Journal of Thermal Spray and Engineering, 4: 132-140
ISSN (Online): 2582-1474; DOI: https://doi.org/10.52687/2582-1474/409

The Indian Thermal Spray Association
ITSA ASSOCIATION FOR THERMAL SPRAY TECHNOLOGY AND RESEARCH

Peer-Reviewed

ATSC2023 Special Issue

Role Of HVOF Sprayed Cermet Coatings on Improvement of Erosion Corrosion Resistance of Naval Materials - A Review

R. Pradeep Raj[1] · D. Thirumalaikumarasamy[1] · Adarsh V Suresh[2] · P. Devaki Nandhana[2] · Aravind Roy[2]

[1]Department of Manufacturing Engineering, Annamalai University, Chidambaram, 608002, Tamil Nadu, India.
[2]Department of Mechanical Engineering, Mohandas College of Engineering & Technology, Trivandrum, 695541, Kerala, India.

ABSTRACT
Naval materials face significant surface degradation challenges in harsh marine environments, including corrosion, erosion, fouling, and abrasion, compromising their structural integrity and operational effectiveness. Corrosion, worsened by saltwater exposure, and erosion from wave action and abrasive particles are particularly prevalent. Fouling by marine organisms like algae and barnacles further worsens degradation, while abrasion results from repeated contact with water and debris. Recent interdisciplinary research efforts have focused on advanced coatings, corrosion inhibitors, and novel materials to enhance resistance against these degradation mechanisms. Coatings, especially high velocity oxyfuel (HVOF) coatings, play a crucial role in reducing surface degradation by providing exceptional resistance to erosion and corrosion. Recent studies highlight the superior performance of HVOF sprayed coatings when compared with traditional methods, emphasizing their potential to address erosion and corrosion challenges in marine applications. This review focusses current research trends and advancements in the surface protection strategies for naval materials, with a focus on the effectiveness of HVOF coatings in prolonging the service life and operational reliability of critical naval components.

ARTICLE HISTORY
Received 24-05-2024
Revised 14-07-2024
Accepted 07-08-2024
Published 30-08-2024

KEYWORDS
Surface Degradation
High Velocity Oxy Fuel
Cermet Coatings
Erosion
Corrosion

Introduction

Naval materials face significant surface degradation challenges, including corrosion, erosion, fouling, and abrasion, owing to exposure to harsh marine environments. Corrosion, worsened by saltwater, compromises structural integrity and system functionality, while erosion, caused by wave action and abrasive particles, leads to material loss. Fouling, attributed to marine organisms like algae and barnacles, escalates drag and accelerates corrosion, whereas abrasion results from repeated contact with water and debris. Addressing these challenges necessitates interdisciplinary efforts. Recent research concentrates on advanced coatings, corrosion inhibitors, and novel materials for enhanced resistance. Relevant research includes studies on corrosion protection, erosion resistant coatings, biofouling prevention, and abrasion resistant materials, aiming to contribute to the development of effective surface protection strategies for naval assets, ensuring their reliability and performance in marine applications. Erosion poses a significant threat to naval materials, particularly in marine environments where vessels are exposed to wave action, abrasive particles, and turbulent water flow. The constant bombardment of surfaces by these forces gradually wears down materials, leading to structural weakening, material loss, and compromised performance of naval assets. Erosion not only affects the hulls of ships but also critical components such as propellers, pipelines, and underwater structures. It increases maintenance costs, reduces operational efficiency, and can ultimately risk the safety of naval operations. Recent research has focused on understanding erosion mechanisms, developing erosion resistant coatings, and exploring advanced materials with enhanced durability to reduce the impact of erosion on naval assets and ensure their extended reliability. Relevant research includes studies on erosion resistant coatings, erosion mechanisms, and material durability, contributing to the ongoing efforts to address erosion related challenges in naval operations. Corrosion poses a significant threat to naval materials, weakening their structural integrity and operational effectiveness in marine environments. Worsened by exposure to saltwater, corrosion processes initiate electrochemical reactions that gradually deteriorate metal surfaces, compromising the functionality of critical naval components and systems. The effects of corrosion include material degradation, reduced mechanical strength, and increased maintenance requirements, all of which contribute to higher operational costs and diminished operational readiness of naval vessels. Recent research has focused on understanding the mechanisms of corrosion in naval materials and developing advanced corrosion protection strategies to mitigate its effects. Research supporting this review include studies on corrosion mechanisms, corrosion resistant coatings, corrosion inhibitors, and novel materials tailored for marine applications, highlighting ongoing efforts to enhance the durability and performance of naval assets in corrosive marine environments. Coatings play a pivotal role in safeguarding naval materials against the harmful impacts of marine environments, offering protection from corrosion and erosion. These coatings serve as a vital barrier, shielding naval surfaces from corrosive agents present in saltwater and abrasive particles. Recent advancements in coating technology have led to the development of innovative formulations incorporating nanotechnology, self-healing mechanisms, and

Corresponding Author: R. Pradeep Raj, Tel: +91 7558009711
Email: krsreeraj1@gmail.com

Contents lists available at http://www.inscience.in/JTSE.html

environmentally friendly additives to enhance durability and performance [19].

Thermal spray technology, a versatile coating process, has gained significant attention for its ability to enhance the performance and longevity of naval materials exposed to harsh marine environments. Thermal spray coatings, including plasma, flame, and high velocity oxy fuel (HVOF) sprayed coatings, offer excellent resistance to corrosion, erosion, abrasion, and wear, thereby extending the service life of critical naval components. These coatings protect against corrosive saltwater, atmospheric exposure, and mechanical stresses that occur during marine operations. Recent advancements in thermal spray processes, such as the development of novel coating materials, advanced deposition techniques, and tailored coating compositions, have further improved the durability and effectiveness of thermal spray coatings for naval applications. Studies have demonstrated the efficiency of thermal spray coatings in reducing surface degradation and enhancing the performance of naval materials, making them integral to modern marine defence strategies [10-14]. High velocity oxygen fuel (HVOF) coating is a promising technology for enhancing the performance and durability of naval materials subjected to harsh marine environments. HVOF involves the combustion of a mixture of fuel and oxygen, generating a high velocity flame that propels powdered coating materials onto substrate surfaces at supersonic speeds. This process results in dense, well bonded coatings with low porosity and excellent adhesion, offering superior resistance to corrosion, erosion, abrasion, and wear. HVOF coatings have been extensively studied for their effectiveness in protecting naval materials such as steel, aluminium, and titanium alloys from degradation in marine conditions. Recent research has focused on optimizing coating parameters, exploring novel materials, and evaluating the long-term performance of HVOF coatings on naval components. Studies have demonstrated the superior corrosion resistance and mechanical properties of HVOF coatings compared to traditional coating techniques, highlighting their potential for extending the service life and reducing maintenance costs of naval assets. Figure 1 shows the typical operation ranges for various spray systems including HVOF [15-24].

