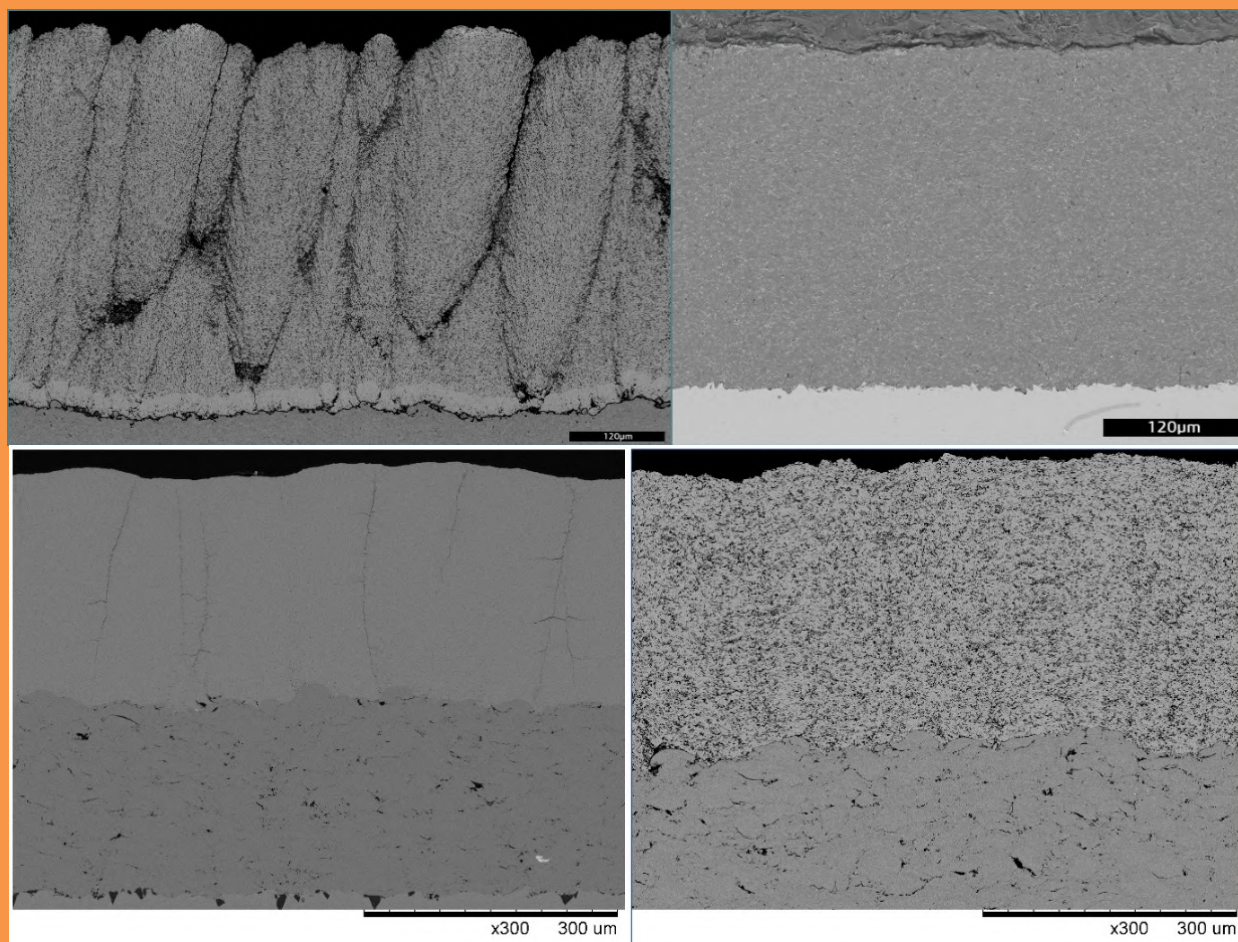


SPRAYTODAY®

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Columnar, dense, segmented-vertically cracked and highly porous coatings SPS coating micrographs

Issue Highlights

- Suspension Plasma Spray in Practice: How Formulation Choices Shape Coating Structure
- Transforming High-Temperature Industrial Waste Heat into Low-Carbon Hydrogen: The Role of High-Energy Deposition and Surface Manufacturing

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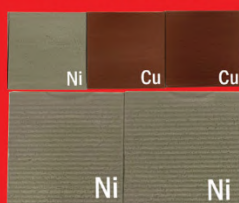
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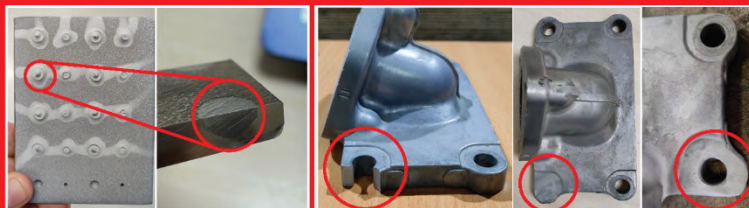
Approx. 110 kg

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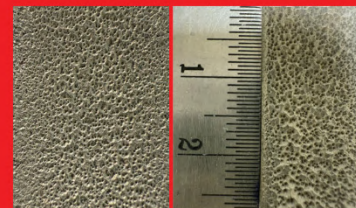
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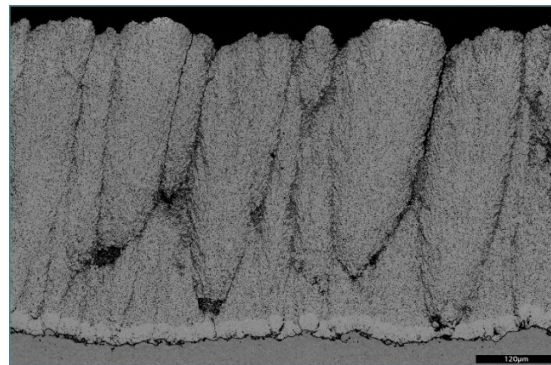
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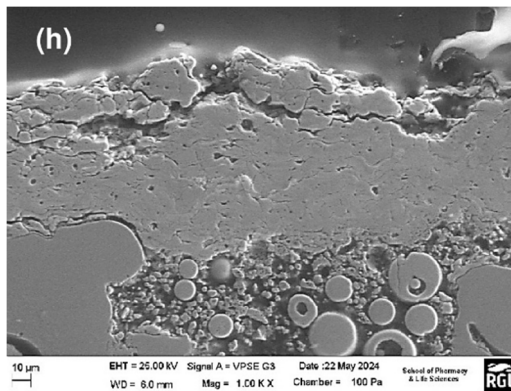
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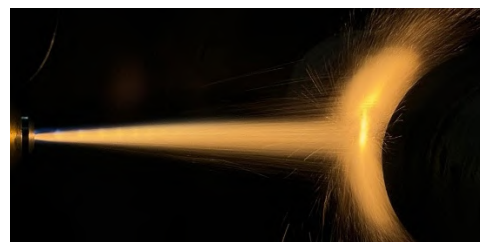
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Editor's Note



Dear Readers,

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

I am particularly pleased to be allowed to recommend to you the latest issue of SPRAYTODAY. This issue includes invited innovative featured articles on “Suspension Plasma Spray in Practice: How Formulation Choices Shape Coating Structure”, “Transforming High-Temperature Industrial Waste Heat into Low-Carbon Hydrogen: The Role of High-Energy Deposition and Surface Manufacturing”; that illustrate current research trends in thermal spray development.

