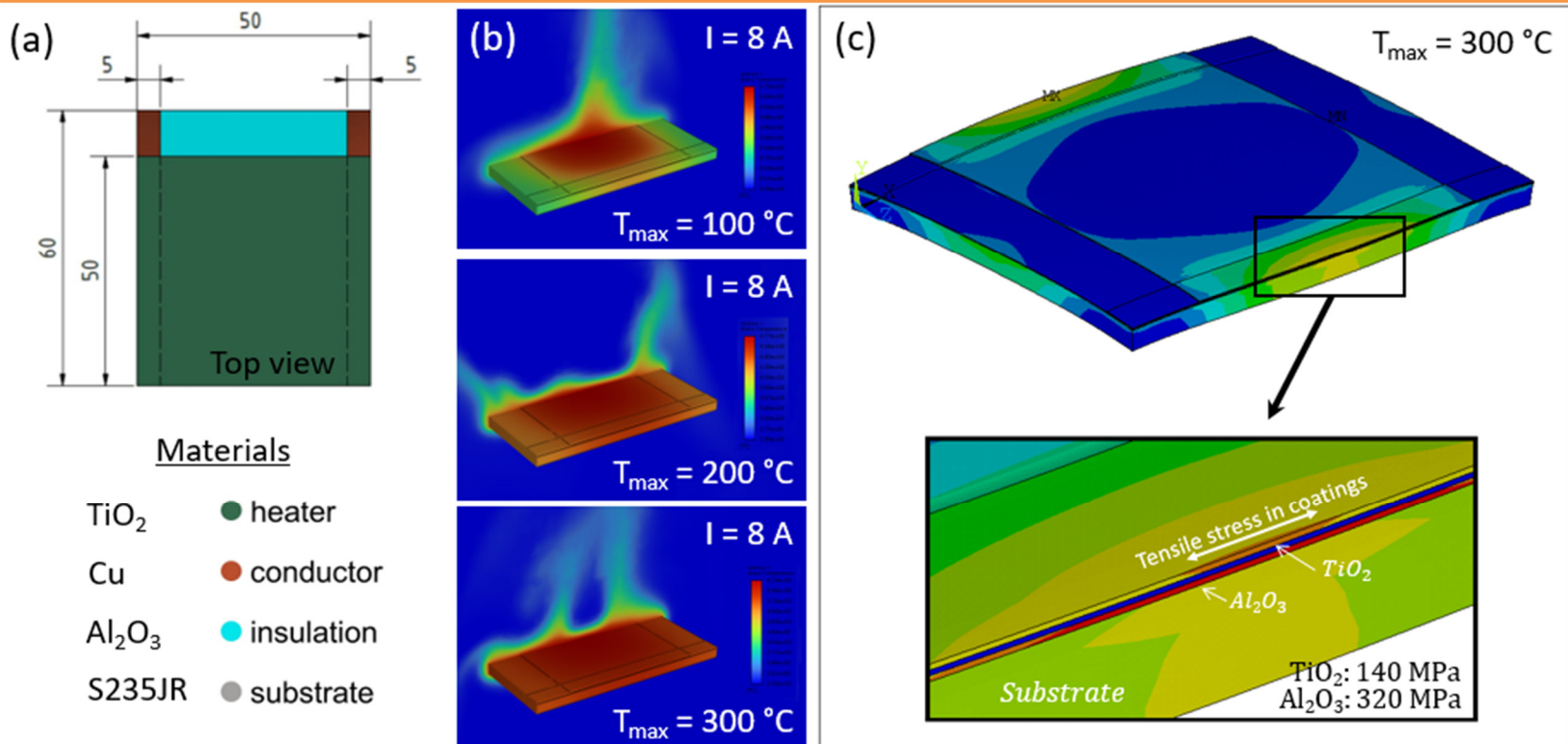


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Issue Highlights

- Featured Article: Thermally Sprayed Resistance Heater Coatings
- Technical Note: Deposition of Protective Coatings Using Waste Marble Dust by HVOF
- Academia Research: Tribological Performance of Nano-Ceria Reinforced Cr₃C₂-NiCr Coatings
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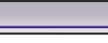
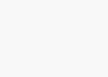
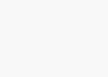
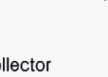
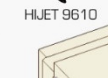
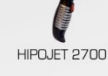


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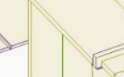
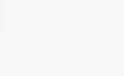
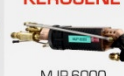
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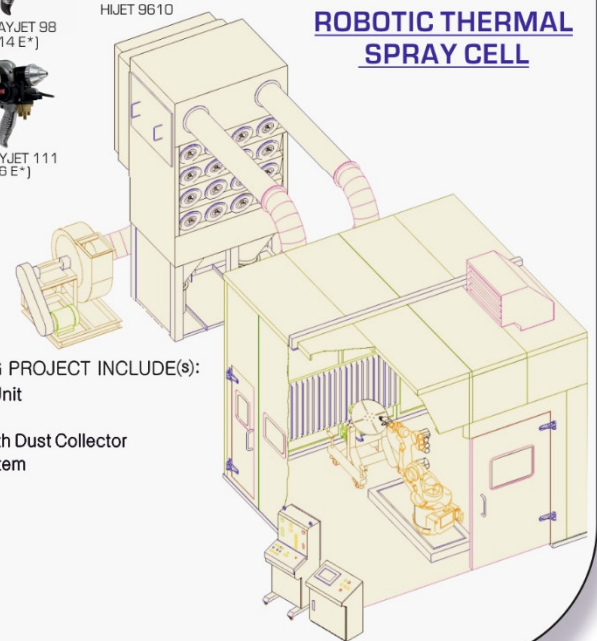
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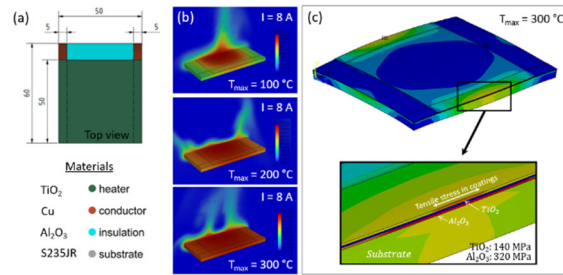
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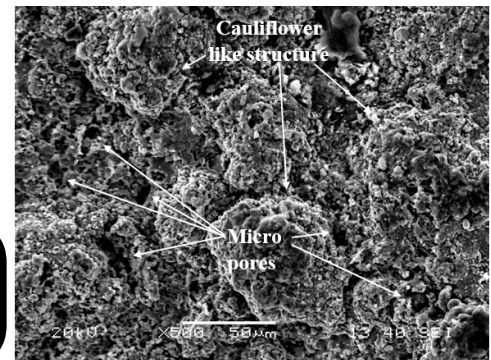
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Contents



