Analyzing microstructural features, surface topography, and scratch resistance of innovative nano-composites coated with high velocity air-fuel technology

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ABSTRACT. New developments in thermal spraying processes may offer higher-quality alternatives to hard chrome plating and possibilities for hard chrome plating in a range of coating applications. These include spraying with high-velocity air fuel (HVAF) and new spray consumables. The low operating temperatures and accelerated particle velocity of the HVAF process enable investigation and development of a wide range of novel coating materials and applications. The High-velocity Air Fuel Process' quality and efficiency are primarily due to the broad combustion chamber and axial injection of the feedstock through it, as well as the relatively low combustion temperature of an air-fuel mixture and the low gas velocity that provides enough time for the mild heating of the powder particles. The current work discusses the inventive thermal spray procedure used for SAE 1008 carbon steel, a cost-effective substrate material. All of the compositions that were treated have undergone microstructure investigations. A scratch test is conducted in accordance with ASTM guidelines. Assessment of surface morphology clearly demonstrates the relationship between the evaluated parameters. According to the occurrence, scratch methods such as delamination, cracking, plastic deformation, and elastic deformation are highlighted. However, the findings of the scratch test showed that the samples' scratch resistance increased as the coating thickness rose. In comparison to samples with thinner coating, those with thicker coating demonstrated a stronger resistance to scratching. This is explained by the fact that coatings with a higher thickness and density can support the subsurface more effectively and stop cracks from scattering. This can retain

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the coating's integrity and stop more damage from occurring, improving scratch resistance. Better scratch resistance was displayed by the samples with denser microstructures and smoother surface morphologies.

The outcome is greater scratch resistance because a higher density covering can withstand deformation and fracture better than a lower density layer. This is due to the mechanism of deformation and fracture in the coating material. This improvement in scratch resistance can be due to the composites' increased HVAF coating's hardness and adherence. The findings imply that using an HVAF coating to increase the scratch resistance of new nanocomposites may constitute a successful strategy.

KEYWORDS. Microstructure, Scratch Test, XRF, HVAF.

INTRODUCTION

By utilizing coatings and surface treatment methods, engineers can affect productivity, lengthen life, and enhance the aesthetics of materials used for engineering components. These technologies were developed because it is possible for manufactured parts to deteriorate and fail as a result of interactions with other manufactured parts, liquid or gaseous environments, or both. Coating technologies also enhance component performance by applying coatings selectively to carry out specific duties without compromising the benefits of the substrate material. By applying the ideal coating to the constituent surface, external forces' effects can be minimized [1]. THERMAL SPRAY refers to a group of coating methods used to apply metallic or non-metallic coatings. These processes fall into three primary categories: plasma arc spray, electric arc spray, and flame spray [2]. The energy sources are used to heat the coating material (whether it is in powder, wire, or rod form) until it is molten or almost molten. The burned particles are accelerated and propelled towards a prepared substrate using process gases or atomization jets. The optimal thermal spray technique is frequently chosen based on considerations such as preferred coating materials, coating performance standards, economy, part size, and mobility. The lamellar structure of thermal sprayed coatings is composed of "splats," or particles that have been swiftly quenched after being flattened by contact with the surface [3]. The main cause of why sprayed metals are frequently tougher than corresponding wrought metals is the inclusion of dispersed oxides formed even during the deposition process. They are less ductile and have more porosity and hardness as a result of the spraying process. In the field of materials science and engineering, the creation of novel materials with enhanced mechanical and physical properties has always been a focus of interest. Nanocomposites have demonstrated considerable promise for enhancing the mechanical and physical characteristics of materials. The limited scratch resistance of these materials, however, restricts their usefulness. Numerous coating techniques have been developed to enhance the materials' scratch resistance in order to solve this problem [4]. Due to their distinctive mechanical, thermal, and electrical properties, nano composites have become a potential class of materials for a variety of technical applications. These materials' susceptibility to wear and surface degradation, however, can restrict the range of things they can be used for. To increase the functionality and endurance of nano composites, it is crucial to improve their surface qualities [5]. One such coating technique that has received a lot of interest recently is the High-Velocity Air Fuel (HVAF) process because it can provide homogenous, dense coatings with outstanding mechanical properties. In order to create a high-velocity gas stream, the HVAF method involves injecting a mixture of fuel and air into a combustion chamber. The coating material is subsequently deposited in a molten condition on the surface of the object to be coated by the gas stream. Due to the high gas stream velocity, the coating is uniform, dense, and has excellent adhesion to the substrate [6]. The thermal spray coating procedure known as HVAF (High-Velocity Air Fuel) coating involves the high-velocity impact of particles on a substrate material. In this procedure, a high-velocity jet of hot gas is created by feeding the coating material into a combustion chamber, where it is combined with fuel gas and ignited. A supersonic nozzle is used to speed the coating material towards the substrate once it is injected into the jet and heated to a molten state. The high density, strong adhesion, and low porosity characteristics of HVAF coating make it the perfect choice for a variety of industrial applications [7]. A number of substances, including steel, aluminum, and titanium, can be coated using this coating method, including metals, ceramics, and composites. Compared to conventional thermal spray coating methods like HVOF (High-Velocity Oxygen Fuel) [8] and plasma spraying, HVAF coatings provide a number of advantages. Higher coating quality, better coating adhesion, greater coating density, and reduced residual stresses are just a few of these benefits. Comparing HVAF coatings to other thermal spray coating techniques, HVAF coatings are also more affordable and environmentally benign. HVAF coatings are comparable to coatings made using the Cold Spray and HVOF (High-Velocity Oxygen Fuel) techniques, however HVAF is a "warm spray" process that runs at a temperature in between the two. Axial powder injection into an air-fuel jet that has a temperature of roughly 1900–1950 °C is used in HVAF guns to effectively apply carbide-based materials. However, compared to high-temperature oxy-fuel jets, the HVAF process generates significantly fewer oxides, enabling the application of metals with minimal oxidation, much like Cold Spray [9]. All things considered, HVAF coating is a very sophisticated and successful process for applying high-performance coatings to a variety of substrates. It is frequently used to increase the reliability, effectiveness, and efficiency of parts and machinery in a variety of industries, including aerospace, automotive, and manufacturing [10]. High-Velocity Air-Fuel (HVAF) spraying and blasting recent innovations have concentrated on a significant increase in spray particle velocity. By enhancing coating quality even more, metallic and carbide-based coatings that are impermeable to gas can now be deposited at thicknesses as low as 40–50 micron. Low dissolved oxygen concentration and a good balance of high hardness and toughness are characteristics of the coatings. This sparked not only the adoption of HVAF technologies in existing thermal spray markets in the oil and gas sector, but also the creation and successful implementation of new coating applications. This was coupled with the improved technological efficiency of contemporary HVAF equipment [11]. Co-Cr-W-C-type coatings: These coatings are frequently employed in the marine industry, especially in dock cranes, where they offer housing wear rings and impeller hubs with wear and corrosion protection [12]. Ni-Cr-Mo-type coatings: These coatings are frequently employed in the oil and gas sector to give vessels in sulphur removal equipment corrosion resistance [13]. Coatings made of tungsten carbide are frequently applied to the restriction grit and slide gate orifices of catalytic towers in the chemical industry to offer wear and cavitation resistance [14]. Chromium carbide-based coatings: These coatings are frequently applied to different components, including boiler tubes and turbine blades, in the power generation sector to provide high-temperature erosion resistance [15]. The study aims to enhance the understanding of the microstructural and surface characteristics of the nano-composites coated with high velocity air-fuel technology, as well as their scratch resistance properties. This knowledge can be valuable in the development and optimization of innovative coatings for various applications, including protective coatings for industrial components, aerospace materials, and wear-resistant surfaces. This study's novelty comes from its innovative coating process, nano-composite materials, thorough analytical methodology, and investigation of relationships between scratch resistance, microstructure, and surface topography. The results might accelerate the emergence of novel materials and coatings with improved mechanical and surface characteristics.