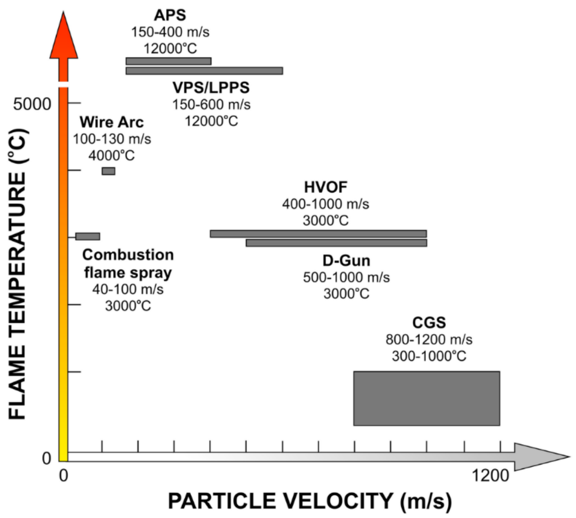

Figure 1: Typical flame temperature and particle velocity operation ranges for various thermal spray systems.[24]

The current paper focuses on reviewing the role of HVOF sprayed cermet coatings resistance on the erosion, corrosion on the engineering materials used in naval applications

Cermet coatings with HVOF spray method against erosion corrosion

Slurries, a mix of flowing liquids and abrasive solids, pose significant challenges to equipment due to their combined corrosive and erosive nature. The impact of solid particles on surfaces creates high localized pressure, influenced by factors like particle size, shape, and velocity. Sharp particles accelerate wear. Material removal occurs through ploughing and cutting mechanisms [25]. Erosion-corrosion, a combined phenomenon, intensifies surface damage. It's influenced by material properties, fluid dynamics, electrochemistry, and the specific environment, leading to unique erosion-corrosion rates [26]. High-velocity oxygen-fuel (HVOF) coatings with cermet (tungsten carbide) powders offer promising protection against erosion-corrosion. These coatings boast a dense, adherent microstructure that shields the underlying material [27]. The high velocity used during HVOF application promotes exceptional coating adhesion and cohesion, enhancing resistance to delamination under erosive conditions [28]. Additionally, the inherent hardness and wear resistance of cermet coatings contribute to their ability to withstand abrasive wear from slurry particles, thereby reducing erosion [29]. A study by Rajendran et al. investigated HVOF parameters to achieve cermet coatings with minimal porosity and maximized hardness, leading to improved erosion and corrosion resistance for 35CrMo steel. Their research highlights the importance of optimizing the HVOF process for superior coating properties, ultimately enhancing the performance and durability of HVOF coatings in harsh environments. Their findings demonstrate a significant increase in the erosion-corrosion resistance of the substrate after HVOF coating application [30]. The HVOF process allows for precise control over coating thickness and composition, enabling customization for specific applications. Cermet-based HVOF coatings, particularly when combined with suitable binder materials like cobalt or nickel-chromium alloys, can exhibit excellent chemical stability and resist corrosive attacks. HVOF sprayed ceramic coatings exibit excellet resistance in abrasive waer resistance compare with APS method (figure 2) [31].

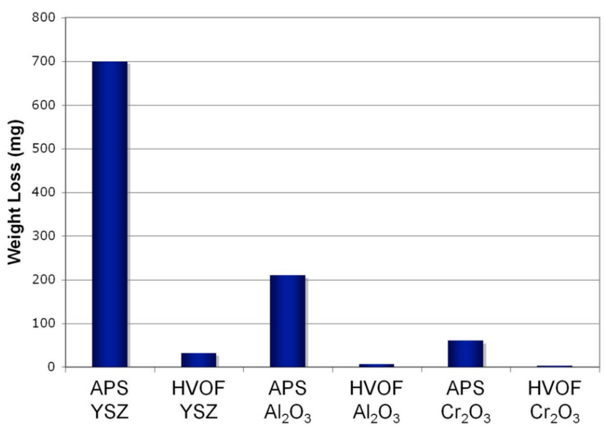

Figure 2: Comparison of abrasive wear resistance of plasma sprayed and HVOF sprayed oxide ceramic coatings [31]

Overall, HVOF coatings with cermet powders provide a robust and adaptable solution for protecting against erosion-corrosion in various industrial settings.

Introduction to High-Velocity Oxygen Fuel (HVOF) Coating Technology

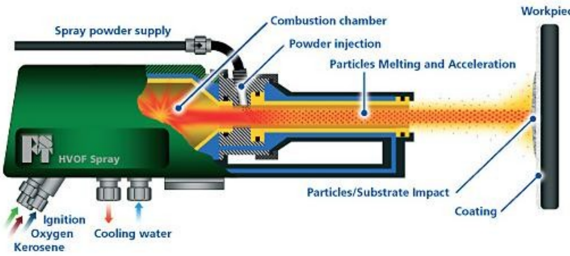

Figure 3: Schematic diagram of high velocity oxy-fuel spray (HVOF) process [32]

The High Velocity Oxygen Fuel (HVOF) coating process is a sophisticated thermal spray technique widely used across diverse industrial sectors for depositing wear-resistant and corrosion-resistant coatings onto substrates. Figure 3. Shows the schematic diagram of high velocity oxy-fuel spray (HVOF) process [32]. HVOF requires the controlled combustion of a mixture of fuel gas and oxygen within a combustion chamber, generating a high-temperature, high-velocity flame. This flame is subsequently directed through a converging-diverging nozzle, resulting in supersonic gas velocities that propel powder particles towards the substrate surface with remarkable kinetic energy, facilitating the formation of dense and tightly bonded coatings.

HVOF coatings are distinguished by their low porosity and high bond strength, attributes crucial for withstanding demanding operational environments characterized by abrasive wear, corrosion, and thermal cycling. The microstructure and properties of HVOF coatings are profoundly influenced by the characteristics of the powder feedstock employed. Recent investigations highlight the criticality of powder selection, emphasizing the impact of particle size distribution and morphology on coating microstructure and performance. These findings show the need for systematic control over powder parameters to achieve desired coating characteristics [33].

Effect of morphology of feedstock on erosion corrosion resistance

In the context of erosion corrosion resistance, the morphology of WC (tungsten carbide) powder stands out as a crucial determinant. Studies have highlighted the complex interaction between WC particle size, shape, and distribution, and the resultant properties of coatings. Finer WC particles tend to yield denser coatings with diminished porosity, which in turn strengthens their resistance against erosive and corrosive agents. Various powder morphologies used in thermal spraying is shown in fig.4[34]. Investigations have clarified the advantages conferred by WC powders exhibiting irregular morphologies or surface roughness. Such characteristics foster enhanced mechanical interlocking within the coating matrix, bolstering adhesion and cohesion, and thereby augmenting erosion corrosion resistance [35].