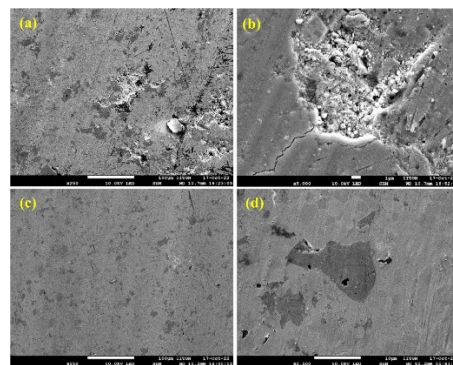
7

Featured Article: Thermally Sprayed Resistance Heater Coatings



10

Technical Note: Deposition of Protective Coatings using Waste marble Dust by HVOF



17

Academic Research: Tribological Performance of Nano-Ceria Reinforced Cr3C2-NiCr Coatings

SPRAYTODAY™

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

PhD, Postdoc & Research Engineer Job Alerts	16
Call for Papers ATSC2023	19
Indian Thermal Spray Asso. Membership	20
Official Journal Publication of the iTSA	20

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Editor's Note



Dear Readers,

I am happy to announce that after the huge success of the 1st National Thermal Spray Conference (NTSC 2023) in the historical city of Jodhpur on 18-19 Feb 2023, The Indian Thermal Spray Association (ITSA), Asian Thermal Spray Society (ATSS) and Indian Institute of Technology Madras are jointly going to organize the Asian Thermal Spray Conference and Expo 2023 (ATSC2023) on 2-4 Nov 2023, at Indian Institute of Technology Madras, Chennai, India. Plan today to attend ATSC-2023! <https://www.indtsa.org/atsc-2023>

In India, the thermal spray market has been growing steadily in recent years due to increasing industrialization, infrastructure development, foreign investments, and the demand for high-performance coatings in sectors such as automotive, aerospace, power generation, and manufacturing. India's top educational institutes are also coming forward and opened CoE with the help of government and thermal spray industries. Now two IITs – IIT Ropar and IIT Patna have Centre of Excellence (CoE) dedicated for thermal spray coatings research. It is good that some companies are manufacturing quality ceramic, metal and HAP powder in India. Now, production of specialized metal and alloy powders is also the need of the hour.

I am particularly pleased to be allowed to recommend to you the latest issue of the **SPRAYTODAY**. This issue includes invited innovative featured articles from industry and academia experts on Thermally Sprayed Resistance Heater Coatings, Technical Note: Deposition of Protective Coatings Using Waste Marble Dust by HVOF, Academia Research: Tribological Performance of Nano-Ceria Reinforced HVOF Sprayed Cr₃C₂-NiCr Coatings; that illustrate current research trends in thermal spray development.

Looking at the future of thermal spray in India, it will be pleasing if the **SPRAYTODAY** can also inspire the spirit of thermal spray research in the country by providing the latest information on thermal spray technology.

Be healthy, active, and curious.

Best Regards,

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


(Dr. Satish Tailor)

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Thermally Sprayed Resistance Heater Coatings

By **Ladislav Čelko¹**, **Karel Slámečka¹**, **Michaela Remešová¹**, **Petr Skalka¹**, **Pavel Škarvada²**, **Tomáš Trčka²**, **Martin Papula³**, **Serhii Tkachenko¹**, and **Karel Záborský¹**

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Introduction

Joule (resistance, Ohmic) heating is a phenomenon of heat production by passing an electric current through a conductor, which is currently appearing in increasingly more applications. Compared to traditional electrical heating elements, thermally sprayed coatings represent an interesting alternative on the scale of industrial objects with the capability to deposit on complex-shaped surfaces. Thermal spraying covers a range of methods suitable for the fabrication of resistant heater functional coatings, including, especially, vacuum plasma spraying (VPS), air plasma spraying (APS), and high-velocity oxygen fuel spraying (HVOF). The choice of the appropriate method and spraying parameters significantly affects the properties of the coatings and hence the performance of a heater. Heaters must meet a number of requirements, especially long-term thermal stability, mechanical strength, and uniform heating, to efficiently transmit converted electric energy.

Architecture

Heaters are composed of several layers that ensure their proper functionality. An electrical insulation layer, often APS alumina (Al₂O₃), separates the heater from electrically conductive substrates if necessary. Interconnectors (conductors) are frequently prepared by HVOF of copper or aluminium on a masked insulator

surface, and they supply connectivity to the power source and determine the homogeneity of the electric charge distribution. A heater layer enables Joule heating and is typically prepared by APS or LPPS. A variety of metallic and ceramic materials were found to be useful as heater coatings. Typical metallic alloys, such as kanthal (FeCrAl) or monel (NiCu), can be used up to 600 °C, while nichrome (NiCr) can be used at temperatures up to 1100 °C, due to its high melting point and good resistance to oxidation and corrosion. Ceramics generally maintain higher temperatures and have better oxidation resistance than metals, which is imperative in high-temperature applications. TiO₂, SiC, Si₃N₄, MoSi₂ can be operated at temperatures approaching 1400 °C, while Ta-, Mo-, W-, and graphite-based heaters can be operated above 2000 °C in vacuum. These materials typically have higher electrical resistance than metals, and therefore the same power output is achieved with a lower electric current. In addition, ceramics also typically bond better to the insulation layer and have a more similar coefficient of thermal expansion, which reduces interfacial stresses. In addition to the described functional layers, an overlay protective film can be applied finally to shield the heater from environmental contamination or to withstand the contact of the heater with the working medium when needed.

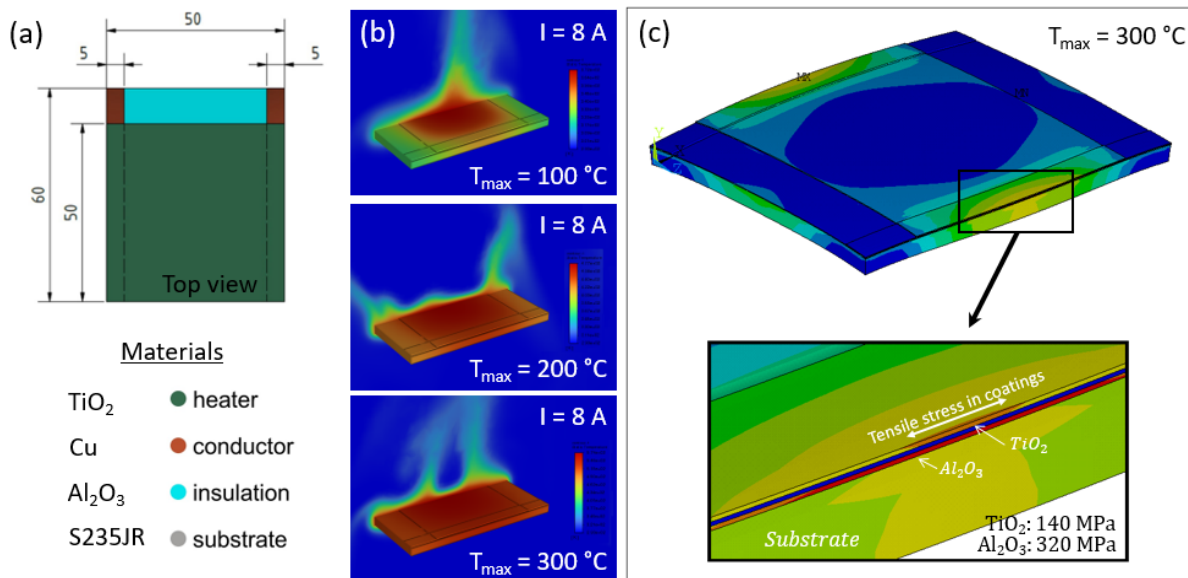


Figure 1: (a) Design of the areal heater and predicted (b) temperature and (c) stress fields considering convection, conduction, and radiation heat transfer