MATERIALS AND METHODS

The High Velocity Air Fuel (HVAF) technique was utilized to develop composite coatings, and SAE1008 cold rolled steel was selected as the substrate material. The substrate material's chemical composition is presented in Tab. 1. Composition results are obtained from the Optical Emission Spectrometer (OES) tests per ASTME415-21 standards and carried out at Raghavendra Spectro Metallurgical Laboratory, Bengaluru, India.

Element	Fe	C	Si	Mn	P	S
%	99.201	0.087	0.234	0.421	0.031	0.026

Table 1: Elements of the substrate material.

Cylindrical steel samples were prepared by cutting and turning them to approximately Ø7.5 × 25 mm length-sized specimens. To create the feedstock powder, a combination of commercially available 308NS(NiGr) from Oerlikon Metco, Switzerland obtained from M/s Spraymet Surface Technologies Pvt. Ltd, Bengaluru-India; Ferrous Sulphide (FeS) provided by JAINSON LABS INDIA, Meerut and Multi-walled Carbon Nanotubes (MWCNT) received from Adnano Technologies, Shivamogga, India was used. The mechanical mixer was used to blend the materials to produce various combinations by varying the weight percentage of NiGr and FeS, respectively. The model used was the AK5, and the HVAF procedure was carried out in Bengaluru by Spraymet Surface Technologies using Kermitco-provided equipment with the following signature as shown in Tab. 2.

For further investigation, several tests were performed on the prepared coupons.

The purpose of conducting density and porosity tests was to assess the effectiveness of the process used, which is known for producing coatings that are dense and have minimal porosity [16]. Archimedes' Principle was utilized to determine density in accordance with ASTM C135-96 (2022) standards, as it provides a practical and accurate method for calculating the volume of an object with an irregular shape. This method, also known as hydrostatic weighing, is commonly employed. To determine the area percentage porosity in thermal sprayed coatings, the ASTM E2109-01 test method was employed. The recommended procedure was followed to prepare transverse sections of the sample for optical microscopy. Commercial software attached to the microscope was utilized to perform quantitative metallographic analysis. An image analyzer software program was used to determine physical properties based on samples with images of the microstructure.

Parameters	Value
Working Temperature	Around 1850ºC
Deposition rate	5kg/hr
Nitrogen Carrier Gas	10 bar
Air Pressure	7.5 bar
Propane Pressure (Fuel)	6.5 bar

Table 2: Process parameters adopted for HVAF technique.

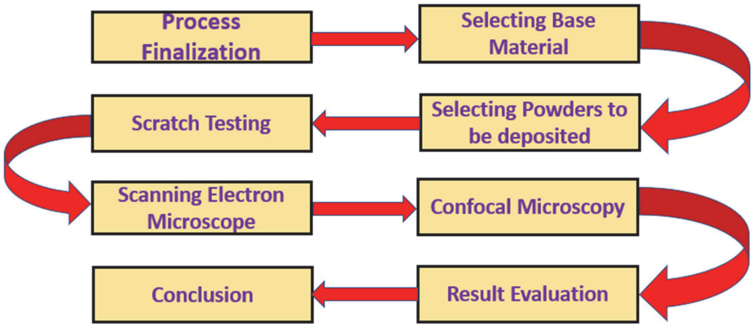

Figure 1: Sequence of the methodology.