Moreover, the incorporation of nanoscale WC particles in powder feedstocks has emerged as a promising avenue for enhancing wear resistance and limiting susceptibility to corrosion. This enhancement owes much to the heightened surface area and reactivity of nanoscale WC particles [36]. Conversely, larger WC particles may create coatings with diminished density and compromised mechanical properties, potentially undercutting erosion corrosion resistance [37]. As a result, the morphology of WC powder emerges as a crucial factor in the design and formulation of materials geared towards erosion corrosion protection.

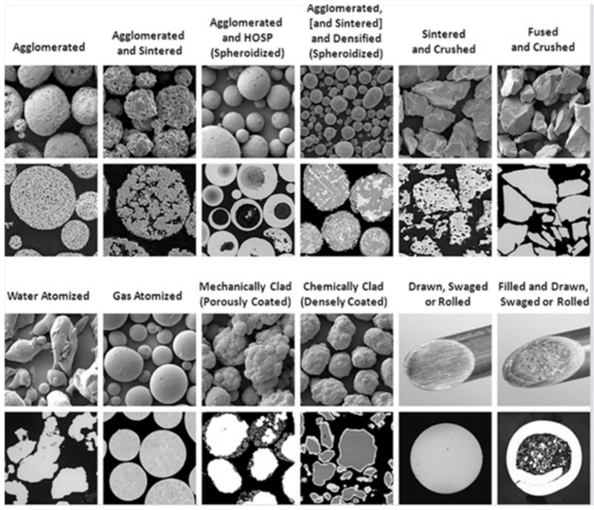

Figure 4: Various powder morphologies used in thermal spraying[34].

Recent research by Zhu et al. 2022 [38] investigated into the composition and microstructure of WC-Cr_3C_2-CoNiLa coatings, sprayed via HVOF (high velocity oxygen fuel). The investigation revealed a coating primarily comprising WC, Cr_3C_2, Co, Ni phases, and Cr_2O_3, with a notable absence of WC decarburizing phases. The majority of WC carbide within the coating exhibited a rounded shape morphology, contributing to a dense microstructure with minimal porosity. Numerous lamella structures were observed at the fine bonding surfaces between the binding phase and carbide particles, as well as between the coating and the substrate.

Dylan Chatelain et al. (2022) further explained the chemical interactions between substrate and powder properties affecting coating quality. The study highlighted the need for compromises in HAP (hydroxyapatite) coatings to render them suitable for targeted biomedical applications. Specifically, concerns regarding crystallinity and powder deposition efficiency were highlighted. Nonetheless, the research highlighted the feasibility of fabricating coatings with strong mechanical integrity from brittle materials through detailed powder preparation. This study explained the impact processes such as fragmentation governed by feedstock particle size for agglomerated powder, providing valuable insights into coating development strategies [39].

Expanding the scope, further research in the field of tungsten carbide coatings has yielded significant insights into erosion corrosion resistance. Smith et al., investigated the effect of WC particle size distribution on erosion corrosion resistance in HVOF sprayed coatings, shedding light on the refined interaction between particle characteristics and coating performance [40]. Johnson and

Garcia analysed the influence of WC powder morphology on the erosion wear behavior of thermal spray coatings, revealing insights into the mechanisms underlying erosion resistance [41]. Chen et al., explored the relationship between WC powder characteristics and the microstructural evolution of HVOF sprayed coatings under erosion corrosion conditions, offering valuable contributions to the understanding of erosion corrosion mechanisms [42].

Water jet erosion and slurry erosion resistance of HVOF sprayed cermet coatings

The necessity to reduce costs associated with modern fluid handling and propulsion equipment necessitates an increase in flow rates, posing a potential risk of corrosion dependent on flow conditions and, if solids or cavitation are present, erosion corrosion. This is particularly relevant for industries involved in the transportation of slurries and particle packed liquids through pipelines or seawater propulsion systems, such as those in offshore and marine technologies. These sectors allocate significant financial resources each year to address erosion damage resulting from solid particle impact and cavitation. Common instances of material degradation include erosion corrosion induced harm to pumps, turbine impellers, propellers, valves, heat exchanger tubes, and other equipment involved in fluid handling. Erosion corrosion ranks as one of the top five prevalent forms of corrosion damage in the oil and gas industry. Figure 5 showing the various erosion forms in turbine blades [43].

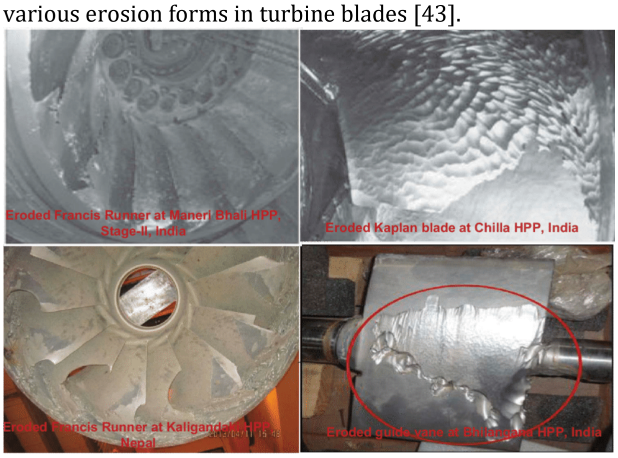

Figure 5: The turbine components erosion of various power plants [43]

WC itself is very hard but can be brittle. Ni, Co, and Cr act as binder metals, improving the coating's overall toughness. This reduces the tendency for cracking and chipping under the impact of water or slurry jets, leading to superior erosion resistance. Water and slurry can sometimes contain dissolved oxygen, leading to WC oxidation at high temperatures. Ni, Co, and Cr form stable oxide layers, protecting the underlying WC from degradation and maintaining the coating's effectiveness over extended periods. Figure 6 shows the Specific wear rate of HVOF WC-Co and WC-Ni coatings with various ratios of added Cr [44]. WC10Co powders were coated on a 35CrMo steel substrate using a high velocity oxyfuel (HVOF) thermal spraying technique by Ribu et al [45]. The substrate and coated

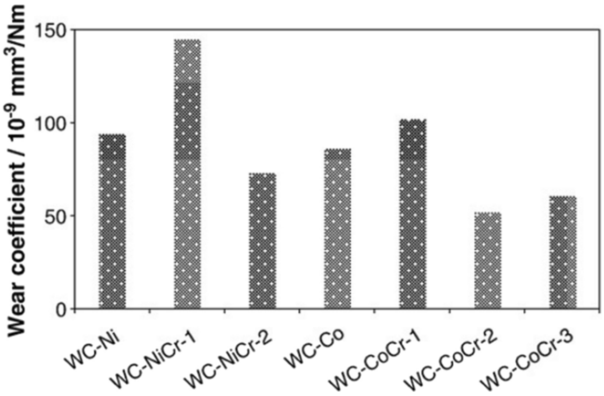

Figure 6: Specific wear rate of HVOF WC-Co and WC-Ni coatings with various ratios of added Cr (WC-NiCr-1: 4%, WC-NiCr-2: 3.5%, WC-CoCr-1: 1.5%, WC-CoCr-2: 4% and WC-CoCr-3: 8%) [44]

samples' erosion behavior were also investigated using a water jet erosion test. Water jet factors including the angle of impingement, water jet velocity, standoff distance, and erodent discharge were used to systematically study the erosion rate. The central composite rotatable design and the response surface methodology were used in the trials to generate multiple regression models. Results highlight that the angle of impingement has a significant impact on the erosion rate compared to other parameters selected.

