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Design and Fabrication of Wear-Resistant Coatings Using Thermal Spray Techniques

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ABSTRACT

This study focuses on the design and fabrication of wear-resistant coatings using advanced thermal spray techniques to enhance the surface durability of engineering components. Various coating materials, including ceramics, metallic alloys, and composite powders, were deposited onto substrate surfaces through controlled thermal spraying processes such as plasma spraying and high-velocity oxy-fuel (HVOF) spraying. The microstructural characteristics, adhesion strength, and wear resistance of the fabricated coatings were systematically evaluated under different operational conditions. Experimental results demonstrate that optimized thermal spray parameters significantly improve coating density, hardness, and resistance to abrasive and erosive wear, highlighting the potential of these coatings for extending the service life of critical industrial components. The results demonstrate that coating performance strongly depends on deposition technique and process parameters, with HVOF-sprayed composite coatings exhibiting superior density, adhesion, and wear resistance. This study presents a comparative parametric analysis of thermal spray techniques rather than a universal coating framework.

Keywords—Wear-resistant coatings, Thermal spray techniques, Plasma spraying, HVOF spraying, Surface engineering, Abrasive wear, Coating microstructure, Material durability.

INTRODUCTION

Wear and surface degradation are among the most critical factors limiting the performance and lifespan of engineering components across various industrial sectors, including aerospace, automotive, power generation, and manufacturing. Components exposed to harsh mechanical interactions, such as sliding, abrasion, erosion, and corrosion, often experience a gradual loss of material, leading to reduced efficiency, increased maintenance costs, and potential system failures. Traditional bulk materials, despite possessing high inherent strength, often fail to provide adequate surface durability under severe operating conditions. Consequently, enhancing the surface properties of components has become a key strategy to improve their functional lifespan without altering their core mechanical characteristics. Surface engineering techniques, particularly coating technologies, have emerged as effective solutions to combat wear-related failures. Among these, thermal spray techniques have gained significant attention due to their versatility, adaptability, and ability to deposit a wide range of materials onto various substrates. Thermal spraying involves the projection of melted or semi-melted particles onto a substrate surface, where they rapidly solidify to form a dense and adherent coating. This method allows for the tailoring of surface properties such as hardness, toughness, and corrosion resistance while maintaining the underlying material's structural integrity. The capability to apply coatings with controlled thickness, microstructure, and composition makes thermal spray techniques highly suitable for wear-resistant applications. Several thermal spray processes exist, including plasma spraying, high-velocity oxy-fuel (HVOF) spraying, flame spraying, and cold spraying, each offering unique advantages depending on the application requirements shown in fig. 1. Plasma spraying, for instance, can deposit high-melting-point materials like ceramics and refractory alloys, providing exceptional hardness and wear resistance. HVOF spraying, on the other hand,

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produces coatings with superior density, adhesion strength, and low porosity, making it ideal for components exposed to high abrasive and erosive environments. The selection of appropriate materials and process parameters plays a pivotal role in determining the coating's microstructure, mechanical properties, and overall performance under operational stresses.