We are excited to announce our upcoming event: **National Thermal Spray Conference and Expo (NTSC 2027), February 19-20, 2027, Research and Innovation Park, IIT Delhi, India.** This conference will serve as a hub of innovation and collaboration for thermal spray technology. More than 300+delegates, including leading experts, researchers, and industry professionals from around the globe will attend the NTSC2027 to discuss cutting-edge developments, share insights, and explore the future of thermal spray technology in the world. With a robust lineup of keynote speeches, technical sessions, and an expansive expo will be showcasing the latest equipment, materials and recent developments. The conference significantly will contribute to learning about the latest advancements and understanding the new applications of thermal spray technology. Visit NTSC2027 website <https://www.indtsa.org/ntsc-2027>

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

Thank you for being part of our journey.

Be healthy, active, and curious! Happy Spraying!

Best Regards,

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

(Satish Tailor | PhD)

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Suspension Plasma Spray in Practice: How Formulation Choices Shape Coating Structure

By **Nicholas Curry**

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Introduction: *The wrong first question*

Suspension plasma spray (SPS) is a development of atmospheric plasma spraying that uses fine particles suspended in a liquid carrier. This allows the injection of powders that would otherwise be too fine to feed and spray using conventional dry powder systems. The liquid carrier transports the fine particles into the plasma jet, where the liquid evaporates and the particles are heated, accelerated and deposited onto the substrate.

SPS has developed from a laboratory curiosity into an industrially relevant coating process. It is now used to produce a wide range of ceramic coating structures, from columnar thermal barrier coatings to highly dense coatings for semiconductor manufacturing applications. Between these two extremes, SPS can also produce porous, segmented and vertically cracked structures, depending on the suspension and process conditions[1].

This flexibility is one of the strengths of SPS, but also one of its challenges. Compared with conventional air plasma spraying using dry powders, SPS is more sensitive to feedstock formulation and process control. The final coating structure is strongly influenced by the particle size distribution, solvent system, solids loading, viscosity, atomisation behaviour and plasma parameters [2].

A common question from people starting with SPS is:

“How do I formulate a good ceramic suspension?”

In practice, this is not the best first question. The better question is:

“What coating structure am I trying to produce?”

A suspension that is optimised for one coating architecture may be completely unsuitable for another. This is especially true when comparing columnar and dense SPS coatings. In many cases, the formulation logic is almost opposite.

Suspension properties that matter

The key objective in SPS is not only to feed a liquid into the plasma jet. The aim is to generate the correct in-flight particle population for the coating structure being targeted. This makes the relationship between the original powder size in the suspension and the final coating structure more complex than in conventional powder spraying.

Several suspension properties become critical:-

Surface tension influences droplet breakup and atomisation. A lower surface tension generally supports finer atomisation and smaller droplets. A higher surface tension tends to resist atomisation and produce larger droplets.

Viscosity affects the feeding behaviour, injection pressure and atomisation. A low-viscosity suspension is generally easier to atomise, while a higher-viscosity suspension can help resist excessive fragmentation. Viscosity also plays an important role in suspension stability, since more viscous systems can reduce sedimentation issues.

Solids loading controls how much coating material is delivered for a given liquid feed rate. Higher solids loading can improve productivity and reduce the relative amount of process energy spent evaporating solvent. However, high solids loading also makes formulation and

feeding more difficult if the suspension is not properly designed.

Particle size distribution can strongly influence the size of the in-flight particles. However the relationship is not one to one. A nano powder may deposit as micrometric splats if the suspension is not correctly formulated.

These properties do not act independently. A change in particle size can change viscosity. A change in solvent can change atomisation behaviour. A change in solids loading can change both stability and droplet breakup. Successful SPS development therefore requires the suspension formulation and process parameters to be considered together.

Formulating for columnar coatings

Columnar SPS coatings are of particular interest for thermal barrier coating applications. The attraction is clear: SPS can produce EB-PVD-like columnar structures using an atmospheric thermal spray process.

Columnar structures are generally produced by very fine in-flight particles interacting with the plasma flow close to the substrate surface. These particles can follow the gas flow, deposit obliquely and generate the shadowing effects needed for column formation [3].

For columnar SPS coatings, the suspension formulation normally needs to support the generation of fine, well-atomised droplets and small in-flight particles.

A typical starting point would be:

Particle size: d_{50} around 0.5–0.7 μm

Particles in this size range are often suitable for producing columnar structures. Finer particles may create excessive viscosity due to their high specific surface area, making the suspension difficult to process. Coarser particles become increasingly difficult to use for columnar coatings because they have more momentum in the plasma stream and are less able to follow the plasma flow near the substrate.

Solvent: ethanol-based systems

Ethanol is commonly preferred for columnar SPS coatings because of its low surface tension and relatively low viscosity. These properties support atomisation and help generate the fine droplets needed for column

formation. Ethanol can also contribute additional heat through combustion downstream of injection.

Solids loading: typically 20–25 wt.%

Lower solids loadings can be sprayed, but often require compromises in spray rate and stand-off distance. Higher solids loadings can be beneficial for productivity, but they are more difficult to formulate and process unless the suspension and feeding system are designed for that purpose.

Dispersant: formulation-specific

Polyvinylpyrrolidone (PVP) can be one possible starting point for ethanol-based ceramic suspensions, but there are many possible dispersant systems. The correct choice depends on the ceramic powder, solvent system, solids loading and stability requirements. Supplier guidance and literature review are often useful starting points.

Preparation is also important. Laboratory-scale suspensions require careful mixing to disperse the powder properly in the liquid. Depending on the material, this may involve a jar mill, high-speed mixer or other dispersion method. Sieving before spraying, for example through a 35 μm sieve, can help remove agglomerates that may block injectors or disturb the coating structure.

For industrial work, a commercial suspension should always be considered if one is available. A commercial suspension will normally have been developed for stability, storage lifetime, atomisation behaviour and coating reproducibility. In simple terms, much of the difficult formulation work has already been done. One major advantage of commercial suspensions is that they can often achieve significantly higher solids loadings — 30%, 50%, or as high as 75% — enabling larger processing windows and substantially improved throughput for industrial production applications.

Water-based suspensions for columnar coatings

A frequent question in columnar SPS coating development is whether ethanol is really necessary. Water-based systems are attractive because they reduce concerns around flammability, solvent handling and explosion-proof equipment.

Water-based columnar coatings are possible. However, the process has to work against the basic properties of water, which makes the development route more difficult.

The first issue is surface tension. Water has a surface tension of approximately 72 mN/m, compared with approximately 22 mN/m for ethanol. This makes atomisation more difficult and generally favours larger droplets. Surfactants can help, but they do not remove the fundamental difference between the two solvent systems.

The second issue is energy demand. Water requires approximately 3.4× more energy to heat and evaporate compared with ethanol. In practical terms, this means more of the plasma energy is consumed by the solvent before the ceramic particles can be effectively heated. More plasma power or longer particle flight time may therefore be required.