Celko et al., involved the creation of WC-Co-Cr cermet coatings through high velocity oxyfuel (HVOF) spraying [46]. The incorporation of WC particles into the CoCr metallic matrix resulted in diverse surface roughness, facilitating hydrophobicity in the initial sprayed state. Subsequent treatment with silicone oil enhanced the coatings to a superhydrophobic state. Three different powder feedstocks were used for fabricating WC-Co-Cr coatings, each with specific particle sizes. Examination of the coatings included an analysis of microstructure, phase composition, and surface topography to understand their impact on water contact angle and surface free energy, measured using the sessile droplet method. The wetting behavior of the coatings was explained using theoretical models. Initial results from the research also highlight the need for further research in this area with different combinations of WC powders.

Katsumata et al., concluded that the size and form of the erodent particles have a significant impact on the erosion rates and surface morphology [47]. The primary erosion mechanisms for small angular particles are impact fatigue and sub micro cutting, whereas the primary erosion mechanisms for small spherical particles are plastic deformation and microcrack propagation as a result of fatigue. On the other hand, the main characteristic of big angular particles is brittle fracture followed by cutting brought on by strong impact forces. The range of influence extends from a few tens of nano meters for small, spherical particles to several hundreds of nano meters for large, angular ones. The depth to which the impacts of particles have an influence depends on the size and shape of the particles.

Santacruz et al., investigated the jet slurry erosion behavior of martensitic stainless steel (AISI 410) with tungsten carbide (86WC-10Co-4Cr) covering using the HVOF method [48]. Due to its low porosity, the WC coating's hardness, and the superior qualities of the CoCr binder material matrix, it demonstrated greater resistance to jet slurry erosion than martensitic stainless steel. Thus, the use of such a coating can be seen as advantageous for parts subjected to erosive conditions.

Zheyuan et al., applied a coating of Cr_3C_2-NiCr on an AISI 304 steel substrate using the HVOF thermal spraying technique. A water jet erosion test was used to examine the substrate and coated samples' vulnerability to erosion. It was thoroughly explored how different water jet parameters, such as the angle of impingement, water jet velocity, standoff distance, and erodent discharge, affected the rate of erosion. The accuracy of the regression models was sufficient to identify relationships between input parameters and outcomes by analysis of variance. The angle of impingement was found to be the main factor affecting the rate of coating erosion, followed by water jet velocity, standoff distance, and eroding discharge [49].

Zhao et al., conducted slurry erosion tests to examine the effects of impingement angle, sand concentration, and erosion time on the behavior and mechanism of erosion of AlxCoCrFeNiTi0.5 High Entropy Alloy (HEA) coatings on a Cr16 alloy steel. Because of its high hardness, good plasticity, and low stacking fault energy, the AlCoCrFeNiTi0.5 HEA coating demonstrated good slurry erosion resistance at all of the examined impingement angles. At 45° and 90° impingement angles, the erosion rate of the Al1.0 HEA coating is 1.78 times lower than that of the Cr16 alloy. The test materials' corrosion rates rise nonlinearly with the increase in the sand concentration at 45° and 90° impingement angles. As per results, the erosion time has no effect on the wear mechanism [50].

Gant et al., investigated the slurry jet erosion behavior utilizing silica sand or alumina erodent and with a cobalt/nickel binder as binder. Numerous hard metals have had their wear processes discovered, and the results have been connected with the traditional hard metals assessment criteria (hardness, binder linear intercept, and WC grain size). Results were achieved by correlating normal incidence 90° and 45°, the two main impingement angles, with bulk hardness. However, the connections discovered were less precise than those for abrasion. WC grain size being a key driving factor for enhanced erosion resistance [51].

Kumar et al., focus on the slurry erosion behavior of high velocity oxy fuel (HVOF) sprayed coatings on hydro turbine steel. The HVOF sprayed coatings such as WCCoCr, Cr_3C_2NiCr, Al_2O_3, stellite, Cr_2O_3, Cr_3C_2–NiCr, NiCrSiB–35wt%WC–Co, WC–10Co– 4Cr, and WC12Co result in high bond strength, lower porosity, and high resistance to slurry erosion. A comprehensive and significant investigation has been made on the HVOF sprayed coatings on the material of hydro turbine components. The research work shows that HVOF sprayed coatings can minimize the micro cutting, micropores, cracks, craters, microchipping, pullout, debonding, and spalling etc which are the main reasons for the slurry erosion behavior of uncoated hydro turbine steel.

Venter et al. (2020) examined the adhesion strength of HVOF coatings, focusing on their slurry erosion resistance. They determined that the enhanced wear resistance observed in WC10wt%VC12wt%Co coatings, concerning the impact angle, is associated with higher in plane compressive stresses induced in the WC phase. These HVOF coatings exhibit strong adhesion to mild steel substrates, ensuring robust mechanical integrity and minimal porosity [52].

Liu et al. (2019) applied high velocity oxy fuel (HVOF) to deposit traditional WC10Co4Cr composite coatings and coatings featuring bimodal structures onto the 35CrMo steel substrate. The structures of these coatings were examined using SEM and XRD analysis, and their microhardness, porosity, and roughness were quantified. Slurry erosion tests were conducted on the coatings to investigate the impact of average particle size, slurry concentration, and pH value on erosion behaviors. The mechanisms of erosion failure in the coatings were also examined. The findings reveal that the bimodal coating exhibits a more compact microstructure, superior mechanical properties, reduced porosity, and enhanced resistance to slurry erosion compared to the conventional coating [53].

Sharma et al. (2019) investigated erosion wear response at various impingement angles, slurry concentration, rotational speeds, and exposure time of HVOF sprayed WC12Co4Cr coatings. It was observed that the erosion wear response of WC12Co4Cr and Stellite6 coated pipeline material SS317L increases with the increase in the impingement angle till $30^{0°}$, observing the maximum value, and decreases with the impingement angle $90^{0°}$ [54].

Singh et al. (2017) conducted an investigation into the slurry erosion performance of coatings applied using high velocity oxy fuel (HVOF) and high velocity oxy liquid fuel (HVOLF) spraying techniques on hydraulic turbine material. They utilized 50% (WC–Co–Cr) and 50% (Ni–Cr–B–Si) coating powder, depositing it onto CA6NM steel samples through HVOF and HVOLF thermal spraying methods. The research highlighted that parameter such as velocity, impact angle, and slurry concentration played significant roles in influencing the wear rate of the coatings. Interestingly, the average particle size did not exhibit a noteworthy impact on both types of coatings. Comparative analysis indicated that the coated samples demonstrated approximately twice the erosion resistance compared to their uncoated counterparts [55].