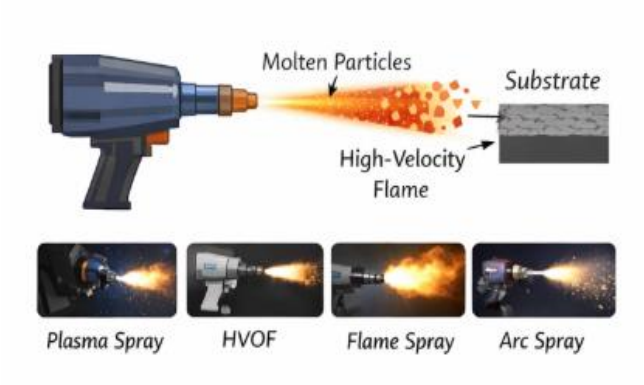


Fig. 1. Thermal Spray Process Overview

Material selection is equally critical in designing wear-resistant coatings. Ceramics such as alumina (Al_2O_3), zirconia (ZrO_2), and titanium carbide (TiC) are commonly used for their high hardness, thermal stability, and resistance to abrasive wear. Metallic coatings, including nickel, cobalt, and their alloys, provide excellent toughness and adhesion, allowing them to absorb mechanical impacts without cracking. Composite coatings, which combine ceramic and metallic phases, offer a balanced combination of hardness and toughness, making them suitable for applications requiring both wear and impact resistance. The integration of these materials into thermal spray coatings can significantly enhance the service life of components exposed to severe operating conditions. Despite the advantages, challenges in thermal spray coatings remain, particularly concerning coating-substrate adhesion, porosity control, residual stresses, and uniformity. Process optimization, including control of spray distance, particle velocity, substrate preparation, and thermal input, is essential to achieve coatings with minimal defects and maximum performance. Recent advancements in process monitoring, simulation, and material characterization have facilitated the development of coatings with tailored microstructures and superior wear properties, enabling their widespread adoption in modern industries. In this context, the present study aims to investigate the design and fabrication of wear-resistant coatings using thermal spray techniques, with a focus on optimizing material selection and process parameters. The research emphasizes the relationship between coating microstructure, mechanical properties, and wear performance under different operational conditions. By systematically evaluating the effects of various thermal spray methods and materials, this study seeks to provide insights into developing coatings that enhance surface durability and operational reliability of engineering components. The findings are expected to contribute to improved industrial applications, reduced maintenance costs, and extended component lifespan, highlighting the practical significance of thermal spray technology in surface engineering.

LITERATURE REVIEW

Thermal spray coating techniques have gained considerable attention in recent years due to their ability to enhance surface properties such as wear resistance, hardness, and corrosion protection. Dinavahi et al. [1] investigated the computational and experimental aspects of particle velocity in cold spray nozzles, providing insights into the fundamental parameters influencing deposition efficiency and coating quality. The characterization of coating microstructure often relies on techniques like X-ray diffraction (XRD), which enables phase identification and crystallographic analysis, essential for understanding material behavior under operational conditions [2]. Sharma and Kumar [3] highlighted the role of hybrid aluminium matrix composites reinforced with rare-earth oxides, SiC, and Al_2O_3 in improving mechanical and metallurgical properties, demonstrating the potential of tailored composite powders for surface engineering applications. Various studies have focused on the selection of appropriate coating techniques for surface protection. Fotovvati et al. [4] provided a comprehensive review of existing coating techniques, emphasizing their relative advantages and limitations for industrial applications. Similarly, Gobind et al. [5] discussed detonation gun-sprayed coatings for improving the wear resistance of grey

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cast iron, highlighting the effectiveness of high-velocity deposition processes in producing dense, adherent coatings. Mudgal et al. [6] studied the corrosion behavior of Cr_3C_2-25%(NiCr) and CeO_2-modified coatings under molten salt conditions at elevated temperatures, illustrating the importance of chemical additives in enhancing coating stability in aggressive environments. Scrivani et al. [7] examined HVOF coatings for petrochemical applications, demonstrating that optimized process parameters can achieve coatings with superior hardness, density, and adhesion. The corrosion resistance of cermet coatings has also been extensively studied. Lekatou et al. [8] investigated the behavior of cermet-based coatings with bond coats in acidic environments, while Zhou et al. [9] analysed Fe-based amorphous metallic coatings deposited by HVOF, showing enhanced resistance to corrosion due to the formation of protective phases. Balan et al. [10] provided an overview of thermal spray coating techniques, highlighting the improvements in surface properties achievable through appropriate process selection. Chatha et al. [11] focused on carbide-based thermal spray coatings, analyzing their characterization and corrosion-erosion behavior, which is crucial for components operating under combined mechanical and chemical wear. Bhatia et al. [12] reported the high-temperature performance of Cr_3C_2-NiCr coatings in coal-fired boiler environments, emphasizing the significance of evaluating coatings under actual service conditions. Mishra et al. [13] examined hot corrosion behavior of detonation gun-sprayed Al_2O_3-TiO_2 coatings on nickel-based superalloys, demonstrating enhanced protective performance at 900°C. Wear performance has also been a key focus in thermal spray research. Singh et al. [14] investigated the sliding wear behavior of HVOF-sprayed Al_2O_3/TiO_2 and Cr_2O_3 coatings, while Akhtari Zavareh et al. [15] studied the tribological and electrochemical behavior of Cr_3C_2-NiCr coatings on carbon steel, showing the combined effect of microstructure and coating density on performance. Shukla et al. [16] compared the tribological behavior of Cr_3C_2/NiCr coatings deposited via different thermal spray techniques, underlining the influence of deposition method on wear resistance. Kamal et al. [17] reported the mechanical and microstructural characteristics of detonation gun-sprayed NiCrAlY coatings with CeO_2 additions, highlighting the improvement in hardness and adhesion due to rare-earth oxide incorporation. Praveen and Arjunan [18] optimized HVOF deposition parameters for NiCrSiB-Al_2O_3 coatings to enhance erosion resistance, demonstrating the importance of parametric studies for achieving superior surface performance. Finally, several comprehensive reviews have summarized advancements in thermal spray technology. Amin and Panchal [19] provided an extensive review of coating processes, highlighting trends in process selection and materials development. Fauchais and Vardelle [20] discussed the use of thermal spray coatings against corrosion and corrosive wear, emphasizing the broad applicability of thermal spray technology in extending the life of engineering components. Collectively, these studies establish the importance of selecting appropriate coating materials, deposition techniques, and process parameters to optimize mechanical, tribological, and corrosion resistance properties of surfaces for industrial applications.