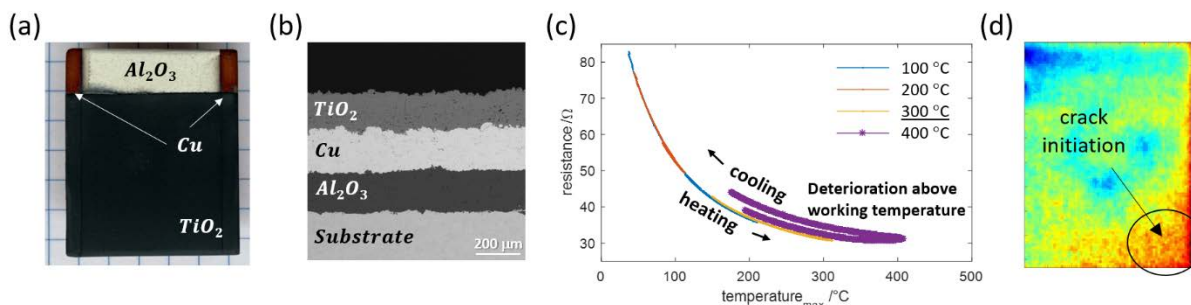


Figure 2: (a) The top and (b) cross-section view on produced areal heater. (c) Stability during thermal cycling and (d) thermographic image during cycling above the working temperature

TiO₂-based areal heater

Among the various ceramic heating elements, TiO₂-based coatings are prototypical heater coatings with excellent chemical stability and relatively stable resistivity of $\sim 0.1 \text{ } \Omega \cdot \text{cm}$, despite that spraying conditions affect the formation of oxygen vacancies and variable oxygen loss leads to a wide range of titanium suboxide (TiO_x) and Magnéli-phases (Ti_nO_{2n-1}) mixture compositions [1, 2]. An example of the design of an areal heater based on TiO₂ coating with a target operating range from room temperature to 300 °C is given in Figure 1. The temperature fields predicted by finite element method calculations show a homogeneous temperature distribution over the functional part at different temperatures and the dominant role of conduction transfer at lower temperatures. The stress field shown in

Figure 1c takes into account the optimised substrate preheating to the temperature of 250 °C before spraying.

The heaters were prepared using GLC5 HVOF (interconnectors) and F4 APS (insulator, heater) guns on a 3 mm thick, degreased, grit-blasted, and preheated S235JR steel substrate, showing typical microstructure of thermally sprayed coatings with adequate uniformity, Figures 2a and 2b. Thermal cycling at higher than design temperatures showed changes in heater resistance caused by interfacial cracking localized at the heater corners resulting in suppressed heat dissipation to the substrate and heater overheating, Figures 2c and 2d. Overall, up to the working temperature, the extensive experiments confirmed the stable operation of a heater with homogeneous temperature distribution as predicted by the numerical models.

Conclusions

Compared to traditional types of industrial heating, such as fuel heating systems, thermally-sprayed heaters based on Joule heating offer significant benefits, such as high efficiency, compactness, easy maintenance, superior temperature control, environmental friendliness, and low costs. Heaters can be tailored on the basis of numerical methods to fit the needs across a range of advanced industries, from automotive and aerospace to medical devices, where even targeted heating of small spaces is required. Future development driven by the transition to green energy will undoubtedly result in finely tuned multilayered scalable heaters with industrial reliability over long periods of time at high temperatures and their common deployment in a wide range of areas of human activity.

Acknowledgements

This work was supported by the Technology Agency of the Czech Republic under grant No. FW03010377.

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Deposition of Protective Coatings using Waste marble Dust by HVOF

By **S K Nayak¹, S Mantry^{*2}, A. Satapathy¹, L. Besra², Satish Tailor³**

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Abstract

Marble dust is a hazardous construction/industrial waste generated during the extraction, cutting, and polishing of marble-producing rocks. The increasing use of marble slabs in civil construction and infrastructure sectors and the inadequate waste disposal system are causing multiplied waste accumulation day by day. In view of the pertinence of the value-added utilization of waste marble dust, the present work explores its potential to be used as a coating material on metal substrates. For this, the high-velocity oxy-fuel (HVOF) spraying route is adopted to deposit marble dust coatings on four different metallic substrates: mild steel, Inconel, aluminum, and copper. LPG is used as the fuel and nitrogen as the carrier gas while the coating deposition is performed by varying the spray distance over a range from 50 mm to 250 mm. The coating microstructure is studied using a scanning electron microscope (SEM) and the developed phases are identified using an X-ray diffractometer. The developed coatings are characterized in terms of the deposition efficiency, coating thickness, and adhesion strength. It is found that the coatings exhibit fairly good interfacial adhesion and thickness values that varied quite significantly with the spray distance. Maximum deposition efficiency of about 68% is obtained for the copper substrate when the deposition is performed at a spray distance of 100 mm. This experimental investigation thus shows that despite being a waste, marble dust is eminently coatable on several metallic substrates through a well-designed HVOF spraying route.

Keywords: Marble dust; HVOF spraying; Coating characterization; Waste utilization

Introduction

Surface modification is a nonexclusive term currently applied to a huge field of different advancements that can

be profitably outfitted to accomplish expanded dependability and upgraded execution of mechanical parts. In this context, thermal spray techniques are gaining popularity in terms of producing hard and reliable coatings, specifically for the ceramic coatings on substrates, to improve their tribological properties [1,2]. Among the various thermal spraying processes, plasma spraying is the most commonly used technique for the modification of engineering surfaces with a wide versatility [3–7]. However, to obtain a highly dense coating with low porosity at low temperature, the high-velocity oxy-fuel (HVOF) spray technique is coming up rapidly and is being adopted by several industries owing to some of its deposition advantages as compared to the other spray coating techniques [8]. The coatings developed using the HVOF process are advantageous compared to the other types of thermal-sprayed coatings in terms of better homogeneity and low porosity [9]. Additionally, HVOF spraying provides high-quality coatings with thicknesses ranging from 20 micron to a few millimeters [10]. During the coating process, the HVOF flame sufficiently preheats the substrate and also exerts a high velocity onto the target surface, leading to high bond strength and low porosity of the developed coatings [11]. The properties of coatings developed by HVOF spraying are not only affected by the powder properties but also by the spray parameters including temperature, velocity, air-fuel ratio, etc. [12]. Therefore, HVOF coating technology could be preferable over other thermal spraying processes to coat the mild steel as well as other metallic surfaces used in engineering applications. Only in the last two decades, low-grade minerals and industrial/construction wastes have fetched the attention of researchers regarding their coating potential. The first successful attempt in this exploration was made by Mishra et al. [13,14] in the year 2000 to develop protective