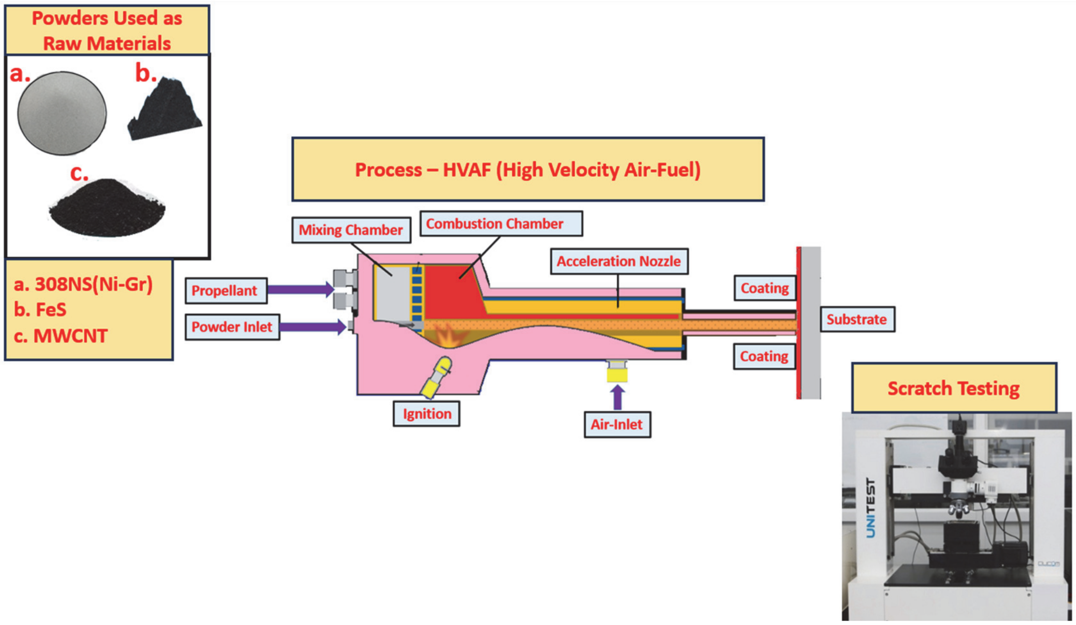

Figure 2: Flowchart depicting materials, fabrication technique used in current study.

Scratch testing is a widely used method for characterizing the mechanical properties of coatings. It involves the use of a sharp stylus to create a controlled scratch on the coating surface and measuring the critical load required to initiate and propagate the scratch. In this report, we will focus on scratch testing of composite coatings, which are coatings consisting of two or more different materials with distinct properties [17]. A nondestructive semi-quantitative technique called portable X-ray fluorescence (XRF) was used to determine the chemical composition of a material's coating in accordance with the ASTM E1476-04 standards. The HVAF samples were assigned the sequence AF1, AF2, AF3, AF4, and AF5.The sequence of operations in the present work is as represented in Fig. 1 and pictorially with the materials, process and testing depicted in Fig. 2 respectively.

The HVAF deposition process is well-known for producing highly dense coatings with minimal porosity [18] across the entire cross-sectional area of the coating as analyzed by imaging software. The superior density of the HVAF sprayed coatings is thought to be a result of the high kinetic energy of the metal powders and the melting behavior of the particles, which allow for the creation of nearly pore-free coatings through intense impact with the substrate.

A practically pore-free covering that is exceedingly dense and has good adherence to the substrate is produced by the forceful impact and flattening. Further lowering the chance of porosity is the HVAF process' use of a high-pressure gas stream, which guarantees that the particles are crushed and heated uniformly.

RESULTS

Powder Morphology

The physical makeup, dimensions, and structure of the nickel-graphite powder particles are referred to as the NiGr powder morphology as shown in Fig. 3. However, NiGr powder typically consists of tiny nickel particles evenly dispersed throughout a matrix of graphite, which can have advantageous properties. The performance of the powder in numerous applications, including electrochemical and catalytic processes, can be impacted by the particle size, shape, and distribution.

More specific details about the size, shape, and surface properties of the powder particles are revealed by the Scanning Electron Microscopy (SEM) analysis of FeS powder morphology. FeS powder particles as depicted in Fig. 4 may emerge under SEM imaging as agglomerates or pieces with erratic shapes and rough, porous surfaces. The size of the particles might range from a few nanometers to tens of micrometers, depending on the production process and intended application. FeS powder performance in diverse applications may be impacted by the surface texture of the powder's particle's reactivity and stability. It offers useful information about the physicochemical properties of the powder particles, which can help with the design and improvement of FeS-based materials for various applications.

Functional MWCNT powder is made up of MWCNTs that have undergone various chemical modifications or functionalization's in order to confer particular qualities or improve their performance in various applications.

Functional MWCNT powder particles can be seen by SEM in Fig. 5 as single nanotubes or tiny agglomerates, and their diameters can range from a few tens of nanometers to a few micrometers. The diameter of the nanotubes can be homogeneous, usually ranging between 5 and 20 nanometers, and they can take the form of either curved or straight structures. Depending on the type and degree of functionalization, the surface of functional MWCNT powder particles can have different characteristics, such as a rough or smooth surface.

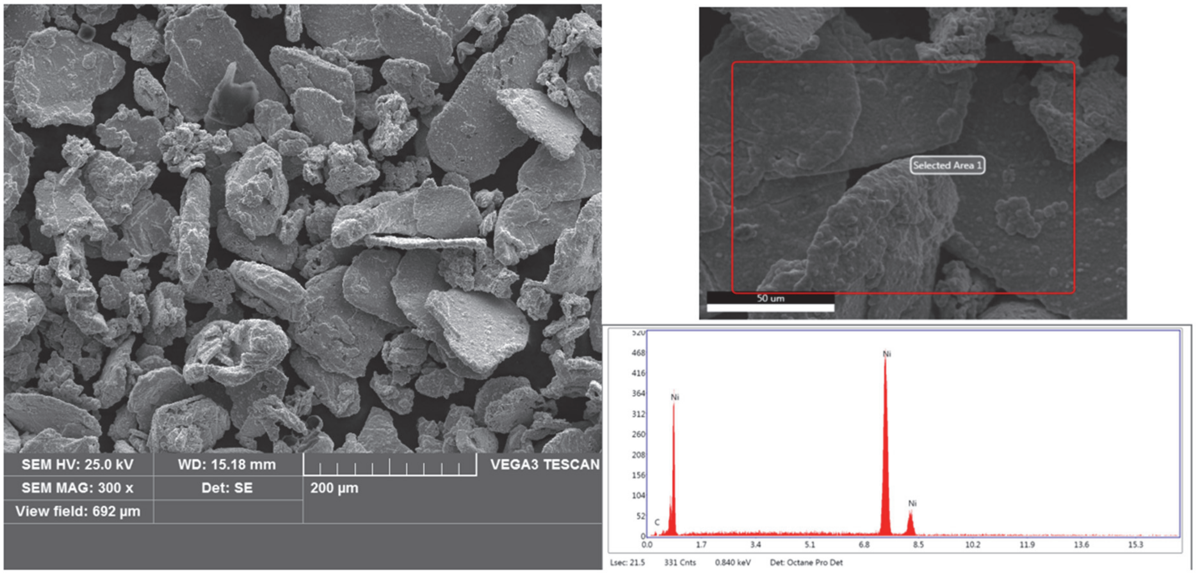

Figure 3: SEM of NiGr powder morphology with EDS analysis.