The third issue is that water provides no additional heat contribution from combustion. With ethanol, combustion downstream can contribute to the overall thermal environment experienced by the particles. With water, this effect is absent.

One example from development work used a water-based suspension with 25 wt.% solids loading to produce a columnar coating. The coating was columnar, but it was sprayed at less than half of the feed rate typically used with an ethanol-based benchmark system: approximately 45 mL/min compared with around 100 mL/min. It also required much more aggressive plasma conditions, operating at approximately 75 kW net power, or around 140 kW gross power.

The conclusion is not that water-based columnar SPS coatings are impossible. They are possible. The point is that achieving stable processing and consistent columnar coating formation with water is considerably more challenging. The lower throughput and higher energy demand may also make it difficult to achieve the economics required for industrial production.

There are now commercial suspensions available for columnar coatings based on non-flammable solvent systems. This may provide a practical compromise for users who want to avoid ethanol handling while still accessing a wider processing window.

Dense SPS coatings: the opposite design logic

Dense ceramic coatings represent a very different application space for SPS. A major example is yttrium oxide coatings for reactive ion etching chambers in semiconductor manufacturing [4]. In this application, the

target is not a strain-tolerant columnar structure, but a highly dense, low-defect coating that can resist plasma erosion and limit particle generation.

The formulation logic for dense coatings is very different from that used for columnar coatings. In fact, many of the things that help produce a columnar SPS coating can work against you when trying to produce a dense coating.

For dense coatings, one of the main problems is the formation of nodular defects or proto-columns. These features can form when fine particles deposit in a similar manner to columnar coating growth. The fine particle population that is useful for columnar coatings can therefore become a defect source in dense coatings.

A typical formulation strategy for dense SPS coatings would be:

Water-based suspension

For dense coatings, the higher surface tension of water can be beneficial. It helps generate larger droplets and reduces the tendency to produce fine, column-forming in-flight particles. This is the opposite of the situation for columnar coatings, where fine atomisation is usually desirable.

Particle size distribution: d50 around 3–6 µm

A coarser primary particle size distribution is better matched to dense coating formation. The fraction of fines below 1 µm should be minimised as far as practical. These fines are often the source of nodules, local porosity or column-like defects.

Solids loading: 30–40 wt.%

Higher solids loading can help resist excessive atomisation, improve throughput and keep stand-off distances within a practical range. It may also improve suspension stability by reducing the relative volume of liquid phase. As always, this only works if the suspension is correctly formulated and can be fed reliably.

Controlled viscosity

For columnar coatings, viscosity is often reduced as far as practical to support atomisation. For dense coatings, a somewhat higher viscosity may be helpful because it promotes larger droplets and reduces fine particle formation during atomisation. However, the viscosity must still be compatible with the feeding system and

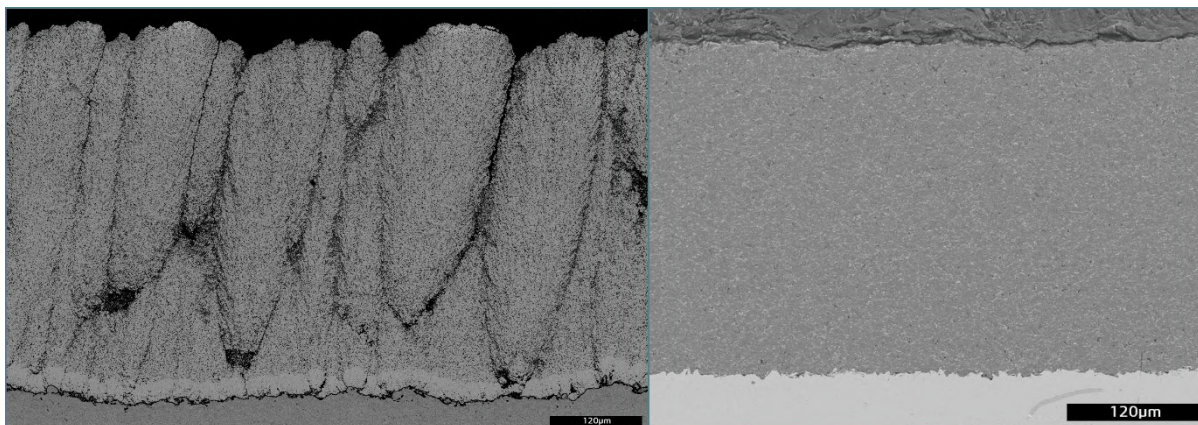


Figure 1: Columnar and dense SPS coating micrographs shown side by side.
(Suspension plasma spray can produce very different coating architectures. Columnar and dense coatings often require opposite formulation and processing strategies)

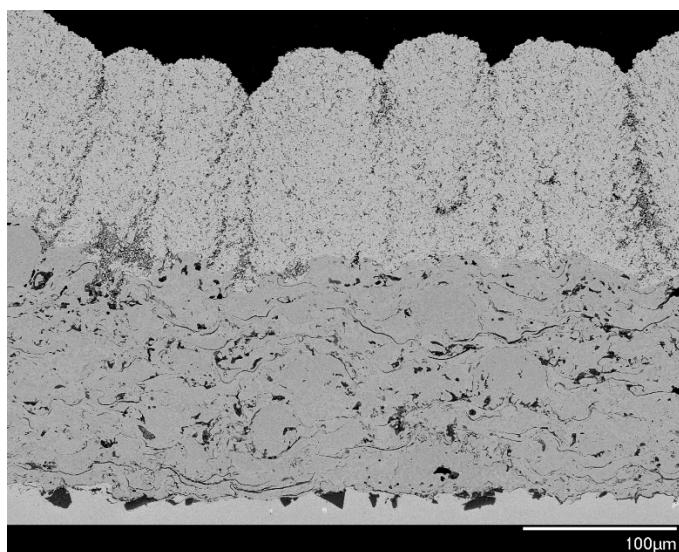


Figure 2: Water based columnar coating
(Columnar coatings are possible with water, if you accept the limitations)

injector. There is normally an optimum range rather than a single ideal value.

Low deposition rate per pass

Dense SPS ceramic coatings do not microcrack in the same way as conventional powder-sprayed ceramic coatings. As a result, stress relief during coating build-up can be limited. Dense SPS coatings should therefore be deposited in thin passes to reduce cracking risk. In practice, this often means around 5 µm per pass or less.

The key point is simple: dense SPS coatings require a different mindset. The goal is not to maximise fine atomisation, but to control the droplet and particle

population so that fine, nodule-forming material is minimised.

Case study: When formulation details dominate the process window

An early SPS development study at University West provided a useful example of how strongly suspension formulation can influence coating structure.