coatings on metal substrates using fly ash and fly ash pre-mixed with alumina as the coating material. Subsequently, quite an impressive number of studies have been reported on the coatability of low-grade minerals and industrial wastes such as fly ash [15,16], red mud [17,18], copper slag [19], blast furnace slag [20], linzdonawitz slag [21], etc. on the metal substrates using conventional atmospheric plasma spraying technique. Marble dust, an industrial/construction waste generated during the extraction, cutting, and polishing of marble-producing rocks is an ever-increasing solid waste owing to the rapidly growing demand for marble. It is also a threat to the environment as adequate avenues for the proper disposal/utilization of this waste are currently not available. Marble dust is therefore categorized as hazardous solid waste and an eco-polluting agent because of its dumping in the open atmosphere. Apart from that, few investigations have recently been reported on its use as a particulate filler in the preparation of polymer composites. However, its utilization as a functional coating material for metals has not yet been explored through any of the available coating deposition techniques. Against this background, the present work attempts to deposit micro-sized waste marble dust with an objective of developing a hard, protective overlay coating on a variety of metal substrates. HVOF spraying which is a versatile thermal spray technique is adopted for this purpose.

Experimental details

Materials

In this investigation, the coating material used is the waste marble dust collected from a nearby marble processing shop generated during the cutting of marble pieces. The as-collected marble dust is screened through sieves to obtain particles with an average size of approximately 50 micron. The SEM micrograph and the particle size distribution chart of the marble dust sample are shown in Figure 1. Mild steel, inconel, aluminum, and copper (procured from M/s Mishra Dhatu Nigam Ltd., Hyderabad, India) are used as the substrate materials. The substrate materials are received in the form of plates with a thickness of 5 mm and are cut to the size of 60 mm×100 mm as per the requirement. The target surface of the substrates is sand blasted to obtain an average roughness value of Ra 4.0–5.0 μm prior to the coating deposition.

Coating deposition

In this study, the high-velocity oxy-fuel (HVOF) spray technique is used to deposit marble dust on the surface of the substrates. The deposition process is conducted using

a Hipojet 2700 HVOF system (MEC, India) designed for gaseous LPG with a pressure of 7 bar and 55–60 g/min feeding rate. The specifications of the HVOF system are listed in Table 1. The coatable powder is placed inside a hooper connected to the carrier gas (N₂) line that carries the feedstock powder to the HVOF flame. The powder is then melted and directed towards the target surface with the high velocity of the flame and produces a coating on the substrate surface following the process fundamentals of any thermal spraying technique. The flow velocity and amount are controlled using a control unit integrated with the system. A schematic diagram of the HVOF spray setup showing the essential units is displayed in Figure 2.

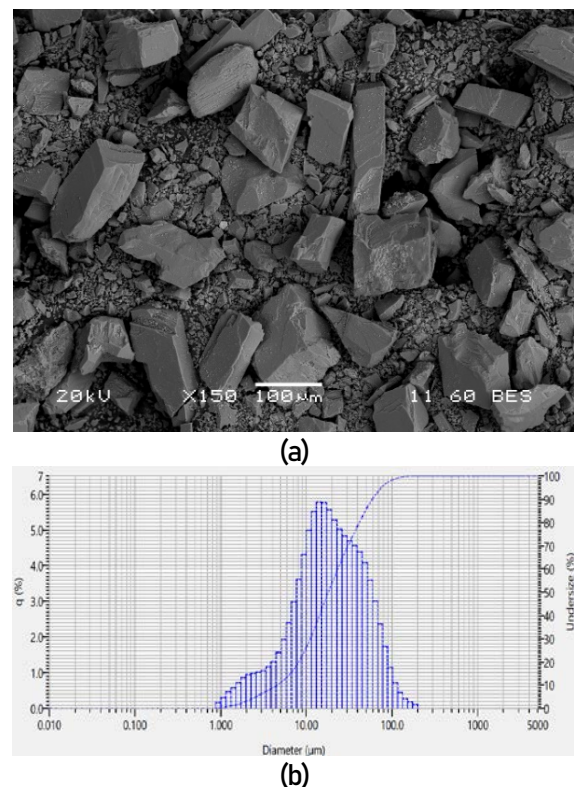


Figure 1: (a) SEM micrograph and (b) particle size distribution chart of waste marble dust

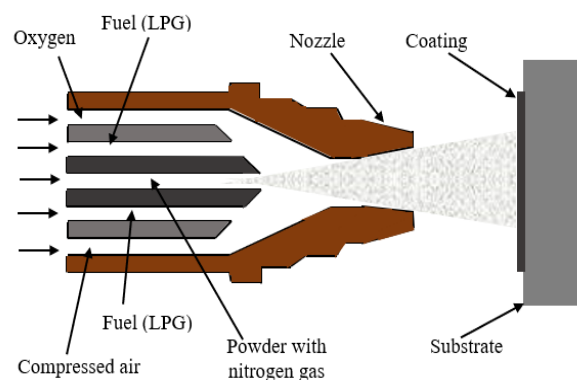


Figure 2: Schematic diagram of HVOF spray process

Table 1: HVOF process parameters

HVOF process parameters	Value
Spray distance	50-150 mm
Powder feeding rate	40-50 g/min
LPG gas feed rate (Pressure)	70 lpm (7 bar)
Oxygen feed rate (Pressure)	265 lpm (10 bar)
Air feed rate (Pressure)	700 lpm (5 bar)
Carrier gas (N ₂) feed rate (Pressure)	6.5 lpm (6 bar)
No of nozzle passes	4-5 passes
Nozzle exit area diameter	3-4 mm

Results and discussion

Phase identification:

To ascertain the phases present in the coating material (raw marble dust) and to identify possible phase transformations during the high-temperature spraying process, the XRD analysis on marble dust and the coated samples are done. The diffractometer outcomes are plotted in Figure 3. Analyzing the peaks, it can be ascertained that the phase composition of marble dust (Figure 3a) is as follows: aluminum oxide (Al₂O₃), quartz (SiO₂), silicon oxide (SiO₂), calcium aluminum silicon (Ca₃Al₂Si₂), calcium carbonate (CaCO₃), and iron oxide (Fe₃O₄). Among these, silicon oxide, aluminum oxide, and calcium carbonate are the major constituents. The high peaks present at diffraction angles (2θ) of 32.59, 36.15, 60.07, and 75.23 indicate the crystalline appearance of the major constituents. Whereas, quartz, calcium aluminum silicon, and iron oxide confirm their appearance in the amorphous phase. Silicon oxide is the key element of marble dust and is present in a purely crystalline nature as it exhibits the highest peak at the diffraction angle (2θ) of 36.15. The X-ray diffraction curve of the developed coating (Figure 3b) ensures the presence of calcium aluminum oxide (CaAl₄O₇) aluminum oxide (Al₂O₃), quartz (SiO₂), calcium silicate (CaSiO₃), and iron silicide (FeSi₂). Except aluminum oxide, all other phases present exhibit a crystalline appearance as these are associated with high peaks. Analyzing both the curves it can be concluded that, during the HVOF spraying, some of the amorphous have transferred to crystalline phases and very few crystallines have transferred to the amorphous phase. The calcium aluminum silicon present in marble dust is transformed to calcium aluminum oxide and the calcium carbonate is transformed to calcium silicate. Similarly, the iron oxide is transformed into iron silicide. In the raw marble dust, silica (silicon oxide) is the major constituent, whereas after being processed in the oxy-fuel flame, the major

constituent of the developed coating turns out to be quartz which is a distinct phase of the same silicon oxide. Some of the diffraction peaks of marble dust are found to be absent in the developed coating. This may be due to the vaporization of oxides from the raw material due to the high heat or the bonding of oxides with other constituents for the formation of complex intermetallic oxides like calcium aluminum oxide (CaAl₄O₇).