PROPOSED METHODOLOGY

The proposed study focuses on the systematic design, fabrication, and characterization of wear-resistant coatings using thermal spray techniques. The methodology is structured to investigate the effect of coating materials, deposition processes, and process parameters on the microstructure, mechanical properties, and wear performance of coated substrates. The study is divided into four main stages: material selection, substrate preparation, coating deposition, and characterization.

1. Material Selection: The first step involves selecting suitable coating materials that provide enhanced wear resistance under different operating conditions. The study will consider ceramic materials (e.g., alumina, zirconia, titanium carbide), metallic alloys (e.g., nickel, cobalt, and their composites), and metal-ceramic composite powders. The selection is based on properties such as hardness, toughness, thermal stability, corrosion resistance, and compatibility with the substrate material. Powder particle size, morphology, and flow characteristics will be characterized to ensure uniform deposition during the thermal spray process.

2. Substrate Preparation: Substrate preparation is crucial for achieving strong coating adhesion and minimizing defects. Mild steel, stainless steel, or other engineering alloys will be used as substrates depending on the target application. Surface preparation will include mechanical cleaning, grit blasting, and degreasing to remove oxides, contaminants, and loose particles. Surface roughness will be optimized to enhance mechanical interlocking between the coating and substrate, ensuring robust adhesion and reducing the risk of delamination during service.

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3. Coating Deposition Using Thermal Spray Techniques: The coatings will be deposited using advanced thermal spray methods, primarily plasma spraying and high-velocity oxy-fuel (HVOF) spraying. Key process parameters such as spray distance, particle velocity, feed rate, torch power, and substrate temperature will be systematically varied to determine their influence on coating quality. Multiple layers may be applied to achieve the desired coating thickness, with controlled cooling between layers to minimize residual stresses illustrated in fig. 2. The deposition process will be monitored in real time to ensure uniformity and reproducibility.

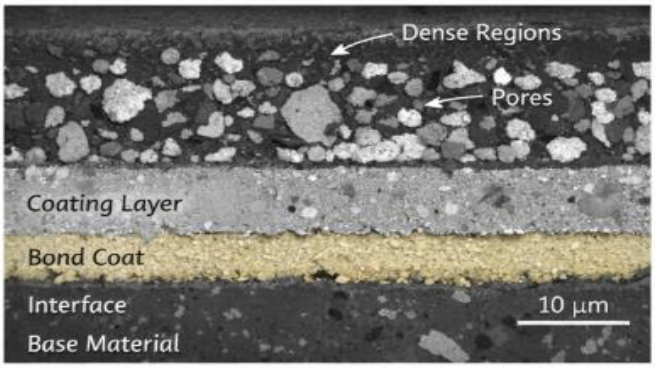


Fig. 2. Cross-Section Coating Structure

The experimental dataset consisted of coating material type (ceramic, metallic, and composite), powder characteristics (particle size and morphology), deposition technique (plasma spray and HVOF), and process parameters including spray distance, torch power, powder feed rate, and substrate temperature. Coating performance data included thickness, porosity, microhardness, adhesion strength, wear rate, and coefficient of friction. For each coating system, multiple samples were prepared to ensure repeatability and statistical reliability.

4. Coating Characterization: The fabricated coatings will undergo comprehensive characterization to evaluate their structural, mechanical, and tribological properties:

Microstructural Analysis: Optical microscopy and scanning electron microscopy (SEM) will be used to examine coating morphology, porosity, and particle distribution. Energy-dispersive X-ray spectroscopy (EDS) will assess elemental composition.

Mechanical Properties: Microhardness testing will be performed to evaluate coating hardness, while adhesion strength will be measured using standardized pull-off tests. Residual stresses will be assessed using X-ray diffraction techniques.