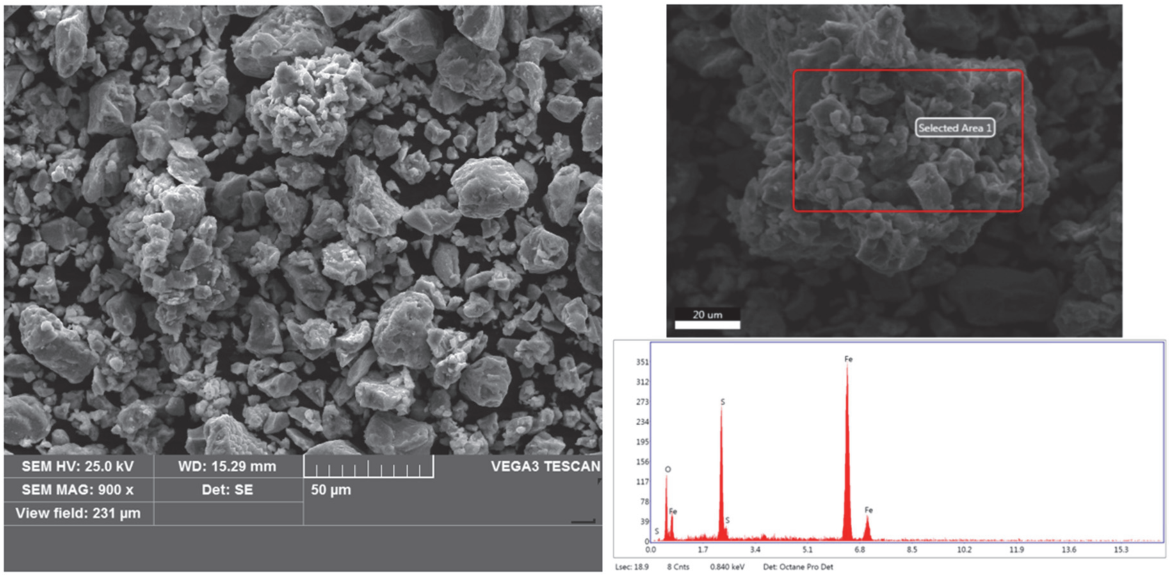

Figure 4: SEM of FeS powder morphology with EDS analysis.

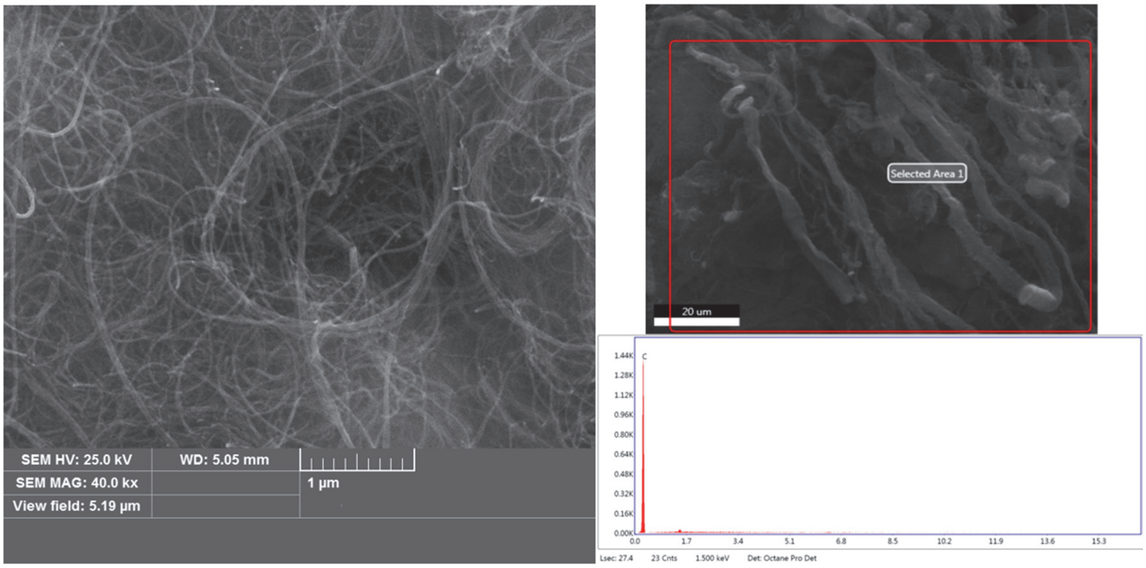

Figure 5: SEM of MWCNT powder morphology with EDS analysis.

SEM Evaluation

Fig. 6 shows the SEM of the HVAF coated sample. The quality and fidelity of the bond between the coating and the substrate can be determined from a cross-section image of the HVAF coating that shows the coating's interface with the substrate. Typically, the coating-substrate interface is revealed by cutting a sample of the coated substrate perpendicular to the interface, polishing it, and then etching it to show the interface. The coating procedure can be optimised using this information, and the coating's functionality while in use can be enhanced. An HVAF coating cross-section often reveals multiple layers of coating material deposited on the substrate, each with a distinct interface. The interface between the substrate and the coating is particularly interesting because it can reveal details about how well the two materials adhere to one another.

In general, the coating's performance depends greatly on the state of the interface between the substrate and the coating. To avoid the coating delaminating or separating from the substrate, which could result in early failure of the coating and harm to the substrate, it is vital to have a robust and resilient interface.