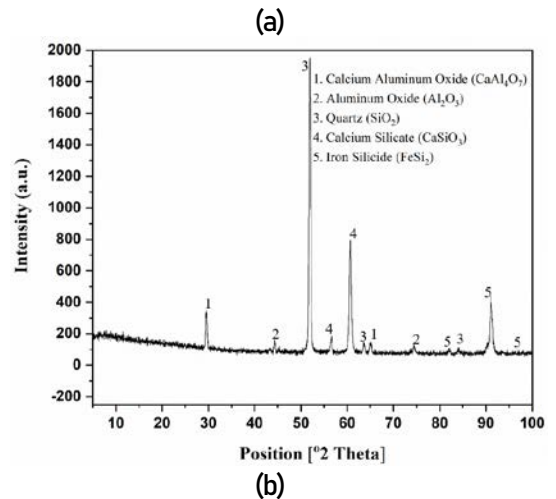
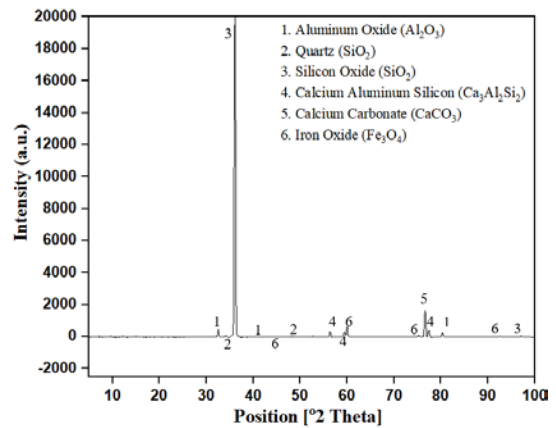


Figure 3: X-ray diffraction plots of (a) raw marble dust and (b) coated sample

Coating surface and interface morphology:

Figure 4 shows typical SEM micrographs of the as-sprayed marble dust coating thickness on Cu and Al substrates. Figure 5 shows typical SEM micrographs of the surface of the as-sprayed marble dust coating. The splat boundaries of the molten and unmolten particles along with the micro-pores can be easily distinguished from the micrograph shown in Figure 5a, which shows that a temperature gradient exists during interaction with the heat of combustion. Molten particles solidify either in-flight or after impingement on the substrate. The morphology of the coatings reveals some regions of fully molten ceramic particles along with small pores. The particle distribution appears to be reasonably uniform

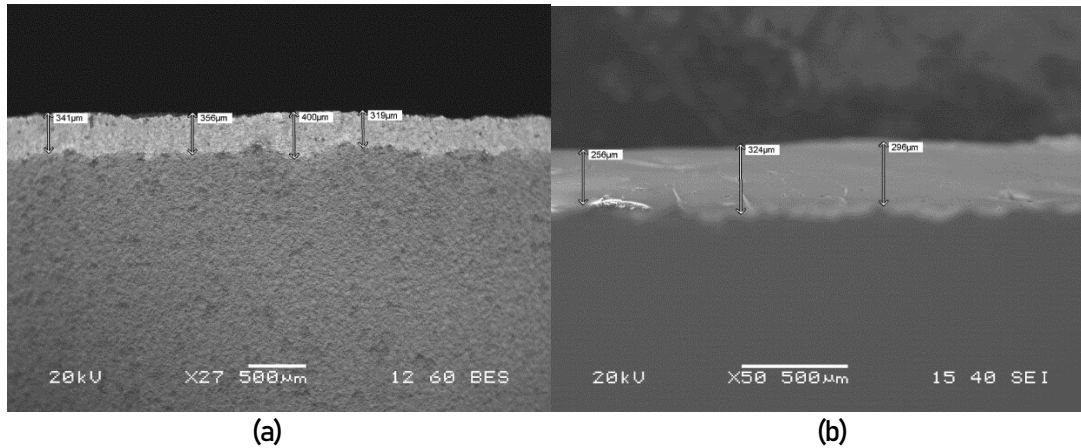


Figure 4: Thickness of developed coating on (a) copper and (b) aluminum substrates

