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Slurry Erosion Behaviour of HVOF Sprayed WC-10Ni-5Cr Coated 35CrMo Steel

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ABSTRACT
Slurry erosion is a serious operational difficulty that results in severe equipment damage, downtime, and material replacement costs. To address this issue, the High Velocity Oxy Fuel (HVOF) spraying process is utilised to impart protective ceramic coatings to steel substrates, increasing their resistance to slurry erosion. In this investigation slurry erosion studies were carried out, with parameters such as rotating speed, impingement angle, slurry concentration, and exposure period being varied to understand their impact on erosion behaviour. Developed empirical correlations that accurately forecast coating mass loss using response surface methodology (RSM). A five-level central composite design matrix is used to optimize the experimental runs, resulting in a model with more than a 95% confidence level. Findings highlight the dominant influence of exposure time, followed by rotational speed, impact angle, and slurry concentrations on coating erosion rates.
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Introduction

Slurry erosion is a type of material degradation caused by the impact of solid particles suspended in a fluid (usually a liquid) on a surface. This phenomenon is particularly relevant in various industrial applications where materials are exposed to abrasive environments. Slurry erosion can result in the gradual removal of material from the surface of components, leading to dimensional changes and loss of structural integrity. This can cause parts to become weaker and less effective at performing their intended functions. In industries where fluid-solid mixtures are processed, such as in pipelines, pumps, and valves, slurry erosion can cause an increase in friction and turbulence, leading to reduced efficiency and increased energy consumption. Slurry erosion can accelerate the wear of equipment components, leading to premature failure. Components that experience erosion, such as impellers, rotors, and chutes, may need to be replaced more frequently, leading to higher maintenance and replacement costs. Slurry erosion can compromise the structural integrity of equipment, increasing the risk of sudden equipment failure. This can pose safety hazards to workers, especially in industries where the failure of certain equipment could lead to accidents. Eroded particles from equipment can enter the surrounding environment, leading to potential contamination of water, soil, and air. This can have negative ecological impacts on local ecosystems [1-7]. In marine environments, where water and abrasive particles are prevalent, slurry erosion can lead to various challenges and consequences. Slurry erosion can cause accelerated wear and tear on equipment surfaces exposed to the abrasive slurry. This includes pipes, valves, pumps, propellers, and other components. The erosion of these components can lead to reduced operational efficiency, increased maintenance needs, and shorter equipment lifespans. This might result in decreased propulsion efficiency for ships, reduced pumping capacity for offshore platforms, and decreased energy generation for marine turbines. Slurry erosion can remove protective coatings and expose underlying materials to the corrosive marine environment, leading to accelerated corrosion rates. The effect of slurry erosion on naval materials depends on several factors, including the composition of the material, the properties of the slurry, the impact velocity, and the angle of impact. To mitigate the effects of slurry erosion on materials, various strategies can be employed, including selecting steel alloys with higher hardness and resistance to abrasion, applying protective coatings, altering the flow conditions to minimize impact velocity, and using designs that minimize the angle of impingement. Preventing slurry erosion in steel components using High-Velocity Oxygen Fuel (HVOF) coatings is an effective approach to extend their service life and maintain their performance. High-Velocity Oxygen Fuel (HVOF) is a thermal spray process where a mixture of fuel gas and oxygen is ignited in a combustion chamber, producing a high-velocity flame. Powdered coating material is fed into this flame, melts, and is accelerated onto the substrate to form a dense, adherent coating. HVOF coatings are known for their exceptional wear resistance properties. They can significantly extend the lifespan of components subjected to abrasive wear, erosion, and friction [7-14].

Several researchers have documented the effectiveness of traditional coating-like plasma spraying and combustion flame process in enhancing resistance to slurry erosion when compared to uncoated base materials, attributing this improvement to their high hardness. The prevailing erosion mechanism observed across various experimental approaches involves the shedding of layers due to crack initiation and propagation induced by fatigue stress [15-16]. Notably, studies have highlighted the substantial enhancement in wear resistance across cavitation, slurry erosion, and dry erosion environments when utilizing high-velocity air-fuel sprayed coatings as opposed to bulk materials [17]. In a study by Men et al. [18], the erosion process was found to induce thermal shock cracks on the