It is possible to evaluate the effectiveness of the adhesion between the two materials by looking at the interface between the substrate and the coating in the cross-section image. The way the substrate is surface-prepared, the kind and content of the coating material, and the deposition conditions used throughout the coating process are all variables that can impact adherence.

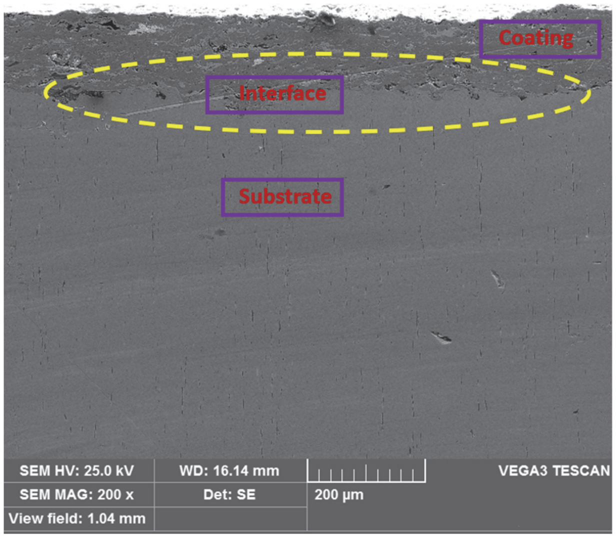

Figure 6: SEM of coated sample.

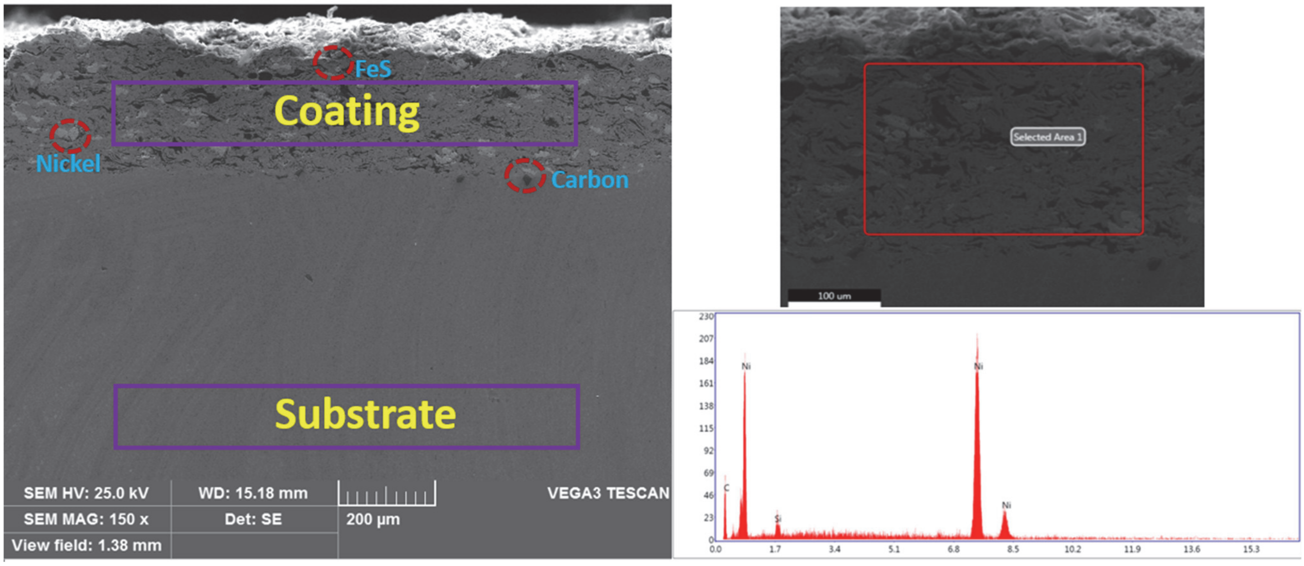

Figure 7: SEM with EDS analysis of cross section of coating and substrate

To examine the coating-substrate interface and gauge a coating's adherence to a substrate, SEM imaging is frequently used and as shown in Fig. 7. The shape, structure, chemical makeup, and characteristics of the coating and substrate, as well as the nature of their contact, can all be learned from SEM pictures.

The coated substrate is often cross-sectioned with a cutting tool or a focused ion beam (FIB) to reveal the coating and substrate interface in order to prepare a sample for SEM imaging. To avoid charging during imaging, a small layer of conductive material, such as gold or carbon, is applied to the cross-sectioned sample before mounting it on a SEM stub.

The coating-substrate interface can be seen in high resolution via SEM imaging, providing information on the coating's thickness and uniformity, the substrate's surface roughness, and the makeup of the interfacial region. By assessing the degree of delamination or cracking at the interface under applied stress, the adhesion strength of the coating to the substrate can also be ascertained from the SEM pictures. The term "coating substrate correlation" describes the connection between a coating's characteristics and the substrate it is applied to. The adherence, endurance, and performance of the coating can be influenced by the substrate's characteristics, such as its surface energy, roughness, and chemical composition. The coating's characteristics, such as its thickness, makeup, and surface energy, can also impact how it interacts with the substrate.

For the coating to attach well to the substrate and carry out as intended, a good coating substrate correlation is essential. For instance, using a coating with a high adhesive strength may be required if the substrate has a high surface energy in order to assure good attachment. It could be required to apply a coating with strong flow and wetting capabilities if the substrate is rough or has a complicated geometry in order to ensure uniform coverage. It's crucial to comprehend the relationship between the coated substrate and the coating when choosing the best coating for a certain application. When choosing a coating, it is important to consider the characteristics of the substrate and the environment where the coating will be applied. For a substrate that will be exposed to severe chemicals or saltwater, for instance, a coating that is resistant to corrosion may be necessary. For a coating to perform and last as required and for the substrate to perform as intended, a good coating to substrate correlation is essential [19].