In 2013, following installation of an industrial suspension-capable plasma spray system, an initial design of experiments was planned to investigate the formation of columnar coatings. The study included 33 spray conditions, with plasma parameters varied to assess their

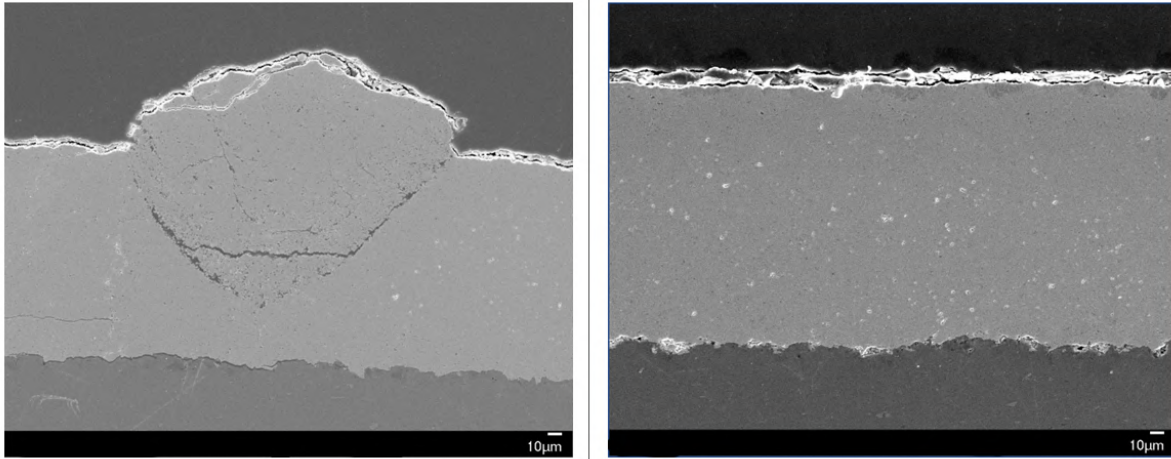


Figure 3: Dense Coatings – with and without nodule
(Fine particles will cause nodules in dense coating applications)

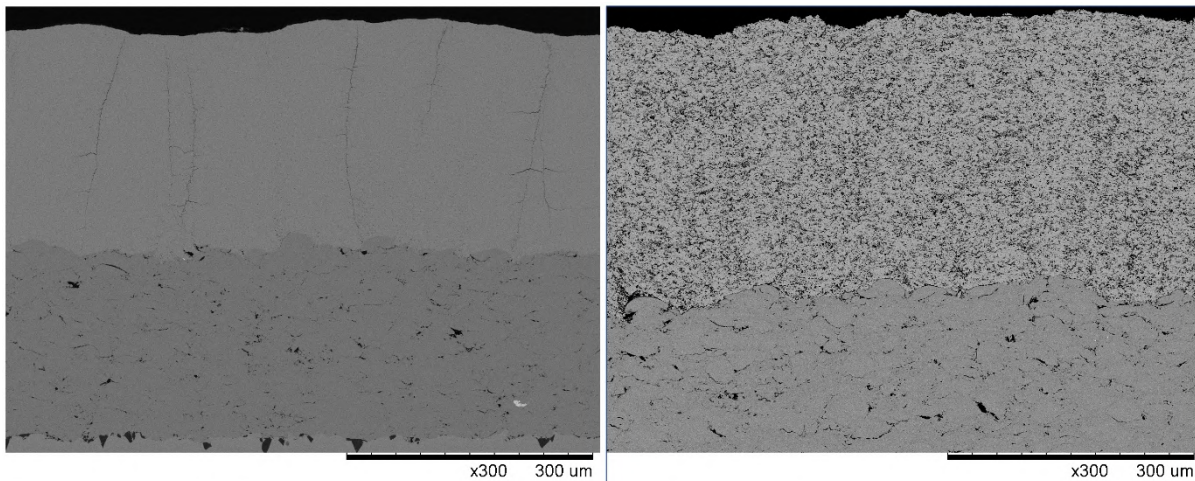


Figure 4: Example coatings from the 33-run DoE case study.
(Not all unsuccessful experiments are without value. Although the target columnar structure was not achieved, the study produced segmented, vertically cracked and highly porous coatings with potentially useful architectures)

influence on coating architecture. For each condition, several bond-coated coupons were sprayed, resulting in approximately 8–10 hours of total spray time over several days.

The objective was clear: identify the processing window for columnar coating formation.

The outcome was equally clear, but not as expected. None of the coatings produced in the study were columnar.

At first glance, this could have been interpreted as a plasma parameter problem. However, the more important issue was related to the suspension formulation.

At the time, the commercial suspension intended for the work had not yet been received. Instead, a laboratory material was used. This material was supplied as a 50 wt.% concentrate and was intended to be diluted with ethanol to approximately 10 wt.% solids before spraying.

The initial qualification trials showed that deposition at this solids loading was very slow, with more than one hour required to produce a coating of approximately 300 µm thickness. To bring the experimental programme into a practical timeframe, the decision was made to increase the solids loading to 25 wt.%, closer to the level expected from the commercial suspension.

The issue was not the increase in solids loading itself. Higher solids loading is often beneficial in SPS when the suspension is correctly formulated. The critical detail was that the 50 wt.% concentrate was water-based.

By only partially diluting the concentrate with ethanol, the resulting liquid phase became a water-ethanol mixture. Such mixtures can show non-linear viscosity behaviour, with certain compositions having higher viscosity than either pure solvent alone. In addition, the suspension did not contain a suitable dispersant system for this modified formulation.

The result was a suspension with poorer atomisation behaviour than intended. The droplet breakup and in-flight particles generated under these conditions were not suitable for columnar coating formation. In effect, the plasma parameter study was being carried out with a suspension that was already working against the desired coating architecture.

Although the experiment did not achieve its original objective, it was still instructive. Several coatings produced during the study showed segmented or densely vertically cracked structures. One coating was particularly interesting, with more than 35% porosity while still maintaining structural integrity. It was not soft or friable, suggesting that this type of architecture could have potential in applications where high accessible surface area is required, such as catalyst-support coatings.

The main lesson from this study was that SPS process development cannot be separated from suspension formulation. A small detail in solvent composition, dispersant strategy or atomisation behaviour can shift the resulting coating structure completely.

It also illustrates a broader point in coating development: unsuccessful experiments are not always without value. They may fail to produce the intended coating, but still reveal alternative structures or processing routes worth investigating further.

Practical takeaways

SPS is not a process where a single “good suspension” can be recommended for all coating structures. The suspension must be designed around the intended coating architecture.

For columnar coatings, fine particles, strong atomisation and ethanol-based systems are often a good starting point. For dense coatings, coarser particles, reduced fines, larger droplets and controlled viscosity may be more appropriate.

The most important message is therefore not that one formulation route is universally better than another. It is that the correct formulation depends on the structure you are trying to produce.

The first question should not be:

“What is the best SPS suspension?”

The better question is:

“What coating structure am I actually trying to produce?”