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coating's surface, leading to the fracture and removal of surface carbides by the hot airflow, resulting in erosion pits. Furthermore, the addition of Ni phase was observed to enhance the substrate's erosion resistance. Another investigation by Sing et al. [19] involved a comparative analysis of Ni-Cr-O and NiCrBSiFe-WC (Co) composite coatings, deposited using the HVOF technique, focusing on erosion resistance. This improvement was primarily attributed to the superior hardness of the HVOF-sprayed coatings in contrast to the bond coating. Tripathi et al. [20] conducted a comprehensive study exploring various coating materials, such as tungsten carbide with traces of cobalt, nickel, and rare earth elements, and assessed the impact of different coating parameters, including impingement velocity, particle size, and impingement angle. Their findings underscored the significant enhancement of erosion resistance behaviour in stainless-steel substrates through the application of cermet coatings.
While extensive research has explored the erosion behavior of thermal sprayed coatings, the interplay between substrate material properties and coating characteristics on erosion resistance remains a subject of ongoing investigation. This study aims to contribute to this understanding by comprehensively examining the slurry erosion behavior of HVOF-coated 35CrMo steel, a commonly used material in critical applications. By investigating the synergistic effect of substrate and coating properties, this research seeks to provide valuable insights for the design and optimization of erosion-resistant coatings in demanding environments. Here, authors employed the HVOF method to apply a conventional WC-10 Ni 5 Cr feed powder onto a 35CrMo steel surface. 35CrMo alloy steel can be used in various applications that withstand impact, bending and high loads and in marine applications and used to manufacture parts such as rolling mill gears, crankshafts, connecting rods, fasteners, automotive engine spindles, axles, engine transmission parts, propeller shafts, bolts for boilers etc. A comprehensive slurry erosion experiment was carried out to evaluate the performance of the coating under varying conditions like slurry composition, rotational speed, impact angle, and duration using response surface methodology (RSM). RSM is a valuable statistical technique for analysing slurry erosion behavior in HVOF-coated 35CrMo steel. Its ability to efficiently design experiments, develop models, optimize processes, and understand complex interactions makes it an indispensable technique for researchers and engineers working in this field.

Experimental

In this study, a WC-10Ni 5Cr powder (Make: Oerlikon metco WOKA-3552) coating was applied using the HVOF spray technology (HIPOJET-2700) provided by Aum Surface Technology, Bangalore, India. The coating was applied onto a 35CrMo steel surface, with a resultant thickness of approximately 250 µm. The chemical composition of both base material and coating powder is shown in table no.1 & 2. The coating thickness was determined using a digital micrometre with a precision of 0.001 mm, varying based on the number of passes during the coating process. Figure 1 shows the SEM image of coating powder. It confirms the nature of the powder particle as agglomerated and sintered with spheroidal morphology. This ensures the consistent particle sizes and shapes. This leads to improved powder flowability, reduced porosity, and enhanced coating consistency, resulting in better overall coating quality. The increased packing density and improved flowability of agglomerated and sintered powders contribute to better adhesion between the coating and substrate. This results in higher bond strength, reduced risk of delamination, and increased overall coating durability. Figure 2 shows the uncoated and coated sample and figure 3 shows the SEM image of coating cross section.

Table 1: Chemical composition of Substrate

Percent comp	C%	Si%	Mn%	P%	S%	Cr%	Mo%
	0.35	0.2	0.602	0.015	0.012	0.972	0.205

Table 2: Chemical composition of coating powder

Percent comp	C%	Cr%	Ni%	Fe%	W%
	5.4	5.03	10.25	0.06	Balance

Before the spraying procedure, the base material underwent preheating, achieved by subjecting it to a complete torch cycle at a velocity of 0.8 m/s, resulting in a temperature range of 120–180°C. The specimens used in this research possessed dimensions of 25 × 25 × 3 mm, featuring chamfered edges with a one-millimetre extension and a 45° angle. The specimens were cleaned using acetone through ultrasonic cleaning. Additionally, the surface roughness of the base material was enhanced by grit blasting process using corundum particles (sized between 320- 500 µm).
A Mitutoyo Surf Test 301 surface roughness tester from Japan was employed to measure the surface roughness. The base materials, after undergoing grit blasting, exhibited an average roughness ranging from 5µm to 10µm.The conventional powder mixture used in the process consisted of the following weight percentages: 85% tungsten carbide (WC), 10% nickel (Ni), and 5% chromium (Cr). The particle size of these powders ranged from +15µm to -45µm.The process parameters for the WC 10Ni 5Cr coating using High-Velocity Oxygen Fuel (HVOF) are presented in Table 3.

