduces the need for costly physical trials. This capability paves the way for real-time adaptive control, where AI systems adjust process parameters on the fly in a closed-loop system. An AI controller can modulate the spray torch speed or powder feed rate based on live sensor feedback to maintain a target coating thickness or microstructure, responding to disturbances faster than a human operator, as shown in Fig. 46.

A practical note on sensor integration is warranted: the coating thickness can be measured in situ using spatially resolved optical/3D measurement approaches, including demonstrated in situ thickness mapping in thermal spraying (Ref 294). By contrast, coating microstructure is typically characterized ex situ (e.g., microscopy/SEM), and real-time microstructure "measurement" is generally achieved indirectly via proxy signals (plume imaging, acoustic emissions, pyrometry, in-flight particle diagnostics) that are then mapped to microstructure descriptors using ML models (Ref 263, 277, 284).

Therefore, a realistic multimodal sensor set for real-time learning/control may combine: (i) optical imaging (i.e., plume shape/ brightness/ dynamics), (ii) thermal sensing (pyrometers, thermocouple, IR camera), (iii) acoustic emission sensor/ microphones (i.e., process anomalies, clogging/ nozzle wear signatures), and (iv) system parameter logs (i.e., gas flows, power, feed rates). Multimodal learning algorithm can fuse these streams so that one modality compensates for another's weaknesses, improving robustness across materials and operating windows (Ref 264, 275, 278, 285).

The feasibility of such systems is supported by the high processing speeds of modern AI models; for example, the YOLOv5 architecture has achieved processing speeds of up to 50 millisecond per frame on a standard smartphone,