References

1. A. Ang, et al., Innovative Coatings for a Greener Sky: The 2026 Strategic Roadmap for Thermal Spray and PVD Coatings, J Therm Spray Tech (2026). <https://doi.org/10.1007/s11666-026-02276-5>
2. P. Fauchais, M. Vardelle, A. Vardelle, S. Goutier, What Do We Know, What are the Current Limitations of Suspension Plasma Spraying?, J Therm Spray Tech 24 (2015) 1120–1129. <https://doi.org/10.1007/s11666-015-0286-3>
3. K. VanEvery, M.J.M. Krane, R.W. Trice, H. Wang, W. Porter, M. Besser, D. Sordet, J. Ilavsky, J. Almer, Column Formation in Suspension Plasma-Sprayed Coatings and Resultant Thermal Properties, J Therm Spray Tech 20 (2011) 817–828. <https://doi.org/10.1007/s11666-011-9632-2>
4. J. Kitamura, Z. Tang, H. Mizuno, K. Sato, A. Burgess, Structural, Mechanical and Erosion Properties of Yttrium Oxide Coatings by Axial Suspension Plasma Spraying for Electronics Applications, J Therm Spray Tech 20 (2011) 170–185. <https://doi.org/10.1007/s11666-010-9585-x>

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Transforming High-Temperature Industrial Waste Heat into Low-Carbon Hydrogen: The Role of High-Energy Deposition and Surface Manufacturing

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Abstract

Steel, cement, glass, refining, petrochemical, fertiliser, nuclear, chemical, power-generation, and other energy-intensive industries produce substantial quantities of high-temperature waste heat that remain underutilised. Recovering this resource could improve energy efficiency, accelerate industrial decarbonisation, and support sustainable hydrogen production. High-temperature electrochemical processes, including Solid Oxide Steam Electrolysis (SOSE) and thermochemical water-splitting cycles such as copper-chlorine (Cu-Cl), can use waste heat to reduce electricity consumption, increase conversion efficiency, and lower hydrogen costs. Their deployment, however, requires durable materials capable of resisting severe thermal, mechanical, corrosive, and hydrogen-rich conditions. High-energy deposition and surface manufacturing, particularly advanced thermal spray technologies, offer scalable methods for producing functional electrodes, protective interconnects, corrosion-resistant coatings, thermal barriers, heat exchangers, and tailored multi-material components. Integrating waste heat recovery with hydrogen production and advanced manufacturing therefore offers a promising route towards efficient, durable, and commercially viable hydrogen systems while supporting resource efficiency, industrial

competitiveness, energy security, and sustainable industrial transformation worldwide.

Industrial High-Temperature Waste Heat: An Untapped Energy Resource

Industrial waste heat is thermal energy, including sensible and latent heat, that leaves a system without performing useful work. Such losses may occur at the level of individual equipment or across entire industrial processes [1]. Energy-intensive sectors, including steel, cement, glass, refining, petrochemicals, fertilisers, nuclear power, chemicals, and power generation, operate at elevated temperatures and reject substantial quantities of thermal energy during their operation (Fig. 1). The scale of this underutilised resource is considerable. Approximately 46% of the energy consumed by UK industry is estimated to be lost, corresponding to industrial waste-heat losses of around 46 TWh/year. Of this, an estimated 14–23 TWh/year could potentially be recovered, depending on the system boundaries and available recovery technologies [1]. Although an estimated 60–70% of industrial waste heat is available at temperatures below 250 °C, a smaller but strategically important fraction occurs at higher temperatures and offers considerable potential for high-value energy recovery. Capturing and productively reusing these thermal streams could therefore reduce primary energy

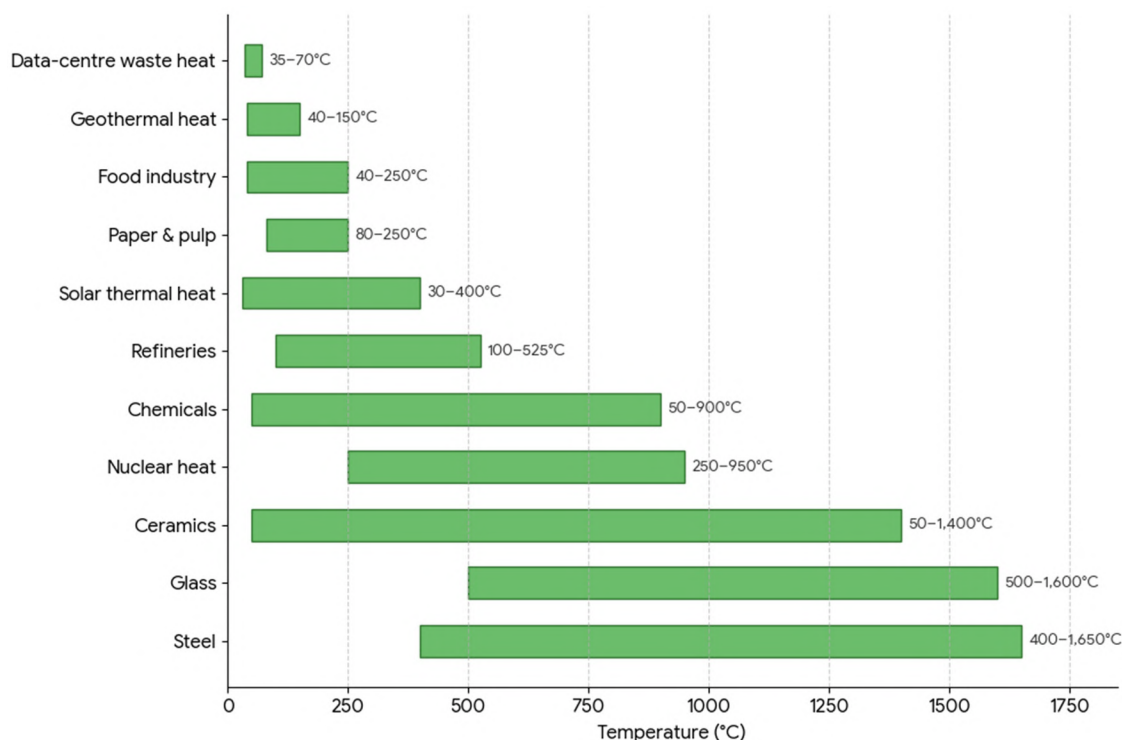


Figure 1: Typical industrial waste-heat sources and potential applications by temperature range.

demand and greenhouse-gas emissions while improving process efficiency and industrial competitiveness [1–2]. Importantly, significant quantities of waste heat are expected to remain available despite continued improvements in process efficiency and the transition to alternative fuels. This residual resource creates opportunities for integration with emerging energy technologies, including high-temperature hydrogen production.

Traditionally, waste heat recovery has focused on improving process efficiency through heat exchangers, waste heat boilers, cogeneration systems, and feedstock preheating. However, increasing demand for low-carbon hydrogen has broadened its role from an efficiency measure to a strategic energy resource [3]. The global hydrogen market, valued at over \$200 billion in 2024, is projected to exceed \$700 billion by 2040 (Research and Markets, 2025–2035). Hydrogen production remains overwhelmingly fossil-fuel based, with unabated natural gas accounting for nearly two-thirds of global production and emitting approximately 10–12 tonnes of CO₂-equivalent per tonne of hydrogen produced [4]. High-temperature hydrogen production technologies, including Solid Oxide Steam Electrolysis (SOSE), hybrid electrolysis, and thermochemical cycles such as the copper-chlorine (Cu-Cl) process, can utilise high-temperature industrial waste heat to reduce electricity

consumption, improve overall efficiency, and lower greenhouse gas emissions.