Table 3: HVOF process parameters

Process parameters	Range
Oxygen flow rate	252.5 slpm
LPG flowrate,	55 slpm,
Powder feed rate	45 g/min
Spray distance	6.5 inch

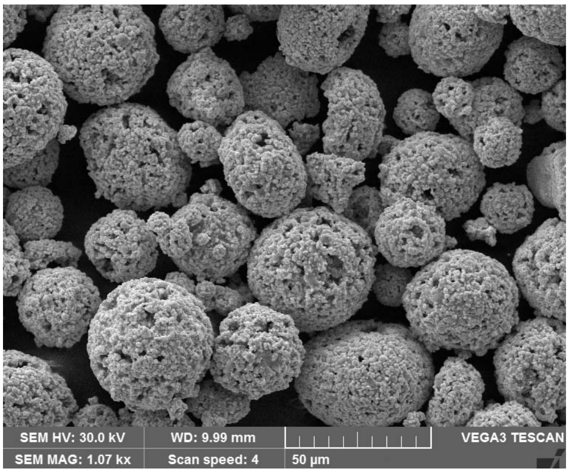

Figure 1: SEM micrograph of WC 10 Ni 5 Cr powder

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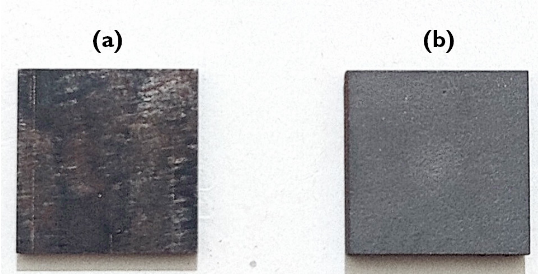

Figure 2: (a) Uncoated Steel (b) Coated steel

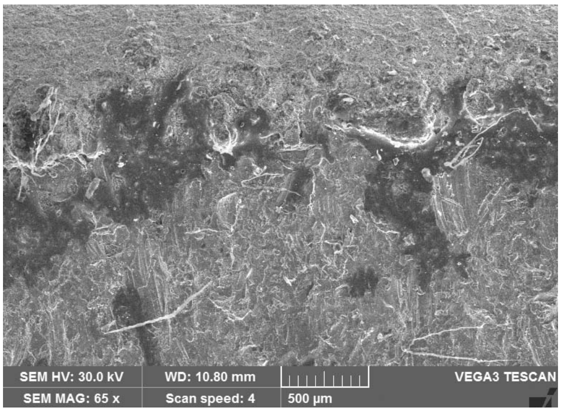

Figure 3: SEM micrograph of coating (Cross section)

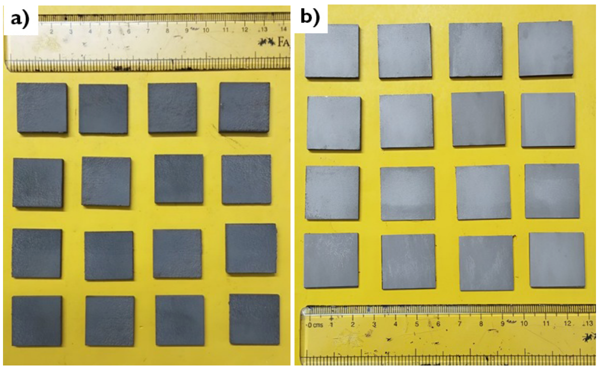

Figure 4: Coated samples(a) before and (b) after slurry erosion testing

Slurry erosions analysis

Samples of 35 Cr Mo steel with dimensions 25 mm x 25 mm x 5 mm were subjected to slurry erosion testing as per ASTM G 73 standards in a slurry erosion tester (Make: DUCOM Instruments, India, Model: TR-40). Figure 4 shows the samples before and after the testing. Prior to the commencement of the experiment, the samples underwent ultrasonic cleaning and were meticulously washed using precise weighing equipment. These samples, which were uniform in size, were securely fastened to a disc at the desired radial distance. The disc, together with the sample, was fully immersed in the slurry. Upon initiating the motor, the samples were set into rotation for a predetermined duration at the desired speed. Upon completion of the experiment, the specimen was extracted and subjected to a thorough washing process. The evaluation of mass loss, influenced by various experimental conditions, was employed to calculate the rate of mass loss. For the slurry erosion investigations, an erodent consisting of 50 µm quartz sand was employed. Figure 5 showing the slurry erosion tester and its schematic arrangement.