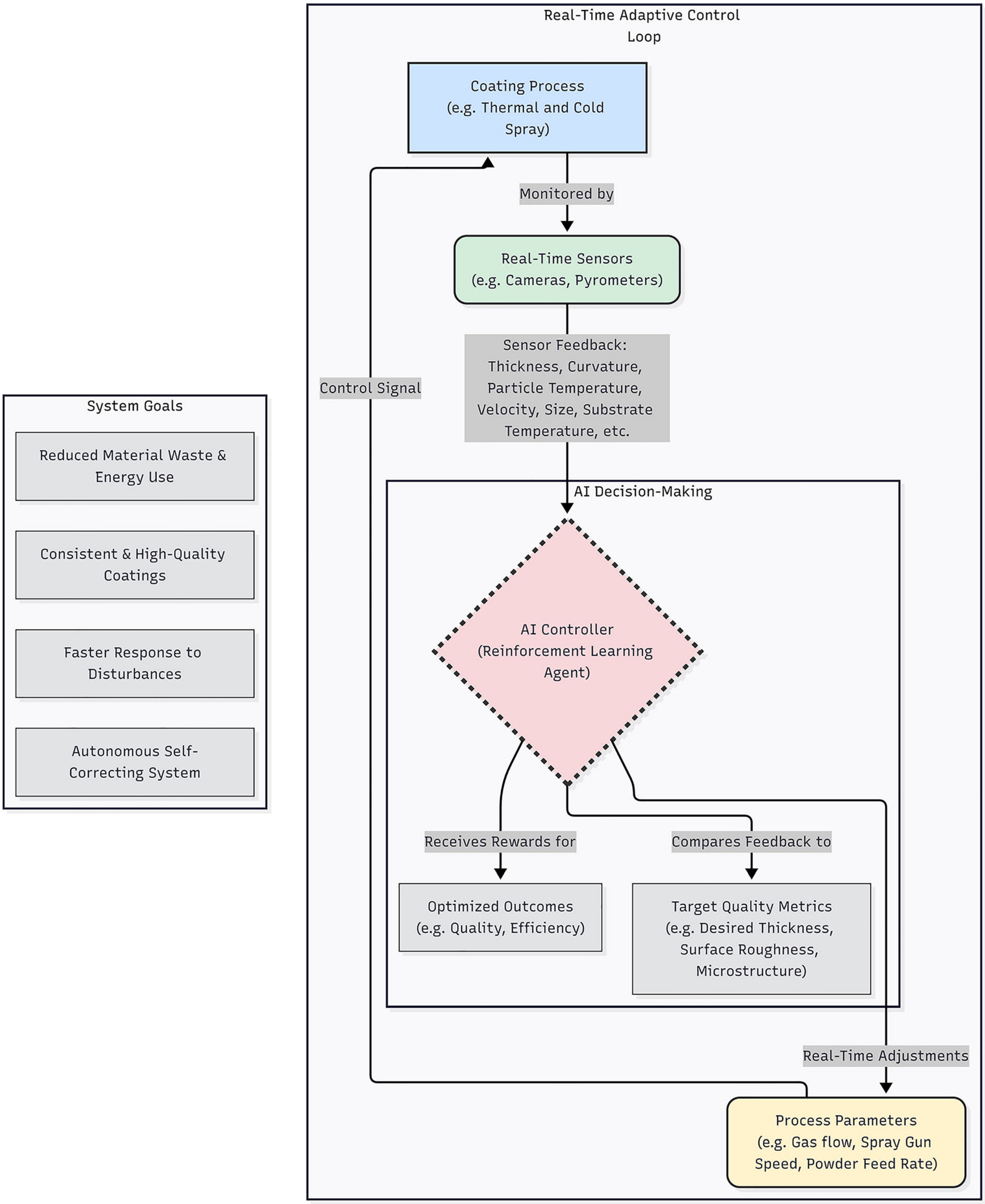

Fig. 46 Real-time adaptive control, where AI systems adjust process parameters on the fly in a closed-loop system

making real-time classification and control viable. These adaptive systems not only improve quality but also enhance sustainability by reducing material waste and energy usage, aligning with the goals of greener manufacturing (Ref 284).

Multimodal learning is being explored to improve model robustness by combining different data sources, such as optical images of the spray plume, acoustic emission signals, and process parameter logs, into a single, powerful model (Ref 263, 274, 277, 285, 295). By fusing data from cameras, microphones, and pyrometers, an AI model can develop a more holistic understanding of the process state, where one modality can compensate for the weaknesses of another. For example, a successful implementation combined visual data from a spray torch, which provided information on temperature- and velocity-sensitive regions, with acoustic spectrograms that were correlated with final coating hardness to achieve a more comprehensive classification of the process state (Ref 274).

Finally, AI is transforming post-spray quality control by automating microstructural analysis, which has traditionally relied on subjective human judgment. Computer vision techniques can now provide objective and repeatable assessments. The Structural Similarity Index (SSIM), for example, offers a quantitative metric to compare a produced coating's microstructure against a certified reference image, automating conformance checks. Furthermore, CNN models can be trained for object detection to automatically identify, locate, and quantify specific microstructural features such as porosity and oxides within an SEM image (Ref 277, 284).

Another advanced development is Graph Neural Networks that treat a coating's microstructure as a graph where splats/particles or pores are nodes, and their contacts are edges. This overcomes the challenge for conventional ML models that use fixed-size grids or images in dealing with complex topologies of coating microstructures. GNNs can effectively capture spatial relationships and connectivity, making them well-suited for predicting properties that depend on the network of features such as pores or splats. For example, a GNN could be trained to model both plasma flow (Ref 291) and particle transport, enabling accurate prediction of coating properties on surfaces with varying geometries.

These AI-driven tools not only accelerate the quality control workflow but also introduce a higher level of objectivity and standardization to microstructural characterization, as well as improving the interpretability of ML predictions for coating performance.

Concluding Remarks and Future Perspectives

In conclusion, AI-driven modeling is a transformative technology for achieving greener aviation by optimizing thermal spray and cold spray coatings. By enabling more accurate predictions of coating lifetime and performance, AI enhances component durability, reduces material and energy waste, and minimizes the need for rework. Current research is still at its infancy but demonstrates the power of AI to monitor and optimize coating processes in real-time using diverse sensor data, predict complex functional coating properties and lifetime, as well as assisting in tool path planning to achieve coating geometrical accuracy, process efficiency and reliability.

To fully realize this potential, future research must focus on creating high quality, standardized datasets and benchmarks to ensure model reliability across the industry. Developing explainable AI (XAI) that is not just a "black box" is critical for building trust and facilitating adoption by industry. The ultimate goal is to advance from predictive modeling to real-time adaptive control systems, creating autonomous "smart thermal spray/ cold spray cells" that continuously optimize coating quality/reliability and process efficiency, which is critical for a greener aerospace sector.

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