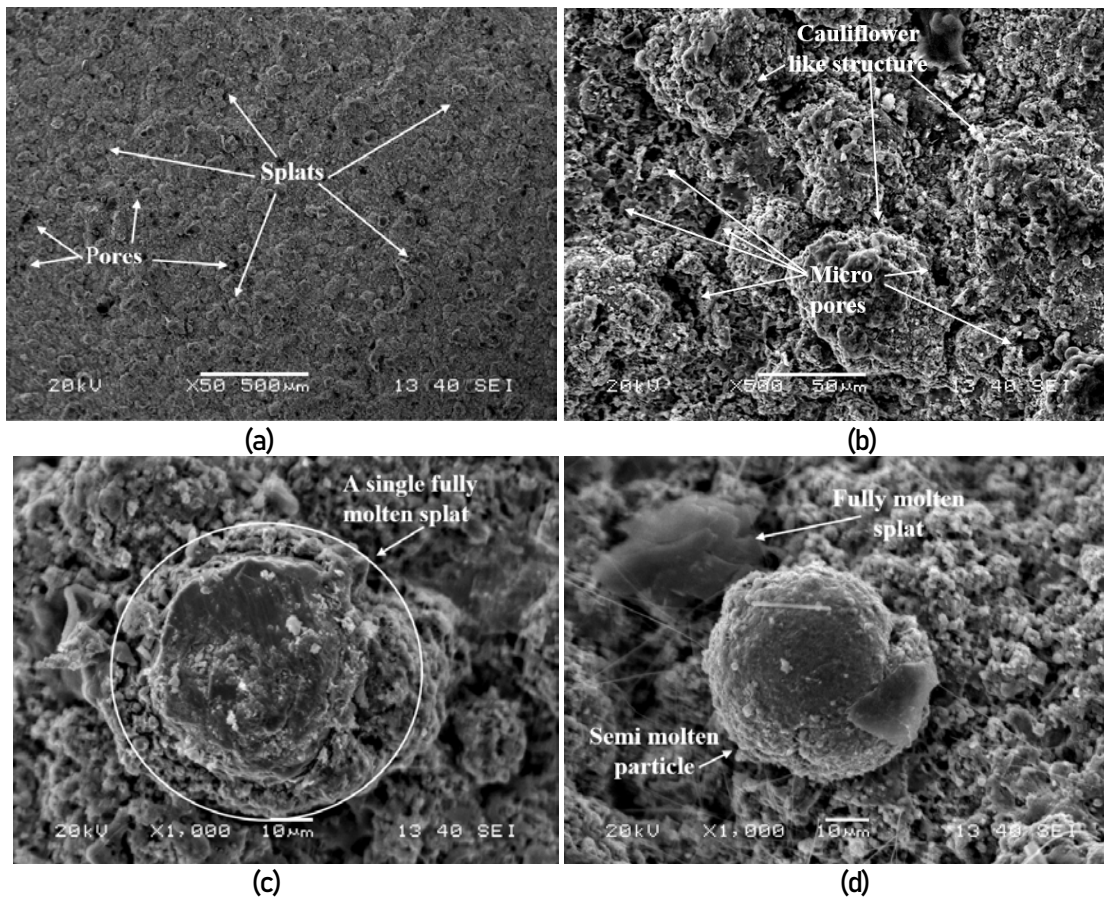


Figure 5: SEM micrographs of the coating surface

throughout the coating surface. Some semi-molten particles unlike molten particles after impact may deform and solidify near the interface. The cauliflower-like structure that appears on the coating surface (Figure 5b) is developed possibly because of the repeated splashing of molten particles forming splats on the substrate surface at high velocity. The dark patches in the SEM images indicate the presence of pores/voids within the coating body. At higher magnification, splats formed by a properly molten and a semi-molten particle on the

coating surface are distinctly displayed in Figures 5c and 5d respectively. These splats are found to be circular in shape with an approximate size of 50–60 micron. During particle heating in the high-temperature gas jet, the melting starts from the outer surface of the particle and advances towards its center. Thus, the semi-molten state of some particles in the coating can be attributed to their short inflight residence time in the high temperature gas jet flame.

SEM micrographs of the substrate-coating interface taken at the transverse section of the coated samples are presented in Figure 6. The images represent a dense and smooth zone, indicating the proper and complete meeting of the particles as a result of uniform heat dissipation. The presence of negligible amount of voids and less number of micro-pores as noticed in the microstructure (Figure 6) indicates a fairly good mechanical anchoring of the molten particles on to the substrate surface. Such a microstructure leads to superior physical and thermo-mechanical characteristics of the deposited coating.

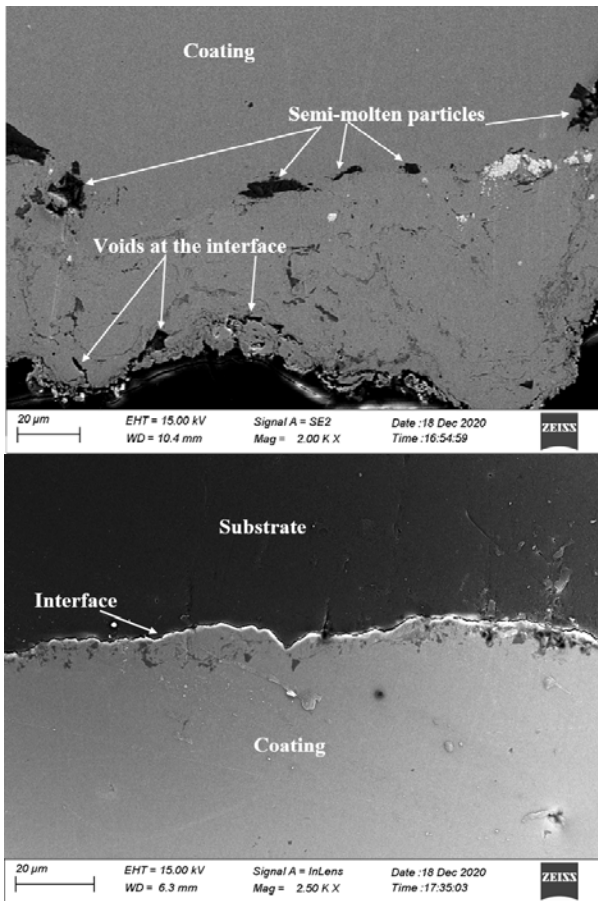


Figure 6: SEM micrographs at the substrate-coating interface

The energy dispersive detector (EDS) diagrams of the marble dust coating are shown in Figure 7. EDS analysis confirms the presence of oxygen (O), aluminum (Al), silicon (Si), carbon (C), calcium (Ca), and iron (Fe) as the major elemental constituents in the developed coating. Figure 7b displays the elements present with their corresponding weight fractions in a single semi-molten particle as shown in Figure 7a. The analysis reveals the presence of O and Fe in a higher amount; also, a moderate amount of silicon is present but very less amount of Al and Ca are present within the splat. The presence of a higher amount of oxygen on the deposited coating can be because of oxidation on the surface due to

the interaction of the molten marble dust particles with the hot combustion gases having atmospheric oxygen. Figure 7d displays the elements present on the coating surface shown in Figure 7c. In addition to the elements discussed to be present in a single molten particle, good amount of carbon is present on the surface, indicating the improper melting and burning of some of the marble dust particles.

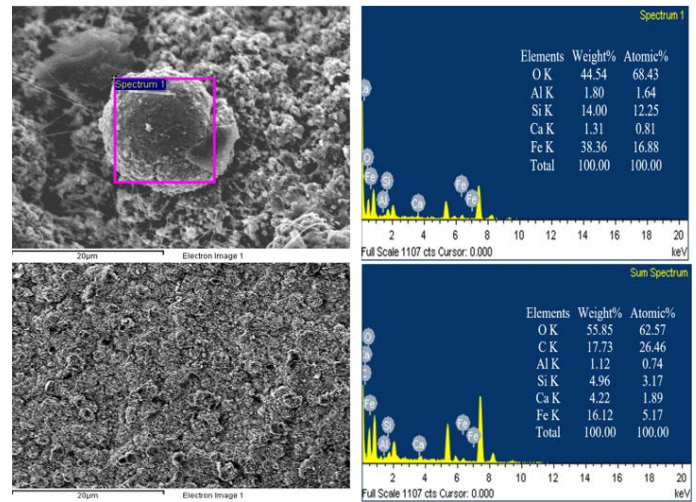


Figure 7: EDS analysis of the deposited coating

Coating adhesion strength:

The values of adhesion strength of marble dust coatings deposited at various spray distances are plotted for the four different substrates in Figure 8. From the figure, it is evident that among all the coated samples, the coating deposited on the inconel substrate possesses the highest adhesion strength followed by mild steel, copper, and aluminum substrates in that order. But these maximum adhesion strengths values are recorded when the coating deposition is made at a spray distance of 200 mm for mild steel and inconel substrates whereas for copper and aluminum substrates these are obtained at 150 mm. As the spray distance is gradually extended from 50 to 250 mm, it is seen that all the resulting coatings exhibit an increase in the interfacial adhesion strength; but this increment continues till an intermediate optimum spray distance is reached. For the coatings deposited on mild steel and inconel at a spray distance of 200 mm, the adhesion strength attains a peak value and beyond 200 mm again the variation curve droops as can be clearly seen in Figure 8. A similar trend is exhibited also for the coatings on copper and aluminum substrates, but for them, the peak adhesion occurs at 150 mm spray distance. The substrate-to-substrate variation in adhesion strength can be attributed to the different physical properties of the substrates such as their

specific heats, densities, and intrinsic thermal conductivities. The substrate surface conditions, degree of roughness, and powder properties are also some of the factors that contribute to the magnitude of interfacial bond strength.