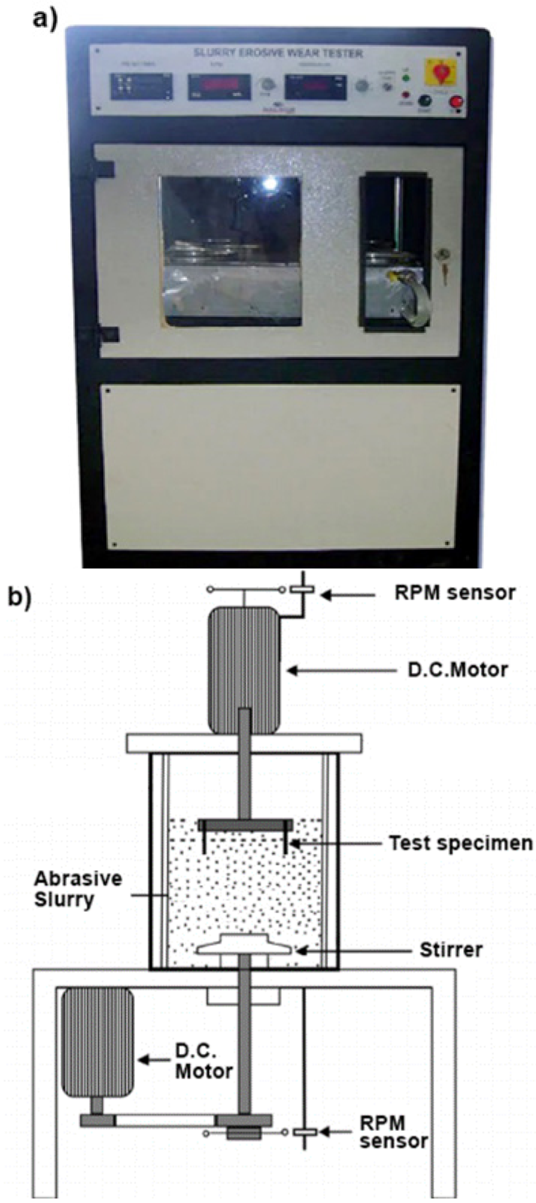

Figure 5: (a) Slurry Erosion Tester (b) Schematic arrangement of slurry erosion testing

The study considers several key factors, including rotational speed, impinging angle, slurry concentrations, and time, which have been identified as significant determinants based on prior research [21-30]. Initial trial tests were conducted to establish operational ranges for the variables impacting slurry erosion. Conducting erosive wear tests is feasible once the applicable ranges for erosion test instrument capabilities have been accounted for within the erosion conditions. To streamline the analysis process, statically generated experiments were employed to assess the impact of varying slurry erosion parameter values on mass loss. The investigation encompasses both the 35CrMo steel aspects, outlined in Tables 4 and 5. To minimize methodological errors, the tests were performed in a random sequence. Reliability assessment involved conducting three tests for each experimental condition to ensure consistent results.

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Table 4: The experiment parameters and levels

No	Factor	Units	Notation	Levels				
				-2	-1	0	1	2
1	Impact angle	degree	A	30	45	60	75	90
2	Rotational Speed	rpm	S	500	750	1000	1250	1500
3	Time	min	T	30	60	90	120	150
4	Slurry Composition	g/cc	F	200	300	400	500	600