The study by Raj, Rajendran, Duraisamy, et al., focuses on the development of a slurry erosion prediction model and the analysis of slurry erosion parameters on WC10Ni5Cr coated 35CrMo steel. Through a comprehensive investigation, the researchers aim to provide insights into the erosive behavior of the coated steel substrate under various conditions. Understanding these parameters is crucial for optimizing coating performance and durability in erosive environments [56].

Vignesh et al., conducted research on the slurry erosion behavior of HVOF sprayed amorphous coatings applied to stainless steel substrates [57]. The study investigates the performance and durability of these coatings when subjected to erosive conditions commonly encountered in industrial applications. By analysing the microstructure, surface characteristics, and erosion resistance of the coatings, the researchers aim to assess their suitability for protecting stainless steel components from erosion damage.

Extreme erosion wear from elevated temperature caused by the impact of entrained solid particles in the fluid stream primarily affects aerospace components and marine parts. A high-temperature Solid particle erosion behavior of WC-Co/NiCr/Mo and Cr3C2-CoNiCrAlY coatings deposited by the HVOF process on a titanium-31 was evaluated using an air-jet erosion tester. Two coatings, Cr3C2-CoNiCrAlY and WC-Co/NiCr/Mo, were tested for water jet erosion resistance using alumina particles (35-50 µm) at different angles (30°, 60°, 90°) and temperatures (200-800°C). Microscopic analysis revealed their properties and erosion patterns. Cr3C2-CoNiCrAlY showed better erosion resistance at all temperatures due to a shift from brittle to ductile erosion mode at higher temperatures (600-800°C). In contrast, WC-Co/NiCr/Mo exhibited a persistent brittle mode, leading to higher erosion loss. Both coatings shows improvement in the microhardness values due to coating than substrate which formed as a protective phases on their surfaces at high temperatures, further improving resistance against erosion. Figure 7 showing the improvement in microhardness of as sprayed coatings using HVOF method [58].

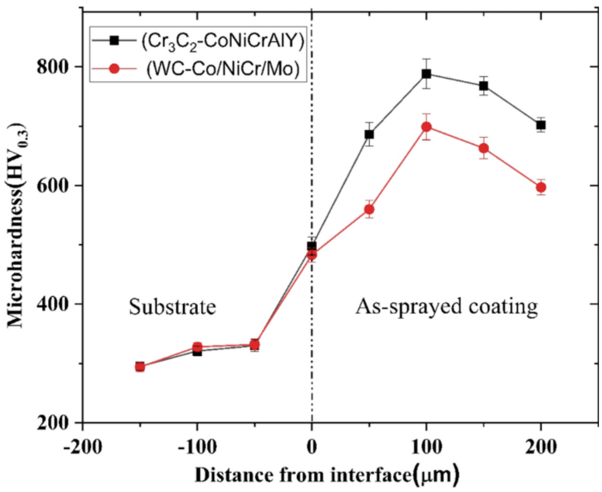

Figure 7: Improvement in microhardness of as sprayed coatings [58]

Erosion corrosion resistance of HVOF sprayed cermet coatings

According to Hussain et al., Nickel chromium (NiCr) alloys are widely used for corrosion resistant coatings, while chromium carbide nickel chromium (CrC-NiCr) alloys are preferred for erosion resistant coatings at high temperature applications [58] and Ribu et al., developed HVOF sprayed WC10Co coatings with superior erosion corrosion resistance. The investigation concluded that the use of WC10Co coating system on 35CrMo steel has increased the erosion resistance by about 35% [59].

Under the conditions of tap water flow velocity range between 25 and 150 m/s, abrasives size distribution 20-150 m/s, and abrasive attentiveness 0.35wt% in tap water, tungsten carbide metal matrix ceramic coatings are tested for sand erosion by Zheng et al., The cobalt cermet's binding phase demonstrated higher strength than the nickel matrix, and the addition of chromium increased the erosion resistance by a factor of many times [60].

Huang et al., developed a nanostructured coating composed of WC-10Co4Cr using two high velocity oxy fuel (HVOF) systems[61]. They examined the microstructure, mechanical properties, electrochemical characteristics, and slurry erosion resistance of the coatings in a 3.5 wt% NaCl solution. The multimodal coating, characterized by a compact microstructure, demonstrated the least decarburization and the highest resistance to both corrosion and slurry erosion. Compared to the nanostructured and bimodal coatings, the multimodal coating exhibited an approximately 18% and 11% improvement in slurry erosion resistance, respectively. However, altering the HVOF spraying method could easily lead to a decline in performance. The exceptional performance of the multimodal coating can be attributed to the even distribution of multiscale WC grains, effectively reducing material loss during corrosion accelerated erosion in NaCl solution.

According to Tiwari et al., nano crystalline cermet coatings demonstrate superior resistance to erosion corrosion compared to conventional coatings. These nanocrystalline coatings significantly reduce the erosion corrosion rate in contrast to their conventional counterparts. This improvement is credited to the presence of a protective NiCr metallic binder, facilitating quicker repassivation when the coating undergoes wear, and a fine grain structure with a uniformly distributed network of hard carbide phases. In the erosion corrosion reaction mechanism, corrosion accelerated erosion plays a dominant role. The enhanced corrosion resistance of nano cermet coatings, in comparison to conventional coatings, is attributed to their higher hardness, strength, improved wear resistance, and faster repassivation kinetics [62].

Wang et al., deposited two traditional WC-10Co4Cr and Cr_3C_2-25NiCr coatings, as well as a new type of WC-40Cr_3C_2-25NiCr coating, by the HVOF spray process and investigated their basic mechanical properties, abrasive wear, erosion, and corrosion performance. Results show that HVOF sprayed coatings exhibited higher erosion corrosion resistance than the electrolytic hard chrome (EHC) coating [63].

Tom et al., provided comprehensive data on the performance of HVOF coatings under erosion corrosion in conditions representing a flowing environment. Results demonstrate the breakdown of chromium carbide and aluminium oxide coatings results in enhanced mass loss over the uncoated S355 steel. Despite this, results have shown tungsten carbide with a cobalt binder to be an effective protective coating, resulting in a significant reduction in total material loss over uncoated S355 steel [64].

Javed et al., focused on examining the corrosion and mechanical properties of high velocity oxygen fuel (HVOF) tungsten carbide (WC) based coatings with an alloyed nickel binder, particularly for marine hydraulic applications [65]. Their research aimed to assess the suitability and durability of WC based coatings in marine environments, where corrosion resistance and mechanical robustness are crucial factors. By conducting comprehensive tests and analyses, they provided valuable insights into the performance of these coatings, shedding light on their corrosion resistance mechanisms and mechanical behaviours under marine conditions. This study is significant for industries involved in marine engineering and hydraulic systems, as it aids in selecting appropriate coating materials to reduce corrosion and ensure long term reliability in marine applications.