Several industrial sectors are well suited to early deployment of these integrated systems. Steel plants can recover blast furnace and coke oven waste heat to generate superheated steam for high-temperature electrolysis while recycling the resulting hydrogen for low-carbon steelmaking. Cement and glass manufacturing can provide continuous high-grade heat suitable for electrolysis or thermochemical hydrogen production, whereas refineries and petrochemical complexes can benefit from existing hydrogen distribution and steam infrastructure. Looking ahead, advanced nuclear reactors and concentrated solar thermal systems could provide reliable low-carbon heat for future high-temperature hydrogen production.

Successful implementation depends on materials and structures capable of operating reliably under prolonged exposure to high temperatures and aggressive chemical environments. High energy deposition and surface manufacturing technologies, particularly advanced thermal spray processes [5–6], provide scalable routes for producing durable functional and protective components for electrolyzers, thermochemical reactors, heat exchangers, and related high-temperature equipment. Together, these technologies enable more

efficient, reliable, and commercially viable hydrogen production while supporting industrial decarbonisation and sustainable manufacturing.

Waste Heat and High-Temperature Hydrogen Production

Water electrolysis is widely recognised as one of the most promising routes for producing green hydrogen using renewable electricity. While conventional alkaline water electrolysis (AWE), proton exchange membrane (PEM), and anion exchange membrane (AEM) systems operate at relatively low temperatures and depend primarily on electrical energy, high-temperature hydrogen production technologies can replace part of this electrical demand with thermal energy, improving overall efficiency and reducing hydrogen production costs [5-6].

Among these technologies, Solid Oxide Steam Electrolysis (SOSE), also known as Solid Oxide Electrolysis Cells (SOECs), is one of the most mature approaches for recovering industrial waste heat. Operating at approximately 600 °C to 900 °C, SOSE utilises superheated steam to reduce electrical energy requirements while achieving higher conversion efficiencies than conventional electrolyzers [7-8]. Similarly, thermochemical water-splitting cycles, including the copper-chlorine (Cu-Cl), sulfur-iodine (S-I), hybrid sulfur, and metal oxide redox cycles, convert thermal energy into hydrogen through a series of chemical reactions. The Cu-Cl cycle is particularly attractive because its operating temperature (approximately 500 °C to 600 °C) aligns well with many industrial waste heat sources. Together, these technologies broaden the range of thermal resources that can be utilised for sustainable hydrogen production [5-6].

Despite their different operating principles, both high-temperature electrolysis and thermochemical processes require materials capable of withstanding prolonged exposure to elevated temperatures, steam, hydrogen-rich atmospheres, thermal cycling, oxidation, and, in some cases, highly corrosive molten salts [9-10]. These demanding environments make materials performance a major factor governing long-term reliability and commercial deployment of such electrolyzers.

High Energy Deposition and Surface Manufacturing: Enabling Technologies for Low-Carbon Hydrogen

High-energy deposition and surface manufacturing technologies encompass advanced processes that utilise

concentrated energy sources to deposit, modify, coat, repair, or manufacture material surfaces with controlled composition, microstructure, adherence strength, and functional properties. These technologies have become indispensable in modern engineering for the fabrication, repair, functionalisation, and life extension of components operating under severe mechanical, thermal, and corrosive conditions [11]. Processes such as thermal spraying, laser-based deposition and surface treatment, plasma-assisted processing, and electron-beam technologies enable localised material deposition or modification while minimising undesirable changes to the bulk substrate [12]. Traditionally applied to enhance resistance to wear, erosion, oxidation, corrosion, and thermal fatigue across the aerospace, power generation, oil and gas, marine, transportation, defence, and heavy manufacturing sectors, these technologies are increasingly evolving from conventional surface engineering approaches into advanced manufacturing platforms for clean-energy systems, like electrolyzers. Among them, thermal spray represents one of the most mature and industrially scalable technologies, offering the capability to deposit metallic, ceramic, cermet, composite, and functionally graded materials with tailored microstructures and properties, making it particularly attractive for the manufacture and functionalisation of next-generation hydrogen production components (Fig. 2).

Advanced thermal spray technologies [11], including Atmospheric Plasma Spray (APS), Vacuum Plasma Spray (VPS), Suspension Plasma Spray (SPS), Solution Precursor Plasma Spray (SPPS), High Velocity Oxy-Fuel (HVOF), High Velocity Air Fuel (HVOF), and Cold Spray, enable the manufacture of dense or porous coatings with controlled microstructures and functional properties. Such capabilities allow engineers to optimise electrical conductivity, thermal conductivity, corrosion resistance, adhesion, and durability while remaining compatible with high-throughput industrial manufacturing.

These capabilities are particularly valuable for high-temperature hydrogen production systems. In SOSEs, high energy deposition and surface manufacturing technologies can manufacture functional electrochemical layers, protective interconnect coatings, diffusion barriers, thermal insulation, and corrosion-resistant structural components. By controlling coating composition, thickness, porosity, and surface chemistry, thermal spray processes enhance electrochemical performance while maintaining mechanical integrity