This dependence of the coating adhesion strength on the spray distance is largely related to the heat interaction between the flame and the substrate, degree of particle melting, in-flight residence time, etc. Initially, when the spray distance is less, the in-flight time is also proportionately less often resulting in improper melting of the particles causing a lack of interlocking of the powder particles with the substrate surface which ultimately leads to low adhesion strength. With the gradual increase in spray distance, the in-flight time along with the velocity of the particles is increased. Therefore, better splashing and mechanical interlocking of the molten particles with the substrate surface occur leading to an increase in the adhesion strength. But with further increase beyond the optimum intermediate spray distance, the fragmentation and vaporization of the particles are likely to rise and with a longer in-flight residence time, the probability of flying off of the smaller particles becomes predominantly high causing a reduction in the adhesion strength.

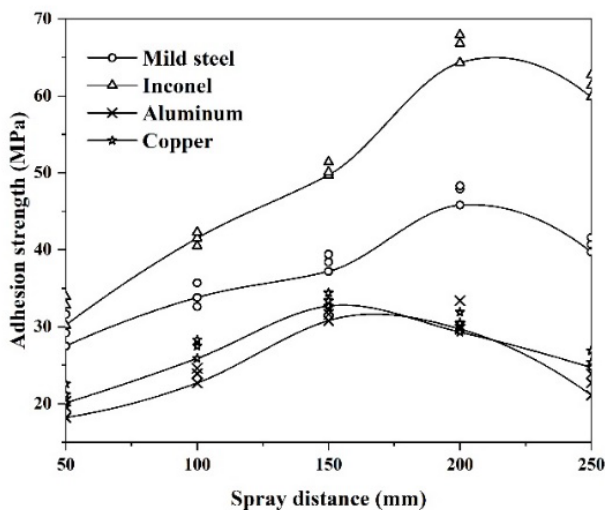


Figure 8: Coating adhesion strength corresponding to spray distance

Conclusions

1. The study reveals that although marble dust is an industrial/construction waste, it is eminently coatable on metal substrates using the high-velocity oxy-fuel spray coating technique.
2. The X-ray diffraction analysis ensures that the coating is completely crystalline in nature and during this high-temperature thermal spray coating

process, several phase transformations in the feedstock material take place leading to the appearance of some new phases in the coating.

3. Scanning electron microscopy of the coating surface and interfacial sections gives an insight into various microstructural features apart from providing quantitative information about the thickness of coatings deposited on different substrates.
4. This research shows that reasonably thick overlay coatings can be developed using waste marble dust on metals. The thickness values measured for the coatings considered in this study lie in the range of 200 to 400 micron and it is found that the coating thickness is very much dependent on both the spray distance as well as on the substrate type.
5. The marble dust coatings developed in this work under controlled laboratory conditions exhibit reasonably good interfacial adhesion with different metallic substrates. Among all the coated samples prepared for this research, the maximum adhesion strength of 66.8 MPa is recorded for the coating deposited on the inconel substrate. Like coating thickness and deposition efficiency, the adhesion strength of the coating is also found to be significantly affected by the spray distance when other operating variables remain unchanged.

This study therefore opens up a new avenue for the value-added utilization of waste marble dust in terms of its use in developing thermal spray coatings on metals. Armed with good adhesion strength and hard ceramic phases, these coatings have high potential for possible use in tribological applications.

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Tribological Performance of Nano-Ceria Reinforced Cr₃C₂-NiCr Coatings

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Introduction

Chromium carbide-nickel chromium (Cr₃C₂-NiCr) is one of the most promising and extensively researched hard metal coatings. It is widely used for protection against high-temperature wear and corrosion up to 850°C [1, 2]. However, for low temperature (< 450°C) applications WC-Co coatings are used due to its superior wear resistance. But W and Co are classified as critical raw materials, while Co is a genotoxic material [3]. Therefore, it is imperative to develop alternative hard metal coating compositions to reduce the consumption of W and Co. Cr₃C₂-NiCr coatings can be used as potential alternative as they have comparable wear and erosion resistance [4]. As a result, there are increasing efforts to enhance the room temperature performance of Cr₃C₂-NiCr coatings [5, 6].

Rare earth oxides such as cerium oxide (CeO₂) can be effectively used to improve the microstructural and mechanical properties of thermal spray coatings. CeO₂ has the ability to refine microstructure, reduce decarburization, improve hardness, and fracture toughness of thermal spray coatings [6]. The above-mentioned features of the coatings can be further enhanced by using nano-CeO₂ particles. But due to Van der Waals cohesive forces, uniform dispersion of nano-CeO₂ particles is a challenging task. Therefore, in the present study a novel blending methodology was used to uniformly disperse nano-CeO₂ particles with Cr₃C₂-NiCr feedstock powders and the coatings were developed using HVOF process. Tribological performance of nano-CeO₂ reinforced Cr₃C₂-NiCr coatings was evaluated and unreinforced Cr₃C₂-NiCr coatings were also prepared for comparison purposes.

Materials and Methods

Agglomerated and sintered Cr₃C₂-NiCr and nano-CeO₂ powders were blended using 3 step process (i) sonication

and stirring (ii) Oven drying and (iii) tumbler mixing. The morphology of unreinforced Cr₃C₂-NiCr, nano-CeO₂ and nano-CeO₂ reinforced Cr₃C₂-NiCr powders are shown in Fig. 1. The final CeO₂ concentration of 1 wt% compared to the weight of Cr₃C₂-NiCr powders were prepared. The powders thus prepared was deposited on SS-304 coupons of size 25 x 25 x 5 mm³ using HVOF process. X-ray diffraction, FE-SEM, EDS mapping, and optical profilometry were used to characterize the coatings. Room temperature tribological studies were performed on the coatings using a modular ball-on-disc tribometer using a load of 10N, linear velocity 0.2 m/s, sliding distance 5000 m, wear track diameter 15 mm and Al₂O₃ ball of 6 mm diameter.