Table 5: The design matrix and measured responses

Exp. condition	Time (min)	Rotational speed (rpm)	Impact angle (Degree)	Slurry composition (g/cc)	Mass loss of uncoated steel (g)	Mass loss of coated steel(g)
1	60	750	45	300	0.06	0.0402
2	120	750	45	300	0.1563	0.1037
3	60	1250	45	300	0.1161	0.0771
4	120	1250	45	300	0.2107	0.1394
5	60	750	75	300	0.1067	0.0709
6	120	750	75	300	0.2034	0.1346
7	60	1250	75	300	0.1582	0.105
8	120	1250	75	300	0.2532	0.1674
9	60	750	45	500	0.041	0.0277
10	120	750	45	500	0.1401	0.093
11	60	1250	45	500	0.0893	0.0596
12	120	1250	45	500	0.1867	0.1236
13	60	750	75	500	0.0829	0.0554
14	120	750	75	500	0.1824	0.1208
15	60	1250	75	500	0.1266	0.0844
16	120	1250	75	500	0.2244	0.1485
17	30	1000	60	400	0.0513	0.0346
18	150	1000	60	400	0.2454	0.1623
19	90	500	60	400	0.0975	0.0649
20	90	1500	60	400	0.1956	0.1296
21	90	1000	30	400	0.1061	0.0705
22	90	1000	90	400	0.1905	0.1262
23	90	1000	60	200	0.1652	0.1095
24	90	1000	60	600	0.1174	0.0781
25	90	1000	60	400	0.1416	0.0939
26	90	1000	60	400	0.06	0.0402
27	90	1000	60	400	0.1563	0.1037
28	90	1000	60	400	0.1161	0.0771
29	90	1000	60	400	0.2107	0.1394
30	90	1000	60	400	0.1067	0.0709

Predictive statistic model for erosion rate

In this work, mass loss was determined in relation to rotation speed, impact angle, slurry concentration, and time using a response surface technique. An experimental quadratic correlation was constructed to determine the response by experiment values in order to compare the experimental components with the rates of erosion [31] .

Output (Responses) = f (T, S, A, and F) can be used to indicate the responses based on impacting angle (A), rotational speed (S), time (T), and slurry concentration (F)

The finalized experimental relation for assessing the output is

Mass loss of uncoating 35CrMo steel base material $= 0.1319 + 0.0485 (T) + 0.0245(S) + 0.0211 (A) - 0.0119 (D) - 0.0004 (T)(S) + 0.0001 (T)(A) + 0.0007 (T)(F) - 0.0012 (S) (A) - 0.0020 (S)(F) - 0.0012 (A) (F) + 0.0041 (T^2) + 0.0037 (S^2) + 0.0211 (A^2) - 0.0024 (F^2)$ ……… (2)

Mass loss of WC- 10Ni 5Cr coatings $= 0.0875 + 0.0319(T) + 0.0162 (S) - 0.0139 (A) - 0.0078 (F) +0.0003 (T) (S) + 0.0001(T)(A) + 0.0004 (T)(F) - 0.0007 (S)(A) - 0.0013 (S)(F) - 0.0008 (A)(F) +-0.0027 (T^2) + 0.0024 (S^2) + 0.0027 (A^2) +0.0016 (F^2)$ ………… (3)

Results and Discussion

In this work, the appropriate empirical relationship was confirmed using the ANOVA methodology. Tables 6 and 7 shows the ANOVA findings for the degree of erosion in both coated and uncoated samples. The process for analysing the ANOVA data is laid out in the literature [32]. The analysis presented in Tables 6 and 7 indicates that erosion rate is significantly influenced by rotation speeds, impingement angles, duration, and slurry concentration – as evidenced by their substantial impact values ('F' value assessment). These findings underscore the robustness of the regression models in accurately capturing these relationships. By manipulating the coded representations of experimental factors, these empirically derived relationships could effectively serve as predictive tools for anticipating outcomes.

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Table 6: ANOVA analysis for erosion rate of uncoated 35CrMo steel substrate

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0862	14	0.0062	7.13	0.0003	significant
T-Time	0.0565	1	0.0565	65.44	< 0.0001	
S-Rotational Speed	0.0144	1	0.0144	16.72	0.001	
A-Impact Angle	0.0107	1	0.0107	12.37	0.0031	
F-Slurry Composition	0.0034	1	0.0034	3.97	0.0649	
TS	2.89E-06	1	2.89E-06	0.0033	0.9546	
TA	1.60E-07	1	1.60E-07	0.0002	0.9893	
TF	7.84E-06	1	7.84E-06	0.0091	0.9254	
SA	0	1	0	0.0245	0.8777	
SF	0.0001	1	0.0001	0.0705	0.7943	
AF	0	1	0	0.0267	0.8724	
T^2	0.0005	1	0.0005	0.5372	0.4749	
S^2	0.0004	1	0.0004	0.4261	0.5238	
A^2	0.0005	1	0.0005	0.5339	0.4762	
F^2	0.0002	1	0.0002	0.1754	0.6813	
Residual	0.013	15	0.0009			
Lack of Fit	0	10	0	0	1	not significant
Pure Error	0.013	5	0.0026			
Cor Total	0.0992	29				