Scratch Test assessment

Figs. 8 and 9 display, respectively, scratch data for coatings with lower and higher thicknesses. The lower range of the coating thickness was roughly 125 microns, and the maximum range was about 250 microns. Scratch testing is important for assessing thermal spray coatings because it can offer both quantitative and qualitative information about the adherence and cohesiveness of the coatings. The strength, hardness, and resistance to wear and abrasion of the coating can be ascertained by examining the shape and features of the scratch.

Scratch testing can also reveal details about the coating's failure mechanisms, such as cohesive failure inside the coating or adhesive failure at the coating-to-substrate interface. The performance of the coating under various operating situations may be understood and its service life can be predicted using this information.

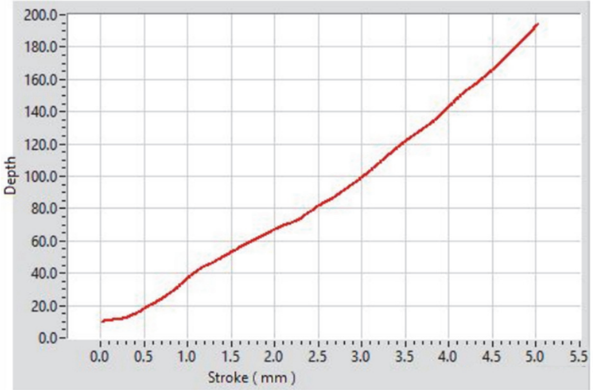

Figure 8: Scratch data at lower coating thickness.

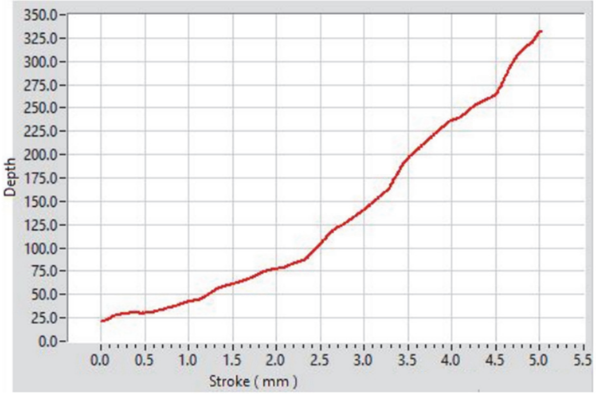

Figure 9: Scratch data at higher coating thickness.

Scratch testing can also be used to improve the thermal spray coating procedure and its various elements, including the distance, angle, and velocity of the spray. The best process variables that provide the required coating performance can be found by conducting scratch tests on coatings made under various conditions.

Accordingly, scratch testing is an effective instrument for assessing and improving thermal spray coatings since it offers crucial details on their adherence, cohesion, strength, and failure processes.

The depth of the scratch is frequently used in scratch testing to determine the thickness and adhesive power of coatings. The characteristics of the coating, those of the substrate, and the scratch test parameters, such as the normal load and the scratch velocity, all have an impact on the depth of the scratch.

In scratch testing, the importance of COF and stroke length is found in their combined impact on the precision and dependability of the test findings. While a lower COF can result in a deeper scratch, a greater COF often causes a shallower scratch. This is so that a shallower scratch may be produced. A larger COF can lead to more energy being lost as frictional heat, which can cause plastic deformation and material displacement around the scratch tip. In contrast, a smaller COF may result in less energy being released as frictional heat, which could lead to a deeper scratch. During scratch testing, the length of the stroke can also affect the COF. By creating higher frictional forces between the scratch tool and the coating's surface, a longer stroke length can raise the COF. This may cause the shallower scrape that was previously mentioned.

The length of the stroke, or the distance covered by the scratch tool during the scratch test, can also affect how deep the scratch is. A deeper scratch will typically occur from a longer stroke length, which can give more precise information on the coating's thickness and adherence.

However, the individual application and required level of accuracy must be considered while choosing the stroke length. Longer stroke lengths might be required for thicker coatings or to gather more specific data on the coating properties, whereas shorter stroke lengths might be adequate to measure the thickness and adherence of thinner coatings.

It is crucial to remember that choosing the stroke length properly is necessary since longer stroke lengths might also raise the chance of the test injuring the substrate or coating. The depth of the scratch can also be influenced by additional elements like the kind of scratching tool used, the size and shape of the tip, and the angle at which the scratch is made.

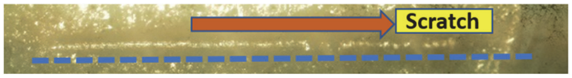

Figure 10 a: Optical microscopy of scratch indentation.

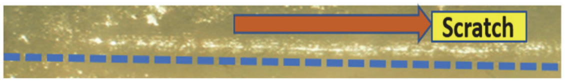

Figure 11 a: Optical microscopy of scratch indentation.

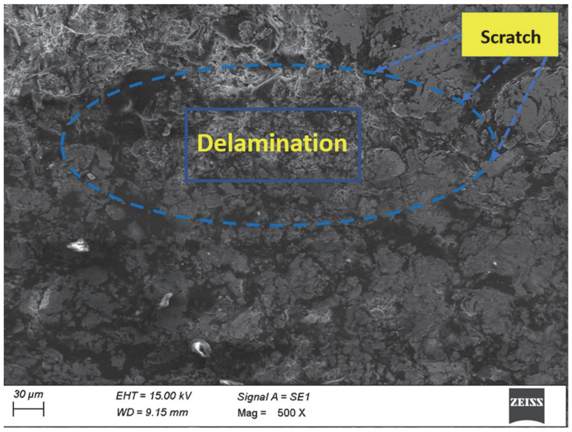

Figure 10 b: SEM of scratch indentation.

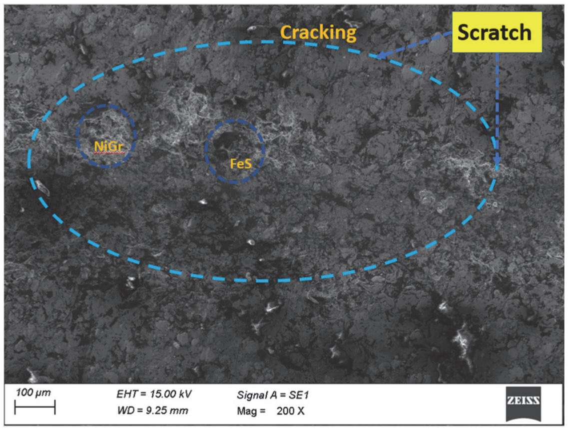

Figure 11 b: SEM of scratch indentation.