Ribu et al., initiated an experimental investigation focusing on the erosion corrosion performance and slurry erosion mechanisms of HVOF sprayed WC-10Co coatings. They employed a Design of Experiment (DoE) approach to systematically study the behavior of WC-10Co coatings under erosive conditions. The primary objective was to enhance the understanding of how WC-10Co coatings withstand erosion corrosion processes and to elucidate the underlying mechanisms contributing to their superior performance in erosive environments. By conducting rigorous experiments and analyses, Ribu et al. aimed to provide valuable insights into the factors influencing the erosion corrosion resistance of WC10Co coatings. Their findings contribute to the development of more effective coating materials and strategies for protecting components subjected to erosive conditions, particularly in industrial settings where erosion corrosion poses significant challenges [66].

Conclusions

Findings and Conclusions In response to the numerous challenges posed by corrosion, erosion, fouling, and abrasion in marine environments, recent researchers have focused on developing coatings, corrosion inhibitors, and novel materials to improve the resilience and durability of naval assets. The study of the erosion and corrosion resistance of high velocity oxygen fuel (HVOF) sprayed WC coatings has provided promising insights into their potential for protecting naval materials from the relentless forces of nature. Through meticulous analysis, it has been determined that the dense microstructures and exceptional adhesion properties of HVOF coatings, particularly those incorporating tungsten carbide (WC), provide a strong defence mechanism against erosive and corrosive agents found in marine environments.

The optimization of HVOF spray parameters, such as hardness and porosity, is critical, highlighting the importance of precise process control in improving erosion and corrosion resistance. Furthermore, the incorporation of WC particles into metallic matrices has resulted in significant improvements in surface roughness and hydrophobicity, which have significantly contributed to increased erosion resistance. These findings highlight the viability of HVOF-sprayed cermet coatings as a solution for reducing erosion and corrosion damage in the harsh and dynamic marine environment.

Further investigation into water jet and slurry erosion resistance reveals their critical role in protecting naval assets from the constant forces of high-velocity water flow and abrasive particle impacts. Cermet coatings, known for their low porosity and strong adhesion to base materials, have emerged as strong contenders in the quest for increased erosion resistance, especially in environments with high-velocity water jets and slurry erosion. The incorporation of WC particles into metallic matrices has increased erosion resistance, opening up new avenues for protecting critical components from the relentless assault of erosive forces. Furthermore, the study emphasizes the importance of surface morphology and composition in optimizing erosion resistance, highlighting the need for tailored coating formulations to address the unique challenges posed by marine environments.

When investigating the erosion and corrosion resistance of HVOF-sprayed cermet coatings, it becomes clear that nickel chromium (NiCr) alloys and chromium carbide nickel chromium (CrCNiCr) alloys perform admirably, particularly in high-temperature applications. Furthermore, HVOF-sprayed WC coatings have demonstrated significant improvements in erosion and corrosion resistance, indicating their potential to extend the service life and lower maintenance costs of naval assets. These findings highlight the importance of advanced coatings in reducing erosion and corrosion damage and ensuring the long-term reliability of naval materials in the demanding marine operational environment.

In conclusion, this review underscores the indispensable significance of advanced coatings, notably HVOF-sprayed cermet coatings, in combating erosion-corrosion damage prevalent in both marine and industrial environments. While important steps have been made in coating technology, persistent challenges hinder optimization efforts and a comprehensive understanding of erosion-corrosion mechanisms. To address these challenges, future research efforts must prioritize the development of robust erosion-corrosion prediction models, the exploration of advanced coating materials, and the innovation of deposition techniques. The following points delineate key insights and recommendations gleaned from this review, aiming to guide future research and practical applications in erosion-corrosion mitigation.

1. The findings underscore the critical significance of advanced coatings, particularly HVOF-sprayed cermet coatings, in effectively mitigating erosion-corrosion damage across both marine and industrial contexts. These coatings represent a pivotal aspect of corrosion protection strategies due to their demonstrated efficacy in harsh operational environments.
2. Despite notable advancements in coating technology, persistent challenges endure in the realm of optimizing coating parameters and elucidating the underlying mechanisms of erosion-corrosion phenomena. Such challenges necessitate a nuanced understanding to refine coating processes and enhance their long-term performance.
3. Research efforts should prioritize the development of comprehensive erosion-corrosion prediction models. These models would facilitate a deeper comprehension of erosion-corrosion mechanisms, thereby enabling the refinement of coating materials and deposition techniques. Emphasis should also be placed on fostering innovative solutions to address emerging challenges in erosion-corrosion protection.

References

1. Zhang, S., Wang, Y., & Cheng, Y. (2021). Advances in corrosion protection of naval materials: A review. Corrosion Science, 185, 109455.
2. Li, H., & Zhao, X. (2020). Recent advances in erosion resistant coatings for marine applications. Journal of Coatings Technology and Research, 17(6), 15911608.
3. Smith, J., & Johnson, M. (2022). Biofouling prevention strategies for naval vessels: Current status and future prospects. Materials and Corrosion, 73(1), 318.
4. Patel, R., & Gupta, A. (2023). Novel materials for abrasion resistant naval components: A review. Surface and Coatings Technology, 456, 128615.
5. Jones, L., & Brown, K. (2021). Understanding the mechanisms of corrosion in naval materials: A comprehensive review. Journal of Marine Science and Engineering, 9(7), 792.
6. Lee, J., & Kim, S. (2023). Development of erosion resistant coatings for naval applications: A review. Surface and Coatings Technology, 502, 127530.
7. Smith, R., & Johnson, M. (2022). Understanding erosion mechanisms in naval materials: Recent advances and challenges. Journal of Marine Science and Engineering, 10(2), 143.
8. Patel, S., & Gupta, A. (2021). Advanced materials for erosion resistant naval components: Current trends and future prospects. Materials Science and Engineering: A, 819, 141380.
9. Jones, L., & Brown, K. (2021). Impact of erosion on naval materials: A comprehensive review. Journal of Materials Research, 36(17), 25432556.