Table 7: ANOVA analysis for erosion rate of coated 35CrMo steel substrate

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0374	14	0.0027	7.12	0.0003	significant
A-Time	0.0245	1	0.0245	65.29	< 0.0001	
B-Rotational Speed	0.0063	1	0.0063	16.76	0.001	
C-Impact Angle	0.0047	1	0.0047	12.42	0.0031	
D-Slurry Composition	0.0015	1	0.0015	3.94	0.0659	
AB	1.63E-06	1	1.63E-06	0.0043	0.9483	
AC	1.56E-08	1	1.56E-08	0	0.9949	
AD	2.98E-06	1	2.98E-06	0.0079	0.9302	
BC	8.27E-06	1	8.27E-06	0.0221	0.8839	
BD	0	1	0	0.0688	0.7967	
CD	9.46E-06	1	9.46E-06	0.0252	0.8759	
A^2	0.0002	1	0.0002	0.5451	0.4717	
B^2	0.0002	1	0.0002	0.4318	0.5211	
C^2	0.0002	1	0.0002	0.5351	0.4757	
D^2	0.0001	1	0.0001	0.1795	0.6778	
Residual	0.0056	15	0.0004			
Lack of Fit	5.83E-09	10	5.83E-10	5.19E-07	1	not significant
Pure Error	0.0056	5	0.0011			
Cor Total	0.043	29				

Investigating the slurry erosion parameters of high velocity oxygen fuel WC-10Ni-5Cr coatings involves a multifaceted approach to enhance the coating's resilience against the abrasive forces encountered in slurry environments. The goal of the optimisation is to reduce the mass loss (g) due to slurry erosion in 35CrMo steel (coated and uncoated). For this, regression-based model analysis is used to optimise the slurry erosion parameters. Figure 6 and 7 presents 3D response surface graphs for mass loss (g) in uncoated and coated steel. According to the findings, samples that were coated and uncoated and exposed to 45° impingement angle, 500 g/cc slurry concentration, and 60 minutes of immersion showed minimum mass loss of 0.041 g and 0.0277 g. When coated with WC-10Ni-5Cr powder using HVOF, the erosion of 35CrMo steel samples is reduced by 32.43%. The 35CrMo steel samples showed a larger mass loss of 0.2532 g and 0.1674 g for both coated and uncoated respectively, when they were exposed rotating speed of 1250 rpm, impingement angle of 75°, slurry concentration of 300 g/cc, and immersion duration of 120 min. This confirms a 51.25% reduction in the erosion rate in the coated samples. These results are evidence for the aptness of WC-10Ni-5Cr HVOF coating for 35CrMo steel in naval applications. The mass loss of the coating shows minimum values when the rotational speed and exposure time are at minimum. At the same time, a larger exposure time and rotational speed appear to be the maximum values. This is due to the fact that abrasive particles have more time to impact and remove material from the coated surface. Erosion might not occur at a constant rate throughout time. Erosion may rise quickly at first, but it may then stabilise at a stable state as a result of things like wear debris saturation of the coating surface and the development of shielding surface layers. More material is removed from the coated surface as a result of more frequent and strong abrasive particle collisions brought on by higher rotational speeds. There can be a speed at which the erosion rate stops increasing noticeably. After this, increasing rotational speed may not significantly affect erosion; in fact, it may even have the opposite effect because of stronger hydrodynamic effects that shield the surface.