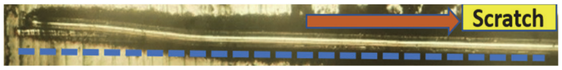

Figure 12 a: Optical microscopy of scratch indentation at higher coating thickness.

Figure 13 a: Optical microscopy of scratch indentation at lower coating thickness.

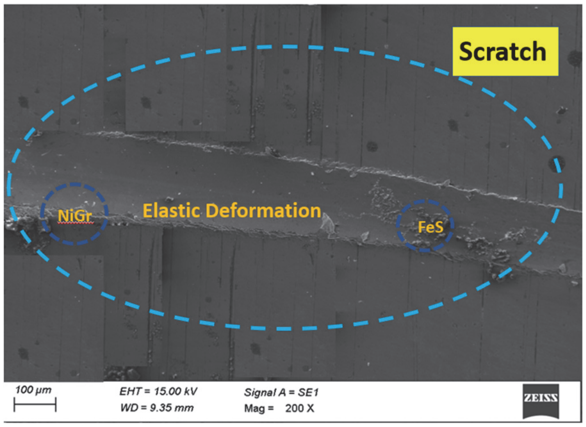

Figure 12b: SEM of scratch indentation at higher coating thickness.

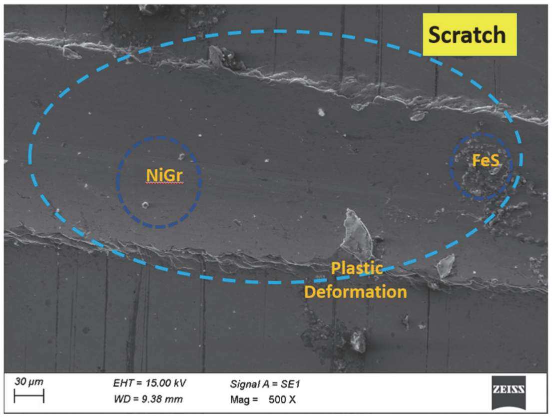

Figure 13 b: SEM of scratch indentation at lower coating thickness.

The most popular technique for assessing the cohesion and adhesive strength of thermal spray coatings is scratch testing. In the scratch test, the coating's surface is scratched with a stylus while being subjected to regulated loads and speeds. The load is then changed while the coating is being watched for deformation or failure.

The reported adhesion strength and coating breakdown mode during a scratch test of thermal spray coatings can be impacted by a number of causes. Among these mechanisms are:

The coating may begin to separate from the substrate as the scratch load rises, either due to cohesive failure inside the coating or adhesive failure at the coating-substrate interface. Delamination might happen as shown in optical image Fig. 10a and SEM Fig. 10b result of the scratch load's tensile strains or as a result of the coating's pre-existing flaws spreading.

Damage to the substrate: In some circumstances, the scratch load may be severe enough to result in cracking or plastic deformation of the substrate. Damage to the substrate can skew the reported adhesion strength and produce an incorrect failure mode.

Fatigue failure: The scratch test may cause the coating to fatigue, which could result in cracking or spalling as shown in optical image of Fig. 11a and SEM in Fig. 11b, for coatings subjected to cyclic loading, such as in tribological applications. A lower adhesion strength than a single scratch test may be the outcome of fatigue failure.

Fig. 12a and 12b respectively reveals the optical image and SEM image of the mild scratch or the resistance to failure of the coating and provides a clear distinguishing feature with the severe wear or deeper scratch (failure).

Plastic deformation as shown in optical image of Fig. 13a and SEM in Fig. 13b. The stylus may cause the coating to deform and flow around the tip of the pen during the earliest stages of the scratch test. Low adhesion strength may be the outcome of this mechanism, which is frequent in soft and ductile coatings.

Confocal Microscopy

Confocal microscopy is an optical imaging method used to capture three-dimensional, high-resolution images of a sample's surface. It is very helpful for researching the topography and microstructure of materials, including coatings.

Confocal microscopy can reveal a multitude of details on the structure, adhesion, and durability of thermal spray coatings when used to examine scratches on those coatings as shown in Fig. 14 and 15 respectively. Confocal microscopy is particularly useful for:

Confocal microscopy may produce high-resolution, three-dimensional images of the scratch on the thermal spray coating, allowing you to see its morphology. The size, depth, and shape of the scratch can be determined using this data.

Confocal microscopy can be used to gauge the coating's thickness at the scratch location and in the surrounding regions. This information can be utilized to determine whether the scratch has reached the substrate after penetrating through the covering.

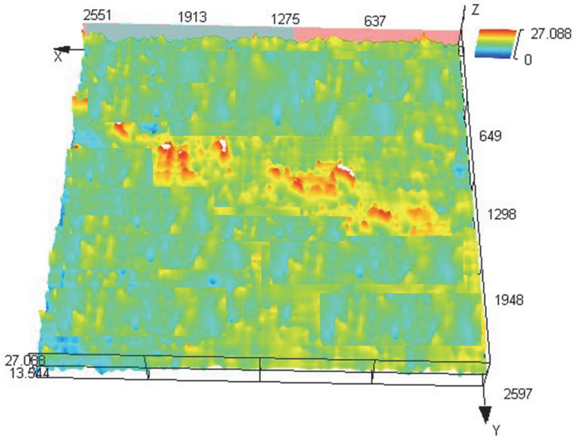

Figure 14: Confocal image of scratch tests showing normal wear

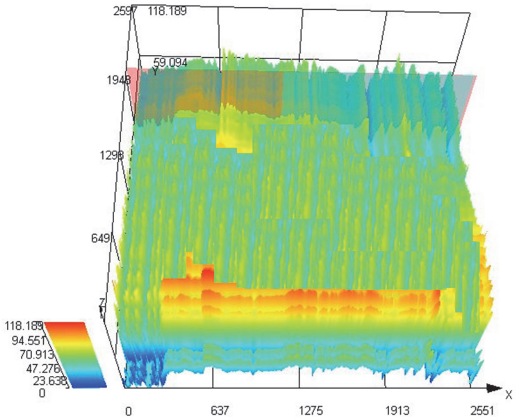

Figure 15: Confocal image of scratch tests showing deeper wear

In order to describe the microstructure, high-resolution photographs of the coating's microstructure, including the grain size, porosity, and orientation of the coating material, can be obtained using confocal microscopy. This data can be used to ascertain whether the scratch has impacted the coating's microstructure.