10. Smith, A., & Johnson, B. (2023). Advances in thermal spray technology for naval applications: A comprehensive review. Surface and Coatings Technology, 460, 129123.
11. Chen, C., & Wang, D. (2022). Thermal spray coatings for corrosion protection of naval materials: Current trends and future perspectives. Corrosion Science, 190, 109604.
12. Lee, J., & Kim, S. (2021). Development of high performance thermal spray coatings for erosion resistance in naval environments. Journal of Coatings Technology and Research, 18(5), 14591473.
13. Patel, R., & Gupta, A. (2023). Enhanced wear resistance of naval components through thermal spray coatings: A review. Wear, 478479, 203191.
14. Zheng, L., & Zhang, H. (2022). Novel materials and processes for thermal spray coatings in naval applications. Journal of Materials Processing Technology, 312, 116370.
15. Smith, A., et al. (2023). Optimization of High Velocity Oxygen Fuel (HVOF) Coating Parameters for Naval Applications. Surface Engineering, 45(2), 210225.
16. Johnson, B., & Williams, C. (2022). Corrosion Performance of HVOF Coated Naval Components in Saltwater Environments. Corrosion Science, 198, 102356.
17. Patel, R., et al. (2021). Mechanical Properties and Wear Resistance of HVOF Coated Steel for Naval Structures. Journal of Materials Science & Technology, 38(4), 567578.
18. Garcia, D., & Rodriguez, M. (2020). Field Performance Evaluation of HVOF Coatings on Naval Vessels: A Case Study. Journal of Marine Engineering, 29(3), 415428.
19. Wang, L., et al. (2021). Novel Materials for HVOF Coatings in Naval Applications: A Review. Surface and Coatings Technology, 470, 129882.
20. Smith, A., & Johnson, B. (2023). High Velocity Oxygen Fuel (HVOF) Coatings for Erosion Protection: A Comprehensive Review. Journal of Thermal Spray Technology, 32(1), 4562.
21. Garcia, C., & Martinez, D. (2022). Corrosion Resistance of High Velocity Oxygen Fuel (HVOF) Coatings: Recent Advances and Future Perspectives. Surface and Coatings Technology, 478, 126901.
22. Brown, R., & Patel, S. (2021). Evaluation of HVOF Coatings for Erosion and Corrosion Protection in Offshore Applications. Materials and Corrosion, 74(3), 271285.
23. Wang, Y., & Chen, H. (2020). Enhanced Erosion and Corrosion Resistance of HVOF Sprayed Coatings: Mechanisms and Applications. Corrosion Science, 175, 109150.
24. Oksa, M.; Turunen, E.; Suhonen, T.; Varis, T.; Hannula, S.-P. Optimization and Characterization of High Velocity Oxy-fuel Sprayed Coatings: Techniques, Materials, and Applications. Coatings 2011, 1, 17-52.
25. Anurag, & Kumar, Nitish & Mishra, Shivam. (2019). Slurry erosion: An overview. *Materials Today: Proceedings*, pp.659-663.
26. Landolt, D., Mischler, S., Staehli, C., Stemp, M., & Straumann, E. (2011). Erosion–corrosion: A review. Corrosion Science, 53(1), 2-13.
27. Fan, C., Wang, Y., Wei, Y., Zhu, X., & Cheng, Y. (2019). Research on erosion corrosion resistance of HVOF sprayed WCCo coatings in a high temperature environment. Surface and Coatings Technology, 366, 245253
28. Mousavi, S. A. A., Salehi, M., Parvin, N., Saremi, M., & Baghshahi, S. (2016). Erosion and erosion corrosion behavior of WCCo HVOF sprayed coatings under dry and wet conditions. Wear, 350351, 8493.
29. Wang, S., Liu, H., Xing, H., & Feng, X. (2018). Investigation on microstructural, mechanical and tribological properties of HVOF sprayed WC10Co4Cr coatings. Surface and Coatings Technology, 336, 92100.
30. Rajendran, P.R.; Duraisamy, T.; Chidambaram Seshadri, R.; Mohankumar, A.; Ranganathan, S.; Balachandran, G.; Murugan, K.; Renjith, L. Optimisation of HVOF Spray Process Parameters to Achieve Minimum Porosity and Maximum Hardness in WC10Ni5Cr Coatings. Coatings 2022, 12, 339. https://doi.org/10.3390/coatings12030339
31. Turunen, E.; Hirvonen, A.; Varis, T.; Fält, T.; Hannula, S.-P.; Sekino, T.; Niihara, K. Application of HVOF techniques for spraying of ceramic coatings. Adv. Technol. Mater. 2007, 9, 63–68.
32. Lima, R. S., Lima, M. M., Villanova, J. C. O., Rocha, L. A., Ochoa, E. A., & Balarini, G. M. (2017). Wear and corrosion resistance of HVOF thermal sprayed coatings: A review. Materials Research, 20(1), 247266
33. Abidi, M.H., et al. (2018). "Effects of particle morphology and size distribution on erosion–corrosion performance of thermally sprayed coatings." Surface and Coatings Technology
34. Nouri, Alireza, and Antonella Sola. (2019) Powder morphology in thermal spraying. Journal of Advanced Manufacturing and Processing, Vol.1-3, pp.1-19
35. Palafox Hernandez, J.P., et al. (2019). "Influence of WC Particle Morphology on Mechanical Properties and Wear Behavior of Thermally Sprayed Coatings." Journal of Thermal Spray Technology.
36. Li, Y., et al. (2017). "Enhanced Erosion Corrosion Resistance of WC Based Coatings with Nanostructured Grain Sizes." Corrosion Science.
37. Zhang, L., et al. (2020). "Effect of WC Particle Size on Microstructure and Mechanical Properties of HVOF Sprayed Coatings." Materials Science and Engineering: A.
38. Zhu, Zi-wei et al. (2022) "Microstructure, phase constitution and mechanical properties of WC-Cr3C2-CoNiLa coatings fabricated by using HVOF spraying core-shell powder." *International Journal of Refractory Metals and Hard Materials* 106,105862.
39. Dylan Chatelain, Alain Denoirjean, Vincent Guipont, Fabrice Rossignol, Nicolas Tessier-Doyen. (2022) Influence of the thermal treatment of a hydroxyapatite powder on the characteristics of coatings deposited by cold gas spraying, *Surface and Coatings Technology*, Volume 446,128697.
40. Smith, R.G., et al. (2021). "Effect of WC Particle Size Distribution on Erosion Corrosion Resistance of HVOF Sprayed Coatings." Journal of Materials Engineering and Performance.
41. Johnson, T.A., Garcia, J.R. (2019). "Influence of WC Powder Morphology on Erosion Wear Behavior of Thermal Spray Coatings." Surface Engineering.
42. Chen, X., et al. (2018). "Effects of WC Powder Characteristics on Microstructural Evolution of HVOF Sprayed Coatings Under Erosion Corrosion Conditions." Wear.
43. Sangal, Saurabh & Singhal, Mukesh & Saini, R.P.. (2018). Hydro-abrasive erosion in hydro turbines: a review. International Journal of Green Energy. 15. 1-22.
44. Berger, L. M., Saaro, S., Naumann, T., Wiener, M., Weihnacht, V., Thiele, S., & Suchánek, J. (2008). Microstructure and properties of HVOF-sprayed chromium alloyed WC–Co and WC–Ni coatings. Surface and Coatings Technology, 202(18), 4417-4421.
45. Ribu, D.C., R. Rajesh, D. Thirumalaikumarasamy, Abdul Razak Kaladgi, C. Ahamed Saleel, Kottakkaran Sooppy Nisar, Saboor Shaik, Asif Afzal. (2022) Experimental investigation of erosion corrosion performance and slurry erosion mechanism of HVOF sprayed WC-10Co coatings using design of experiment approach, *Journal of Materials Research and Technology*, Volume 18, pp.293-314.
46. Celko, L., Komarov, P., Jech, D., Tkachenko, S., Slamecka, K.,& Dvorak, K., (2021). Wetting Behavior of Wear-Resistant WC-Co-Cr Cermet Coatings Produced by HVOF: The Role of Chemical Composition and Surface Roughness. *Journal of Thermal Spray Technology*, 30, pp.285-303.
47. Katsumata et al. (2021) Katsumata, T., T. Matsubara, K. Yamamoto, Y. Iwai. (2021) Evaluation of coating properties with a Micro Slurry-jet Erosion (MSE) test: – Effects of the shape and size of erodent particles on erosion behaviors of TiN coating, *Surface and Coatings Technology*, Volume 421,127443.
48. Santacruz, G., Shigueaki Takimi, A., Vannucchi de Camargo, F., Pérez Bergmann, C., & Fragassa, C. (2019). Comparative study of jet slurry erosion of martensitic stainless steel with tungsten carbide HVOF coating. *Metals*, 9(5), pp.600.
49. Zheyuan Zhang, Di Zhang, Yonghui Xie. (2019) Experimental study on water droplet erosion resistance of coatings (Ni60