Results and Discussions

The tribological tests revealed that the coefficient of friction, wear volume loss and specific wear rate of nano-CeO₂ reinforced Cr₃C₂-NiCr coatings was least as compared unreinforced Cr₃C₂-NiCr coatings. The FE-SEM examination of the coatings indicated that the wear mechanism was predominantly abrasive in nature. But the damage caused to unreinforced Cr₃C₂-NiCr coatings was extensive, and the wear track had deep grooves, carbide pullouts and fatigue cracks (Fig. 2 a & b). Also, the tribo-oxide layer was damaged due to abrasive wear and the coatings was left unprotected. While nano-CeO₂ reinforced Cr₃C₂-NiCr coatings showed the least damage with shallow grooves with no visible fatigue cracks (Fig. 2 c & d). The tribo-oxide layer remained intact for the entire test duration. The superior wear resistance of nano-CeO₂ reinforced Cr₃C₂-NiCr coatings can be attributed to the enhanced microstructural and mechanical properties achieved due to the addition of nano-CeO₂ powders. The addition of nano-CeO₂ powders also helped to reduce the extent of Cr₃C₂ decarburization and contributed to the development of a stable tribo-oxide layer.

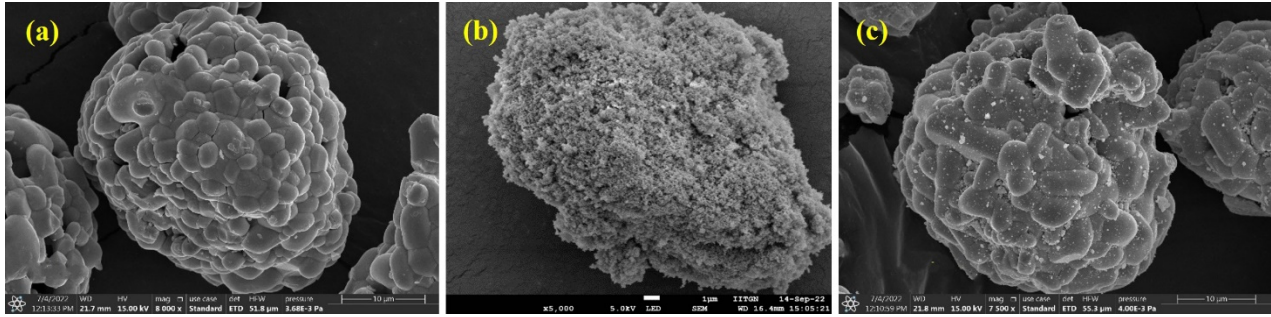


Figure 1: FE-SEM analysis of (a) Unreinforced Cr₃C₂-NiCr and (b) nano-CeO₂ and (c) nano-CeO₂ reinforced Cr₃C₂-NiCr powders

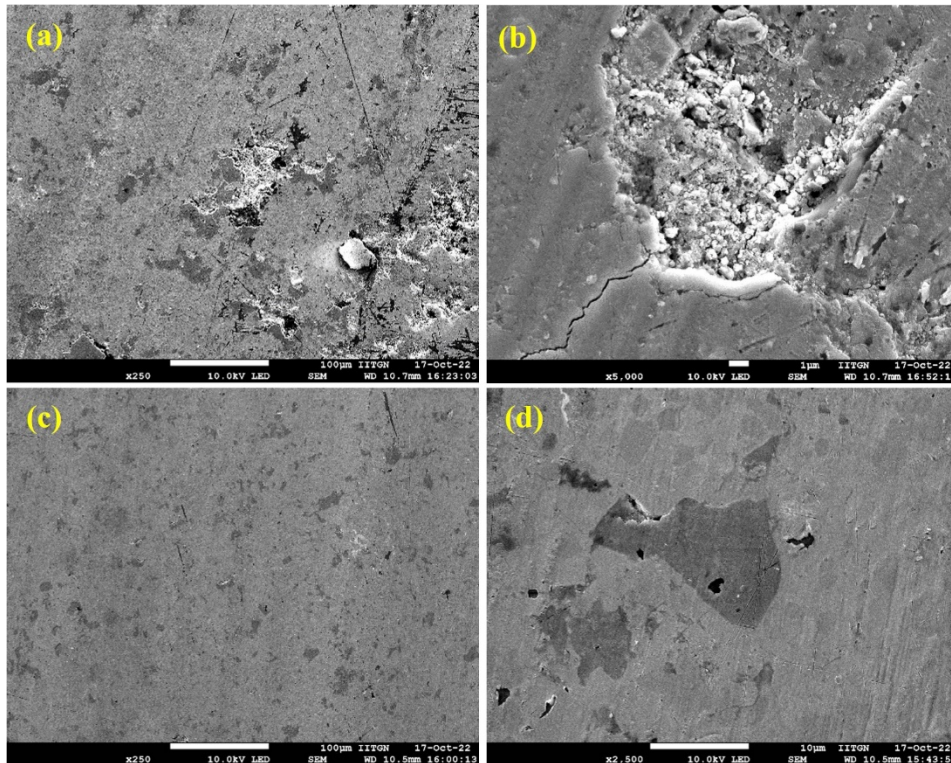


Figure 2: FE-SEM analysis of wear track (a & b) unreinforced Cr₃C₂-NiCr coatings and (c & d) nano-CeO₂ reinforced Cr₃C₂-NiCr coatings

Conclusions

The current study provides a cost effective and scalable blending methodology to manufacture nano-enabled feed stock powders for thermal spray processes. The addition of nano-CeO₂ to Cr₃C₂-NiCr coatings contributed to reducing the CoF and specific wear rate by more than 40% and 35% respectively.

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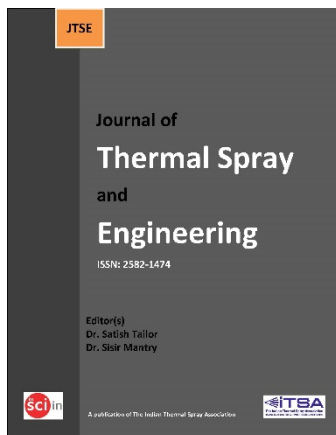
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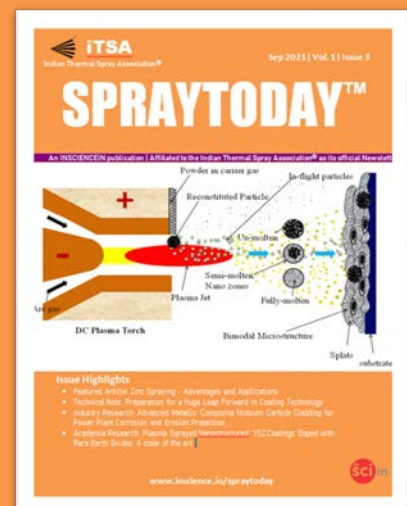
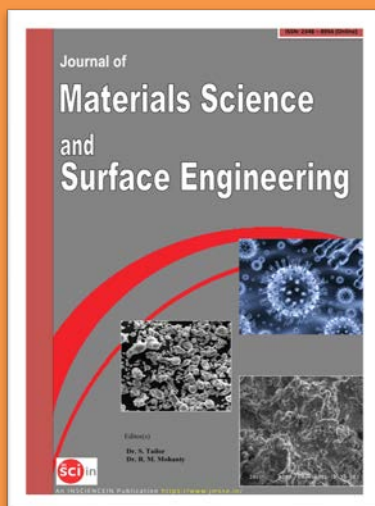
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