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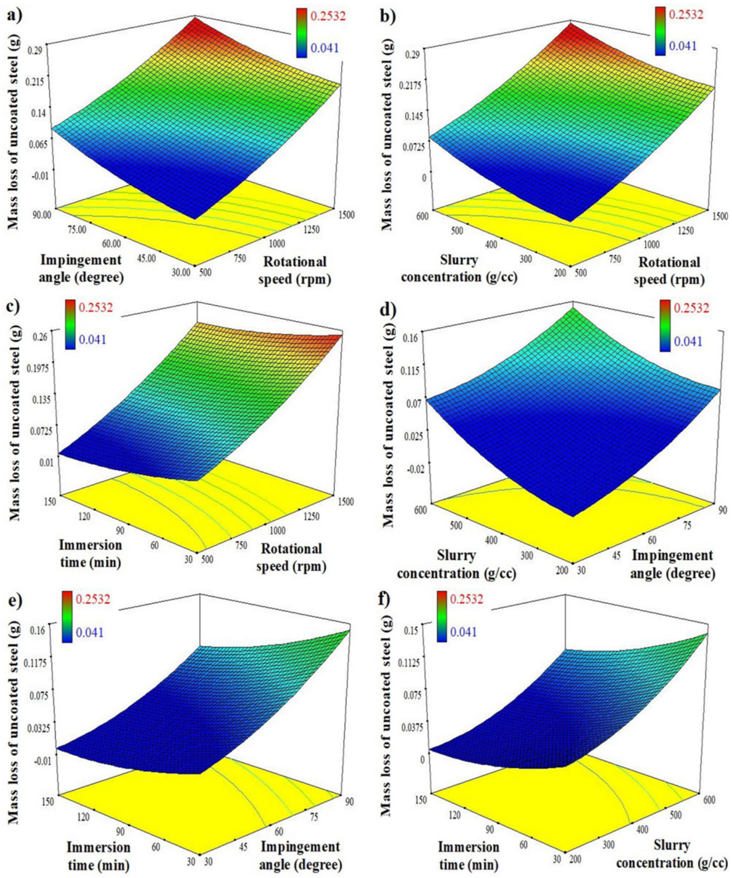

Figure 6: 3D response surface graphs for uncoated 35CrMo steel

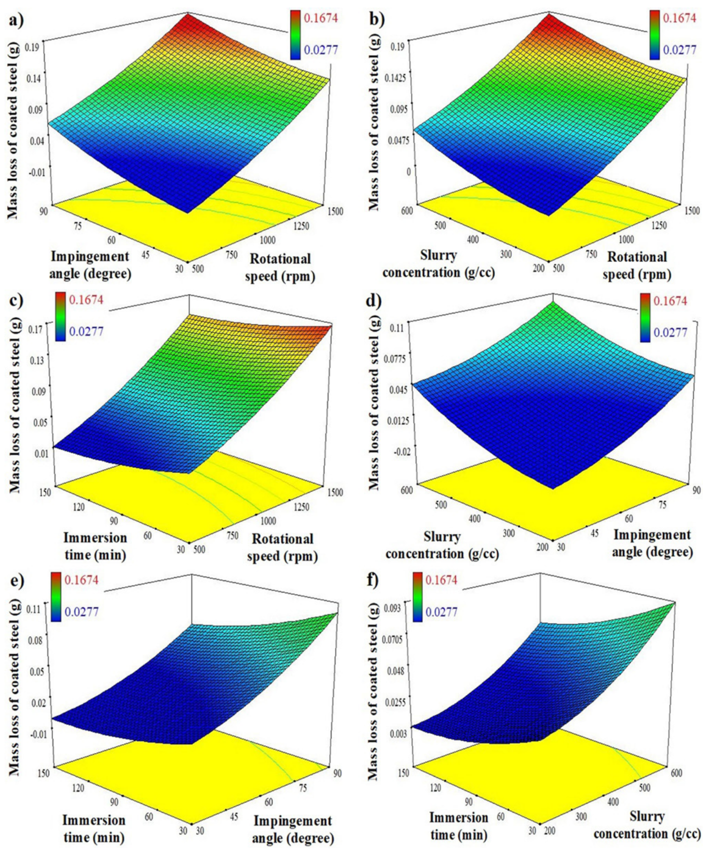

Figure 7: 3D response surface graphs for coated 35CrMo steel

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This coating, composed of tungsten carbide (WC) particles embedded in a nickel-chromium (Ni-Cr) matrix, exhibits distinctive characteristics under slurry erosion conditions. The dynamic interplay of factors such as impact angle, slurry concentration, rotational speed, and exposure time influences the overall erosion performance of these coatings. Investigation revealed that the erosive wear of WC-10Ni-5Cr coatings is influenced by the duration of exposure, with longer periods contributing to increased material removal due to a higher number of impact cycles. The cumulative effect of even minor impacts becomes evident over time, showcasing the coating's response to prolonged exposure. Moreover, the initial surface damage acts as nucleation sites for further material removal, accelerating the propagation of damage with continued exposure.