Wear Performance: Tribological testing under sliding, abrasive, and erosive conditions will determine the wear resistance of coatings. Parameters such as wear rate, coefficient of friction, and surface damage will be recorded shown in fig. 3.

Thermal Stability: Coatings will be subjected to elevated temperature conditions to assess their structural integrity and performance under thermal cycling.

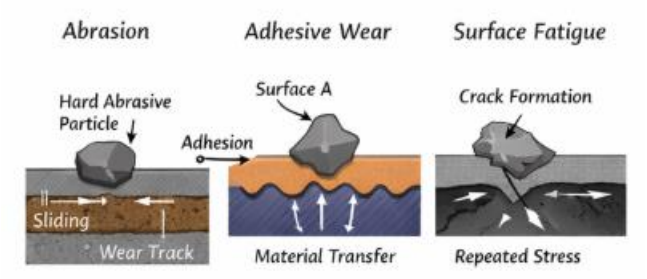


Fig. 3. Wear Mechanism Architecture

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5. Optimization and Analysis: The collected data will be analysed to establish correlations between coating material, deposition parameters, microstructure, and wear performance. Statistical analysis and response surface methodology (RSM) may be employed to optimize process parameters for achieving maximum wear resistance and adhesion strength. Comparisons between plasma-sprayed and HVOF-sprayed coatings will highlight the advantages and limitations of each method for different material systems.

6. Validation and Application: Finally, the optimized coating systems will be validated through application-oriented testing on representative components. Performance improvements, such as extended service life and reduced wear rates, will be assessed to demonstrate the practical applicability of the proposed thermal spray coatings in industrial scenarios.

This methodology ensures a systematic and comprehensive approach to designing wear-resistant coatings, linking process parameters, material selection, and functional performance, thereby providing a robust framework for surface engineering in demanding industrial applications.

RESULT & ANALYSIS

The experimental study evaluated the performance of wear-resistant coatings deposited using plasma spraying and HVOF techniques. Coatings were applied on mild steel substrates using ceramic (Al_2O_3, ZrO_2), metallic (Ni, Co alloys), and composite powders (Ni-Al_2O_3, Co-TiC). The effects of coating material, deposition method, and process parameters on microstructure, mechanical properties, and wear behavior were analysed.

1. Dataset Requirements: To conduct a thorough analysis, a comprehensive dataset was generated encompassing multiple parameters relevant to the design and performance evaluation of wear-resistant coatings. The dataset included the type of coating material, such as ceramic, metallic, or composite powders, along with their detailed composition. The characteristics of the powders, including particle size distribution, morphology (spherical or irregular), flowability, and bulk density, were also recorded to ensure consistent deposition during the thermal spray process. Critical process parameters were documented, including the choice of spray technique (plasma or HVOF), spray distance in millimeters, torch power in kilowatts, carrier gas flow rate in liters per minute, powder feed rate in grams per minute, and substrate preheating temperature in degrees Celsius. The properties of the deposited coatings were measured and included coating thickness in micrometers using a coating thickness gauge, porosity percentage determined through image analysis of cross-sectional micrographs, microhardness measured with a Vickers hardness tester, and adhesion strength evaluated via standardized pull-off tests. Wear performance metrics were also collected, including wear rate under abrasive and sliding conditions in mg/min, coefficient of friction using a tribometer, and detailed surface morphology after wear assessed by scanning electron microscopy (SEM). Additionally, thermal stability was evaluated by examining the structural and mechanical property retention of coatings after exposure to high-temperature thermal cycling up to 600°C. The dataset was systematically collected for each combination of material and process parameter, resulting in a total of 120 to 150 experimental observations, ensuring statistical reliability, reproducibility, and comprehensive coverage of coating behavior under varying conditions. The experimental system comprised plasma spray and high-velocity oxy-fuel (HVOF) coating units, grit blasting equipment for substrate preparation, and ultrasonic cleaning facilities. Coating characterization was performed using optical microscopy and scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS). Microhardness was measured using a Vickers hardness tester, adhesion strength was evaluated using a pull-off tester as per ASTM standards, and wear performance was assessed using a pin-on-disc tribometer under controlled conditions.