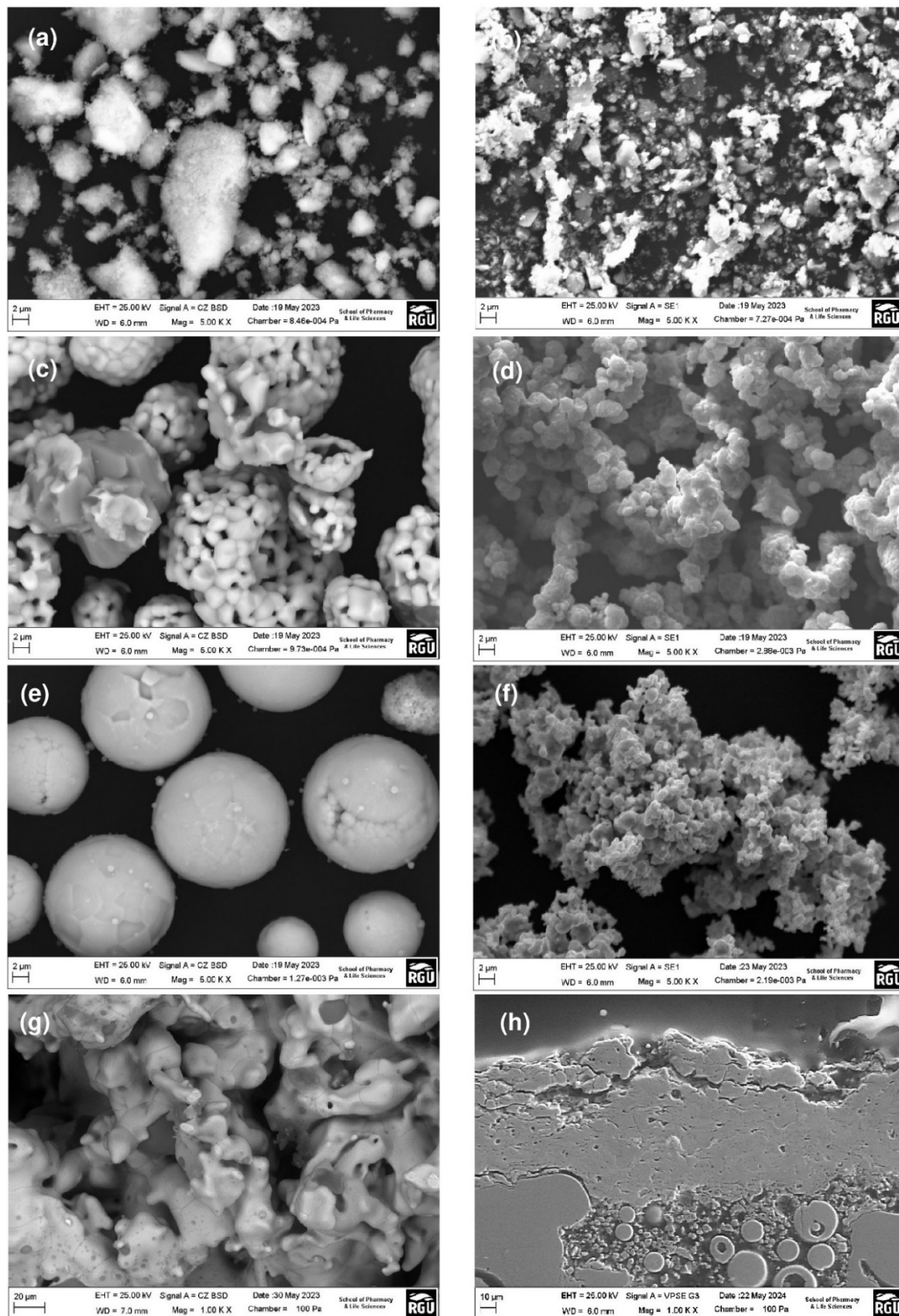


Figure 2: Representative feedstock powders and materials used in solid oxide steam electrolyzers: (a) GDC/electrolyte, (b) LSCF/anode, (c) LSM/anode, (d) NiO/cathode, (e) Ag/current collector, (f) YSZ/cathode, and (g) porous 316L stainless-steel support; (h) cross-sectional micrograph of an air-plasma-sprayed NiO-YSZ cathode coating deposited on an electrochemically Ag-coated porous 316L stainless-steel substrate.

during prolonged operation at temperatures approaching 900 °C. Traditionally, SOSE architectures have been fabricated using conventional ceramic processing techniques such as dip coating and screen printing. However, recent developments have also demonstrated the feasibility of manufacturing SOSE architectures using thermal spray techniques, highlighting their potential for more rapid, scalable, and cost-effective production compared with conventional ceramic fabrication methods [5].

The importance of advanced surface manufacturing extends beyond electrolysis to thermochemical hydrogen production technologies such as the copper–chlorine (Cu–Cl), sulfur–iodine (S–I), and hybrid sulfur cycles, where components operate in aggressive environments involving molten salts, superheated steam, oxidising gases, and repeated thermal cycling. Under these conditions, thermal spray coatings provide chemically stable protective barriers that significantly improve corrosion resistance, minimise thermal degradation, and extend component service life. Recent advances in processes such as SPPS and HVOF have demonstrated considerable promise for developing multilayer coating systems capable of meeting the demanding requirements of next-generation thermochemical reactors [6].

Beyond their functional performance, advanced surface manufacturing technologies contribute directly to sustainable manufacturing through component repair, refurbishment, remanufacturing, and near-net-shape fabrication [11]. These capabilities reduce material consumption, minimise manufacturing waste, lower lifecycle costs, and extend the service life of high-value engineering components. Integration with digital manufacturing, robotic automation, computational materials engineering, artificial intelligence, digital twins, and real-time process monitoring further enhances manufacturing efficiency, quality assurance, and lifecycle performance while strengthening regional supply chains.

As the hydrogen economy continues to expand, various surface manufacturing technologies are expected to become key manufacturing enablers for advanced electrolyzers, thermochemical reactors, heat exchangers, corrosion-resistant process equipment, and other high-temperature energy systems. By combining advanced surface engineering with scalable manufacturing, these technologies bridge the gap between materials innovation and industrial deployment, accelerating the commercialisation of efficient, durable, and economically

viable low-carbon hydrogen systems while supporting industrial decarbonisation and sustainable manufacturing.

Challenges and Opportunities

The transition towards a hydrogen-based economy presents significant technical challenges, particularly in the multi-material manufacturing of electrodes (e.g., Fig. 2(h)). Hydrogen systems increasingly require combinations of metals, ceramics, cermets, coatings, and functionally graded materials to provide mechanical strength, thermal stability, corrosion resistance, conductivity, and catalytic functionality. Differences in thermal expansion, elastic properties, thermal conductivity, and chemical stability can generate residual stresses during deposition and thermal cycling, causing cracking, delamination, distortion, and premature failure. Interdiffusion, oxidation, undesirable reaction phases, and compositional changes can further degrade interfaces and functional performance.

High-energy deposition, like thermal spray, introduces additional complexity through localised heating, rapid solidification, steep thermal gradients, and non-equilibrium microstructures. Functionally graded materials and engineered interlayers offer potential solutions but require precise control of composition, microstructure, interfaces, and processing conditions [5–6]. Scalability, repeatability, inspection, qualification, repairability, and recyclability remain further barriers. Multiple interfaces and spatially varying properties complicate defect detection and quality assurance, highlighting the need for standardised testing, non-destructive evaluation, durability assessment, and qualification frameworks.

Despite these challenges, the transition towards a hydrogen-based economy provides an opportunity to transform industrial high-temperature waste heat from an underutilised by-product into a valuable resource for sustainable hydrogen production [13]. Energy-intensive industries already possess some infrastructure that could integrate waste heat recovery with high-temperature hydrogen production. Such integration could improve energy efficiency, reduce greenhouse gas emissions and hydrogen production costs, and strengthen industrial competitiveness. This transition also creates demand for advanced materials and manufacturing technologies capable of producing durable, high-performance components for next-generation hydrogen systems.

Steel manufacturing represents a particularly promising early deployment pathway. Integrated steel plants generate substantial high-temperature waste heat from blast furnaces, coke ovens, reheating furnaces, and rolling operations, providing favourable conditions for SOSE and thermochemical hydrogen production. The resulting hydrogen could support low-carbon steelmaking while improving overall energy utilisation. Similar opportunities exist in the cement, glass, refinery, petrochemical, fertiliser, and chemical industries. Advanced nuclear reactors and concentrated solar thermal systems could additionally provide reliable low-carbon heat, diversifying high-temperature hydrogen production pathways and strengthening energy security.

These developments create emerging opportunities for high-energy deposition and surface manufacturing. Advanced thermal spray technologies can produce functional electrochemical components, corrosion-resistant coatings, thermal barriers, heat exchangers, reactor components, and other equipment for demanding hydrogen environments [5–6]. They can also support repair, refurbishment, remanufacturing, and component life extension, thereby reducing material consumption and lifecycle costs.

Future digital manufacturing ecosystems integrating robotics, computational materials engineering, artificial intelligence, digital twins, and real-time monitoring could help predict residual stresses, interfacial reactions, and defects while enabling closed-loop process control. Coordinated research, pilot demonstrations, and industrial validation will ultimately be essential to overcome the identified challenges, establish robust multi-material manufacturing strategies, and accelerate the commercial deployment of viable and sustainable hydrogen technologies [14].