Slurry erosion behaviour of the HVOF spray WC-10Ni-5Cr coatings

The slurry erosion behavior of High-Velocity Oxygen Fuel (HVOF) spray WC-10Ni-5Cr coatings is a subject of significant interest and investigation. This coating, composed of tungsten carbide (WC) particles embedded in a nickel-chromium (Ni-Cr) matrix, exhibits distinctive characteristics under slurry erosion conditions. The dynamic interplay of factors such as impact angle, slurry concentration, rotational speed, and exposure time influences the overall erosion performance of these coatings. Studies have revealed that the erosive wear of WC-10Ni-5Cr coatings is influenced by the duration of exposure, with longer periods contributing to increased material removal due to a higher number of impact cycles [33]. The cumulative effect of even minor impacts becomes evident over time, showcasing the coating's response to prolonged exposure. Moreover, the initial surface damage acts as nucleation sites for further material removal, accelerating the propagation of damage with continued exposure.

In addition to exposure time, other variables such as impact angle and slurry concentration play crucial roles in shaping the slurry erosion behavior of these coatings. Higher slurry concentrations and more severe impact angles can intensify the erosive effects, leading to enhanced material removal. Furthermore, the microstructure of WC-10Ni-5Cr coatings undergoes alterations during slurry erosion, including deformation, strain hardening, and, in some cases, phase transformations.

The primary mechanism of erosion for coatings based on carbides was attributed to the low hardness of the metal binder. Initially, silicon oxide was employed by the binder to execute cutting and chiselling actions before ultimately breaking up carbide particles. Following a substantial impact from a higher velocity slurry, the carbide particles were eventually dislodged from the surface with assistance from the dissociation of the binder [34]. In contrast, HVOF-sprayed WC coatings, owing to their inherent hardness, demonstrated effective resistance against micro cutting and chiselling. Additionally, irrespective of impingement angles, HVOF-sprayed WC coatings were able to prevent brittle spallations by absorbing a portion of the energy generated by the impacting erodent. Notably, a discovered correlation revealed an approximately inverse log-linear relationship between slurry erosion wear loss and metal hardness. The coating loses durability as erosion increases noticeably. The weak inter-plate link and inter-lamelle porosities of the coating must be combined to cause this elevation, as no single characteristic could explain it. Plastic flows and fractures frequently occur simultaneously when hard particles are used in thermal spray coating degradation [35]. It has been determined that elastic modules are not suitable for estimating the wear of thermal spray coats when anticipating the wear of brittle materials, nor are they sufficient for industrial ceramics. In this examination of the erosion performance of thermal spray technique to their microstructure properties, the most significant interrelations were determined to be the hardness, range of porosity, and erosion level of the material.

Conclusions

The erosion resistance of materials is the most important tribological variable that influences their performance in various industrial applications like marine industries. One of most cost-effective means of addressing the issues is to develop HVOF sprayed WC-10 Ni 5Cr coatings with superior erosion corrosion resistance. The following are some of the most important findings from the study.

1. Empirical relations were established using response surface methodology to predict the slurry erosion rate of uncoated and coated specimens of 35 Cr Mo Steel
2. Among the four factors that observed, the most predominant factor impacting erosion rate was exposure time followed by rotational speed, impact angle, slurry concentrations.
3. The HVOF sprayed WC-10 Ni 5 Cr deposit on outperformed the uncoated substrate in terms of erosion resistance. Compared to the WC-10 Ni 5 Cr coated 35CrMo steel, uncoated steel experiences greater mass loss at higher exposure time and rotational speeds.
4. The 35CrMo steel samples showed a larger mass loss of 0.2532 g and 0.1674 g for both coated and uncoated respectively, when they were exposed rotating speed of 1250 rpm, impingement angle of 75°, slurry concentration of 300 g/cc, and immersion duration of 120 min.
5. The results confirm a 51.25% reduction in the erosion rate in the coated samples and support the suitability of WC-10Ni-5Cr HVOF coating for enhancing the erosion resistance of 35CrMo steel in naval applications.

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