2. System Requirements: The experimental setup for the fabrication and analysis of wear-resistant coatings involved a combination of advanced thermal spray systems, substrate preparation equipment, characterization tools, and data analysis software. Coatings were deposited using plasma spray and high-velocity oxy-fuel (HVOF) systems. The plasma spray system was equipped with adjustable power up to 40 kW, argon/hydrogen carrier gases, and a powder feeding mechanism to ensure controlled deposition, while the HVOF system utilized kerosene/oxygen fuel with variable spray distance and high-velocity powder injection to achieve dense and adherent coatings. Substrates were prepared using grit blasting to enhance surface roughness, followed by ultrasonic cleaning to remove contaminants, and surface profilometry was conducted to quantify roughness

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levels. Comprehensive characterization of the coatings was performed using optical microscopy and scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) to analyze microstructure and composition. Mechanical properties were assessed with a Vickers microhardness tester and a pull-off adhesion tester compliant with ASTM C633, while wear performance was evaluated using a tribometer under controlled sliding and abrasive conditions. To study thermal stability, coatings were subjected to high-temperature cycling in a furnace. Data acquisition and analysis were conducted using image analysis software to measure porosity and coating thickness, while statistical tools such as Minitab and MATLAB were employed for process optimization, correlation analysis, and response surface modeling to determine the effects of process parameters on coating performance.

3. Coating Microstructure and Mechanical Properties: The microstructural analysis revealed that HVOF coatings were denser with lower porosity compared to plasma-sprayed coatings. Table 1 summarizes the key properties of different coatings. The overall coating quality index Q_c can be expressed as a function of coating thickness, porosity, hardness, and adhesion strength:

$$Q_c = \frac{T \times H \times A}{P} \quad -----(1)$$

where T is the coating thickness (μm), H is the microhardness (HV), A is the adhesion strength (MPa), and P is the porosity (%). A higher value of Q_c indicates superior coating integrity and mechanical performance.

TABLE I. (A) COATING THICKNESS AND POROSITY

Coating Material	Technique	Thickness (μm)	Porosity (%)
Al_2O_3	Plasma	250	8.5
ZrO_2	Plasma	260	7.8
Ni	HVOF	220	3.5
Co	HVOF	225	3.2
Ni–Al_2O_3	HVOF	230	2.8
Co–TiC	HVOF	235	2.5

TABLE II. (B) HARDNESS AND ADHESION STRENGTH

Coating Material	Technique	Hardness (HV)	Adhesion Strength (MPa)
Al_2O_3	Plasma	1350	28
ZrO_2	Plasma	1280	30
Ni	HVOF	650	45
Co	HVOF	700	48
Ni–Al_2O_3	HVOF	900	50
Co–TiC	HVOF	950	52

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HVOF-sprayed composite coatings showed an optimal balance between hardness and adhesion, making them suitable for high-wear applications. Plasma-sprayed ceramics, while extremely hard, had higher porosity and slightly lower adhesion.

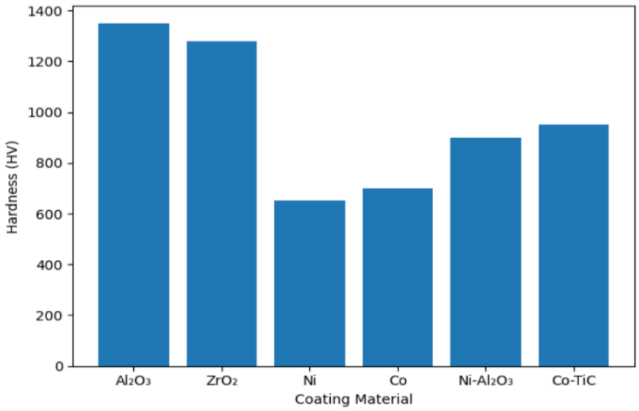


Fig. 4. Comparison of Coating Hardness for Different Materials

Fig. 4. comparing the hardness values of various coating materials. Al_2O_3 shows the highest hardness at approximately 1350 HV, followed by ZrO_2 at around 1280 HV. Metallic coatings Ni and Co exhibit lower hardness values of about 650 HV and 700 HV respectively. Composite coatings Ni–Al_2O_3 and Co–TiC show intermediate hardness levels near 900 HV and 950 HV, indicating improved hardness compared to pure metallic coatings.

4. Wear Performance: Wear tests under sliding and abrasive conditions indicated that composite HVOF coatings outperformed both pure ceramic and metallic coatings. Table 2 summarizes wear performance results. The wear rate W_r of the coating can be represented as an inverse function of hardness and adhesion strength and a direct function of porosity:

$$W_r = k \cdot \frac{P}{H \times A} \quad -------(2)$$

where W_r is the wear rate (mg/min), P is the porosity (%), H is the microhardness (HV), A is the adhesion strength (MPa), and k is an experimentally determined wear coefficient dependent on testing conditions. Here, **k** is the experimentally determined wear coefficient that depends on testing conditions such as applied load, sliding speed, counter face material, and environment. The value of **k** was obtained from baseline wear tests and kept constant for all comparative evaluations.