Conclusions

High-temperature industrial waste heat represents a significant opportunity to improve energy efficiency while supporting sustainable hydrogen production. Harnessing this underutilised thermal resource through high-temperature electrolysis and thermochemical processes could increase industrial productivity, reduce greenhouse-gas emissions, and strengthen the economic viability of low-carbon hydrogen across energy-intensive sectors. Realising this potential will require durable materials and scalable manufacturing technologies that can operate reliably under severe thermal, chemical, and hydrogen-rich conditions. High-energy-deposition and

surface-engineering technologies, particularly advanced thermal-spray processes, offer promising routes for producing functional and protective materials for electrolyzers, thermochemical reactors, heat exchangers, and other high-temperature process equipment. However, multi-material manufacturing remains challenging because differences in thermal expansion, mechanical properties, chemical compatibility, and processing behaviour can generate residual stresses, promote interfacial reactions, and lead to cracking, delamination, or premature failure. Ensuring interfacial stability, process repeatability, scalability, effective inspection, and robust qualification is therefore critical. Close collaboration among industry, academia, equipment and material manufacturers, and policymakers will also be essential to translate these technological advances into commercially viable, resilient, low-carbon hydrogen systems.

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Declaration of competing interest

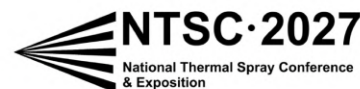
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. The Royal Society. Unlocking thermal energy: Capture, storage and re-use of industrial waste heat. London: The Royal Society; 2026. ISBN 978-1-78252-818-0.
https://royalsociety.org/-/media/policy/projects/thermal-energy-efficiency/thermal-energy-efficiency-in-industry_policy-report.pdf
2. Forman et al., Estimating the global waste heat potential, Renewable and Sustainable Energy Reviews, 57, 2016, 1568–1579.
<https://doi.org/10.1016/j.rser.2015.12.192>
3. International Energy Agency (IEA) (2023), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, IEA, Paris
<https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach>
4. International Energy Agency (IEA) (2024), Global Hydrogen Review 2024, IEA, Paris.
<https://iea.blob.core.windows.net/assets/89c1e382-dc59-46ca-aa47-9f7d41531ab5/GlobalHydrogenReview2024.pdf>

Faisal et al., Application of thermal spray coatings in electrolyzers for hydrogen production: advances, challenges, and opportunities, ChemNanoMat, 8(12), e202200384, 2022.
<https://doi.org/10.1002/cnma.202200384>

5. Faisal et al., Thermal spray coatings for molten salt facing structural parts and enabling opportunities for thermochemical cycle electrolysis, Engineering Reports, 6(9), e12947, 2024.
<https://doi.org/10.1002/eng2.12947>
6. Kurushina et al., Modelling metasurface patterned anode for enhanced performance of solid oxide electrolyser, Journal of Power Sources, 648, 2025, 237436
<https://doi.org/10.1016/j.jpowsour.2025.237436>
7. Soman et al., Fabrication and characterisation of electrodeposited silver current collectors for metal-supported solid oxide electrolysis cells, Journal of Alloys and Compounds, 1038, 2025, 182868; <https://doi.org/10.1016/j.jallcom.2025.182868>
8. Muthukrishnan et al., Machine learning approach to investigate high temperature corrosion of critical infrastructure materials, High Temperature Corrosion of Materials, 101 (Suppl 1), 309-331, 2024. <https://doi.org/10.1007/s11085-024-10312-4>
9. Xu et al., Technological limitations and recent developments in a solid oxide electrolyzer cell: A review, International Journal of Hydrogen Energy, 50, Part C, 2024, 548-591.
<https://doi.org/10.1016/j.ijhydene.2023.08.314>
10. Ang et al., Innovative Coatings for a Greener Sky: The 2026 Strategic Roadmap for Thermal Spray and PVD Coatings, Journal of Thermal Spray Technology, 2026. <https://doi.org/10.1007/s11666-026-02276-5>
11. Tucker, R.C. Jr. (2013) 'Surface engineering', in Tucker, R.C. Jr. (ed.) ASM Handbook, Volume 5A: Thermal Spray Technology. ASM International, pp. 10-30.
<https://doi.org/10.31399/asm.hb.v05a.a0005707>
12. Ahmad et al., Waste heat valorization for hydrogen production: a meta-analytic review of technologies, challenges, and paths to net-zero, Applied Energy, 414, 2026, 127792.
<https://doi.org/10.1016/j.apenergy.2026.127792>
13. Project Spotlight: METASIS; <https://www.speeri.ac.uk/speeri-news/project-spotlight-metasis>



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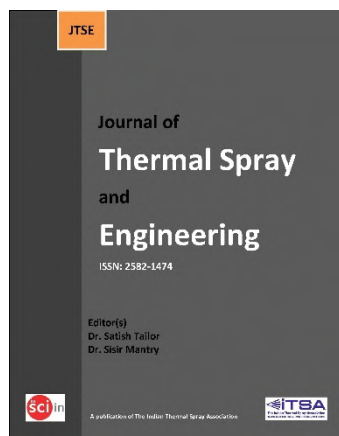
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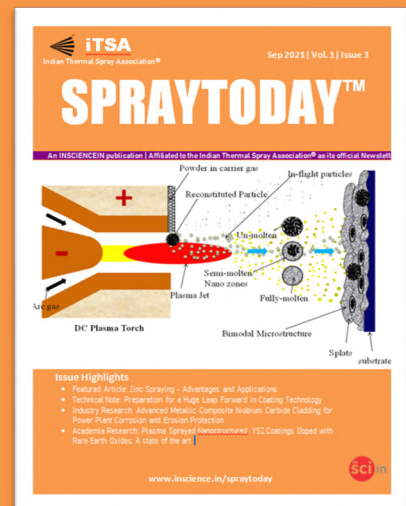
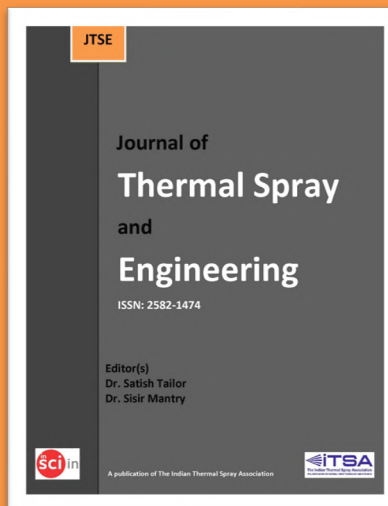
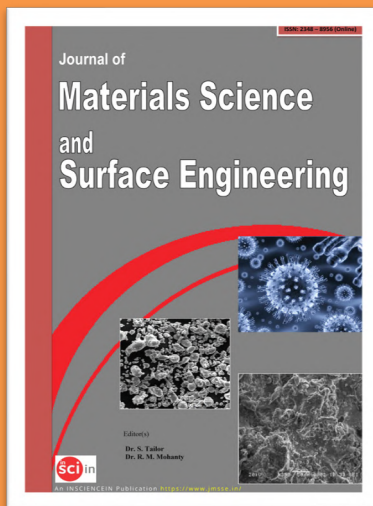
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