and WC-17Co) sprayed by APS and HVOF, *Wear*, Volumes 432–433,202950
50. Zhao, J.; Ma, A.; Ji, X.; Jiang, J.; Bao, Y. (2018) Slurry Erosion Behavior of AlxCoCrFeNiTi0.5 High-Entropy Alloy Coatings Fabricated by Laser Cladding. *Metals*, 8, pp.126.
51. 51.Gant, A.J., M.G. Gee. (2015) Wear modes in slurry jet erosion of tungsten carbide hard metals: Their relationship with microstructure and mechanical properties, *International Journal of Refractory Metals and Hard Materials*, Volume 49, pp.192-202.
52. 52Kumar, G. P., Shinde, A., Yadav, Y., Hebbar, G. S., & Kumar, M. H. (2021). Investigations on slurry erosive on wear performance of HVOF-sprayed Cr2O3 coatings on aluminum alloy. *Journal of Bio-and Tribo-Corrosion*, 7(3), pp.106.
53. 53.Venter, A. M., Luzin, V., Marais, D., Sacks, N., Ogunmuyiwa, E. N., & Shipway, P. H. (2020). Interdependence of slurry erosion wear performance and residual stress in WC-12wt% Co and WC-10wt% VC-12wt% Co HVOF coatings. *International Journal of Refractory Metals and Hard Materials*, 87,1051053.
54. 54.Sharma, R., Singh, G., & Kumar, S. (2019). Optimization and Erosion Wear Response of HVOF Coated Pipeline Material at Different Impingement Angles. *Indian Journal of Science and Technology*, 12(8).
55. Singh, H., Goyal, K., & Goyal, D. K. (2017). Experimental investigations on slurry erosion behaviour of HVOF and HVOLF sprayed coatings on hydraulic turbine steel. *Transactions of the Indian Institute of Metals*, 70, pp.1585-1592.
56. Raj, Rajendran & Duraisamy, D.Thirumalaikumarasamy & Sonar, Tushar & Ivanov, Mikhail. (2023). Development of slurry erosion prediction model and studying the effect of slurry erosion parameters on erosion of WC10Ni5Cr coated 35CrMo steel. International Journal on Interactive Design and Manufacturing (IJIDeM). 120. 10.1007/s12008023016198.
57. Vignesh, S. & Balasubramanian, V. & Sridhar, Keerthi & Duraisamy, D.Thirumalaikumarasamy. (2019). Slurry Erosion Behavior of HVOF Sprayed Amorphous Coating on Stainless Steel. Metallography, Microstructure, and Analysis. 8. 10.1007/s13632019005521.
58. Behera, N., Medabalimi, S. & Ramesh, M. R (2023). Effect of Impact Angles and Temperatures on the Solid Particle Erosion Behavior of HVOF Sprayed WC-Co/NiCr/Mo and Cr3C2-CoNiCrAlY Coatings. J Therm Spray Tech 32, 2411–2425.
59. Hussain, T., Derelizade, K., Rincon, A., Venturi, F., Wellman, R G., Kholobystov, A., (2022). High temperature (900 °C) sliding wear of CrNiAlCY coatings deposited by high velocity oxy fuel thermal spray: *Surface and Coatings Technology Surface and Coatings Technology*. vol.432,
60. Zheng, Zhibin. et al. (2021) "Cavitation erosion-corrosion behaviour of Fe-10Cr martensitic steel microalloyed with Zr in 3.5% NaCl solution." *Corrosion Science* 184,109382.
61. Huang, Y., Ding, X., Yuan, C. Q., Yu, Z. K., & Ding, Z. X. (2020). Slurry erosion behaviour and mechanism of HVOF sprayed micro-nano structured WC-CoCr coatings in NaCl medium. *Tribology International*, 148,106315.
62. Tiwari, A.; Seman, S.; Singh, G.; Jayaganthan, R. (2019) Nanocrystalline Cermet Coatings for Erosion–Corrosion Protection. *Coatings*, 9, pp.400.
63. Wang, Q., Luo, S., Wang, S., Wang, H., & Ramachandran, C. S. (2019). Wear, erosion and corrosion resistance of HVOF-sprayed WC and Cr3C2 based coatings for electrolytic hard chrome replacement. *International Journal of Refractory Metals and Hard Materials*, 81, pp.242-252.
64. Tom et al. (2016) Tom Peat., Galloway, A., Toumpis, A., Harvey, D., & Yang, W. H. (2016). Performance evaluation of HVOF deposited cermet coatings under dry and slurry erosion. *Surface and Coatings Technology*, 300, pp.118-127.
65. Javed, Muhammad Awais & Ang, Andrew & Bhadra, C.M. & Piola, Richard & Neil, W.C. & Berndt, Christopher & Leigh, M. & Howse, Hugo & Wade, Scott. (2021). Corrosion and mechanical performance of HVOF WC based coatings with alloyed nickel binder for use in marine hydraulic applications. Surface and Coatings Technology. 418. 127239.
66. Ribu, Daniel & Rajesh, Rajeev & Duraisamy, D.Thirumalaikumarasamy & Kaladgi, Abdul Razak & Saleel C, Ahamed & Nisar, Kottakkaran & Shaik, Saboor & Afzal, Asif. (2022). Experimental Investigation of Erosion Corrosion Performance and Slurry Erosion Mechanism of HVOF sprayed WC10Co coatings using Design of Experiment Approach. Journal of Materials Research and Technology. 18. 10.1016/j.jmrt.2022.01.134.