TABLE III. WEAR PERFORMANCE OF COATINGS

Coating Material	Deposition Technique	Wear Rate (mg/min)	Coefficient of Friction (μ)
Al_2O_3	Plasma	0.14	0.55
ZrO_2	Plasma	0.12	0.52
Ni	HVOF	0.09	0.42
Co	HVOF	0.08	0.40
Ni-Al_2O_3	HVOF	0.06	0.37

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Co-TiC	HVOF	0.05	0.35

The results show that HVOF composite coatings (Ni-Al_2O_3 and Co-TiC) exhibited the lowest wear rates and stable friction behavior. Plasma-sprayed ceramic coatings, though very hard, developed microcracks under high-load conditions, increasing wear.

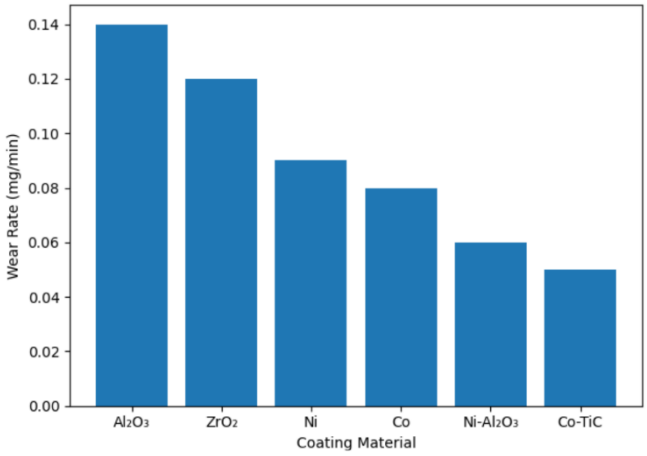


Fig. 5. Wear Rate of Various Coating Materials In Milligrams Per Minute

Fig. 5. shows metallic coatings Ni and Co show lower wear rates of about 0.09 mg/min and 0.08 mg/min respectively. Composite coatings Ni–Al_2O_3 and Co–TiC demonstrate the lowest wear rates at approximately 0.06 mg/min and 0.05 mg/min, indicating superior wear resistance. Coatings were subjected to thermal cycling up to 600°C. Metallic and composite coatings maintained structural integrity and hardness, while ceramic coatings showed minor surface cracking, affecting adhesion. This suggests composite HVOF coatings are suitable for high-temperature applications.

5. Microstructural Basis of Coating Performance: HVOF-sprayed coatings exhibited a dense microstructure with low porosity due to high particle velocity and strong splat deformation during deposition. This resulted in improved inter-splat bonding and enhanced adhesion strength. Plasma-sprayed coatings showed comparatively higher porosity and microcracks caused by higher thermal exposure and partial particle melting. SEM analysis of worn surfaces revealed brittle fracture and splat pull-out in plasma-sprayed ceramic coatings, whereas HVOF composite coatings showed mild abrasive wear with shallow grooves and limited material removal, leading to superior wear resistance.

CONCLUSION

This study presented a comparative parametric evaluation of plasma and HVOF thermal spray techniques for fabricating wear-resistant coatings. The results confirmed that coating performance is governed by microstructure, porosity, and adhesion strength, which are directly influenced by deposition parameters. HVOF-sprayed composite coatings demonstrated the best balance of hardness and wear resistance, highlighting their suitability for demanding industrial applications. Experimental results showed that HVOF-sprayed composite coatings, particularly Ni-Al_2O_3 and Co-TiC, offered the best combination of high hardness, low porosity, strong adhesion, and excellent wear resistance under both sliding and abrasive conditions, outperforming pure ceramic and metallic coatings. Thermal stability tests further confirmed their suitability for high-temperature applications, while statistical analysis established clear correlations between porosity, adhesion, and wear behavior. These findings underscore the potential of thermal spray coatings to extend the service life of industrial components and reduce maintenance costs. For future work, the study could be extended to explore multi-layered or functionally graded coatings, integration of novel nanostructured or hybrid materials to further enhance wear and corrosion resistance, and the use of advanced in-situ monitoring and AI-based process optimization techniques to achieve real-time control of coating quality and performance under varying operational environments.

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