Confocal microscopy can be used to assess the coating's adherence to the substrate at the scratch location and in the surrounding regions. This data can be used to determine whether the scratch has led to coating delamination or detachment.

A potent tool for analyzing scratches on thermal spray coatings is confocal microscopy. In order to optimize the coating process and enhance the coating's performance in use, it gives extensive information regarding the structure, adherence, and durability of the coating.

DISCUSSION

Examining the microstructure, surface morphology, and scratch testing of innovative high-velocity air fuel (HVAF) coated nano composites is a crucial part of determining their mechanical characteristics and durability. In comparison to conventional coatings, these composites, which are made of a matrix material and nanoscale reinforcement particles, can offer greater strength, wear resistance, and other mechanical properties.

The HVAF coated new nano composites' microstructure analysis can provide information on the size, shape, and distribution of the reinforcing particles as well as any flaws or irregularities in the coating. Grain size, porosity, and interparticle spacing are examples of microstructural characteristics that might affect a composite's mechanical capabilities. For instance, enhanced hardness and strength can be achieved by using smaller grain sizes and denser reinforcing particles.

The HVAF coated new nano composites' surface morphology study can reveal details about the surface topography, roughness, and uniformity, all of which can impact the material's resistance to wear and abrasion. During the HVAF coating process, surface roughness can be adjusted by altering the spray parameters. A smoother surface can improve adhesion between the coating and the substrate.

The scratch test is a widely used technique to assess coating adherence and cohesiveness as well as to gauge the coating's resistance to mechanical damage. The force necessary to cause a visible scratch is assessed during the scratch test, which involves moving a stylus with a sharp tip across the coating's surface. The scratch test can reveal details regarding the mechanical characteristics of the coating, including its toughness, hardness, and substrate adherence.

Scratch testing, surface morphology analysis, and microstructure analysis data can all be compared to provide a more complete knowledge of the mechanical characteristics and behaviour of HVAF coated new nano composites.

The mechanism of deformation and fracture in the coating material can be used to explain the relationship between greater thickness and greater density and increased scratch resistance. A significant stress concentration is created at the tip of a scratch when it is developed on the coating's surface. A ploughed groove is created as a result of the coating material deforming due to the stress concentration. The characteristics of the coating, such as its hardness, ductility, and toughness, have an impact on how easily the coating material deforms.

In the scratch test, a thicker covering offers more material to withstand deformation and fracture. Additionally, a greater density coating has a microstructure that is more compact and homogenous, which can increase the coating's hardness and strength. The outcome is greater scratch resistance because a higher density covering can withstand deformation and fracture better than a lower density layer.

Additionally, the thicker and denser coatings might give the subsurface better support and stop cracks from spreading. This can retain the coating's integrity and stop more damage from occurring, improving scratch resistance.

CONCLUSIONS

The present work's numerous experiments can be used to draw conclusions about HVAF coating. -

1. A nickel-graphite/ferrous sulphide/MWCNT feedstock was manually combined and agglomerated in order to effectively meet the requirements for the HVAF spraying process.
2. The scratch resistance of new nano composites was effectively increased by the HVAF coating method.
3. The scratch resistance of the samples was greatly influenced by microstructure and surface shape.
4. The findings of the scratch test indicated a correlation between thicker coating and higher scratch resistance.
5. The size, distribution, and orientation of the particles in a composite material can be determined using microstructure analysis, and these factors influence the material's toughness and strength.
6. The coating had very little porosity, excellent substrate contact, and little to no oxide content. The layer has a thickness of between 125 and 250 microns as determined by ASTM standards. The coatings didn't contain any non-melted or semi-melted particles.
7. It was determined that the coating had a porosity value of less than 1%.
8. Surface morphology study can reveal details regarding surface homogeneity, porosity, and roughness, all of which have an impact on a material's capacity to withstand wear and abrasion.
9. Scratch testing evaluates cohesion, adhesion, and resistance to failure and deformation under mechanical stress.
10. These tests can be used to better understand the material's mechanical properties and performance as well as point up opportunities for development.

The coating material's hardness is a key factor in scratch resistance. Greater resistance to deformation and penetration during scratching is typically found in harder materials, which lessens the depth and degree of surface damage. Scratch resistance is improved by a strong bond between the substrate and the thermal spray coating. When exposed to scratching forces, a coating is protected by a well-bonded interface that prevents delamination or separation. Scratch resistance is influenced by the coating material's capacity for plastic deformation without breakage. Stress may be absorbed and distributed by ductile materials, which minimises scratch damage and stops cracks from spreading. Due to their higher bulk material, which can absorb and disperse the applied load over a wider volume, thicker coatings typically offer better scratch resistance. Scratch resistance can be influenced by the coating material's microstructural characteristics and grain size. Comparing fine-grained coatings to coarse-grained structures, crack propagation resistance is frequently increased. Scratch resistance in thermal spray coatings might be lowered by porosity, voids, or other flaws. When scratched, these flaws can serve as stress concentrators and cause localised deformation, cracking, and delamination. The coating surface's roughness may have an impact on scratch resistance. The likelihood of abrasive contacts is decreased and the generation of wear particles during scratching is minimised on a smoother surface.

In general, scratch testing, surface morphology analysis, and HVAF coating studies can all be used to enhance the performance and design of novel nanocomposites.

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