ENHANCING WEAR RESISTANCE OF MARINE STEEL WITH Fe BASED AMORPHOUS COATING VIA HVOF SPRAYING

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SUMMARY

Mechanical friction in marine environments poses significant challenges, leading to resource depletion and energy consumption. Tribocorrosion, combining electrochemical corrosion and friction wear, jeopardizes metal components, necessitating robust protective measures. Despite minimal wear of marine equipment, even slight mass reductions can trigger catastrophic failures, resulting in substantial maintenance expenses. Steel structures in marine settings are vulnerable to corrosion from aggressive external and internal factors. ASTM AH36 steel, widely used in marine construction, faces wear challenges despite corrosion resistance, prompting the need for surface treatments and coatings to enhance longevity. Previous research emphasizes thermal spray methods, particularly HVOF-applied coatings, as eco-friendly solutions for improving wear resistance on marine steels. Fe-based coatings, characterized by improved hardness and corrosion resistance, offer promising solutions in abrasive marine environments, igniting fervent research efforts. This study conclusively demonstrates that AH36 steel samples coated with Fe-based amorphous layers exhibit substantially reduced wear rates.

KEYWORDS

Wear, HVOF, Fe based amorphous coating, AH36 steel

NOMENCLATURE

Gpm	Gram per minute
Lpm	Litre per minute
ASTM	American society for testing and Materials
HVOF	High velocity oxyfuel coating
S	Surface condition
C	Coated
UC	Uncoated
F	Frequency
P	Load
WR	Wear rate
L	Level

1. INTRODUCTION

In the marine environment, mechanical friction leads to significant resource consumption and energy expenditure. Tribocorrosion, a phenomenon where mechanical components undergo both electrochemical corrosion and friction wear simultaneously, poses a serious threat to metal components. Despite the low relative wear of marine equipment parts, even minor reductions in mass can cause overall mechanism failure, contributing to considerable wear-related expenses in shipbuilding maintenance [1-4]. Indeed, marine structures crafted from steel face significant corrosion challenges owing to the harsh environments in which they function. Whether exposed to the corrosive marine atmosphere or subjected to aggressive substances internally such as cargo, fuel, oil, or ballast water, steel structures are vulnerable to deterioration over time. ASTM A131 AH36 steel, widely used in marine construction, is susceptible to wear from abrasion, marine organisms, and water flow. Despite its corrosion resistance, its surface may lack the hardness needed for long-term durability. To combat this, surface treatments and coatings are essential. These enhancements significantly improve the steel's resistance to abrasive wear. Ensuring its longevity in harsh marine conditions thus requires these additional protective measures [5-7]. The traditional HVOF spray technique is widely recognized as highly efficient among thermal spray methods, primarily because of its exceptional gas and particle velocities, which can reach speeds approx five times faster than the sound velocity. During HVOF, the combustion of fuels mixed with oxygen supplies both thermal and kinetic energies essential for heating and propelling feedstock powder. Consequently, this process yields denser coatings, enhanced adhesion, and more consistent microstructures of coating due to deformation of particle on collision. The process is well-suited for depositing metal, alloy, and cermet coatings [27-29]. Previous research papers focused on enhancing wear resistance through diverse thermal spray methods featuring

HVOF-applied coatings on marine steels underscores a notable improvement in wear resistance presenting eco-friendly solutions [5]. HVOF sprayed an amorphous Fe-Ni-P-B mixture, became the preferred method for applying these robust coatings, opening new pathways for material science advancements [8]. Fe-based amorphous metallic coatings (AMCs) sprayed using the HVOF technique have been developed to address the need for cost-effective solutions with improved hardness and excellent resistance to both abrasive wear and corrosion. These coatings aim to provide dual protection against corrosion and wear, thus filling a critical gap between corrosion and wear protection [9-12]. Amorphous alloys, renowned for their notable hardness, strength, and ability to resist corrosion, serve as ideal coating materials in environments demanding durability and wear protection. Fe-based amorphous coatings, produced via the high-velocity oxygen fuel (HVOF) process, present promising solutions for high-temperature wear, marine, and acidic corrosion scenarios [13-14]. HVOF-sprayed amorphous Fe alloy coatings on SUS316 showed enhanced hardness and mixed microstructures but increased corrosion in seawater due to Mo and Cr oxidation, as revealed by XPS analysis [13]. The wear resistance of HVOF-sprayed FeCr-P-B-C amorphous coating surpasses that of mild steel and stainless steel (SS) coating [15]. Fe43Cr20Mo10W4C15B6Y2 amorphous coatings demonstrate superior wear resistance at elevated temperatures compared to SS316L, both in vacuum and air [16]. The study compared the resistance to wear of Fe–Cr–Ni–Si–B–C powder, applied via HVOF spraying, to other materials. At room temperature, Colferoloy exhibited higher wear than Cr3C2–NiCr and tool steel but outperformed Ni-based alloys and hard chromium plating. Under high temperatures and against steel, it showed limited wear and was comparable to Cr3C2–NiCr, indicating its potential as an alternative for sliding wear applications [18]. Similarly, Fe-Cr-Ni-Si-B-C amorphous coatings, when HVOF sprayed, exhibit better dry sliding behaviour than Ni-based superalloys at both room temperature and 400°C [18]. Fe-based coatings applied via HVOF exhibit superior wear resistance, high density, and low oxidation, making them promising, eco-friendly alternatives to Ni-based alloys for wear applications [19]. The remarkable properties of amorphous metal coatings, including ultra-high strength, toughness, and exceptional wear and corrosion resistance, have sparked rapid research and development efforts. Academia and industry are fervently pursuing advancements in amorphous metal coatings due to their unique and superior attributes [17]. Specifically, the wear rate of HVOF sprayed NiCrBSiFe coating was 3.5 times higher when tested against silicon nitride than against alumina [20]. In previous study, a novel Fe–Cr–B based metamorphic alloy optimized for thermal spray processes was developed and applied using the HVOF process. The coating layers exhibited dense microstructures composed of α-Fe, (Cr, Fe)2B, and metallic glass phases. Control over Mo and Nb content improved high-temperature resistance to oxidation and decreased oxidation during the HVOF spraying procedure. wear tests showed M2 had the best wear resistance due to reduced microcracks and frictional force from type 2 oxides, making it a promising candidate for high-wear applications [22]. In conclusion, while significant strides have been made in enhancing the wear resistance of ASTM AH36 steel through various surface treatments and coatings, research gaps persist in understanding the full extent of their effectiveness in harsh marine environments. Although Fe-based amorphous coatings applied via the HVOF technique show promise in improving wear resistance, there remains a need for comprehensive studies evaluating their long-term performance, particularly in corrosive marine conditions. Furthermore, investigations into the optimization of coating parameters, such as composition and deposition methods, are warranted to maximize their protective capabilities. Additionally, there is a dearth of research on the synergistic effects of combining different coating materials and techniques to achieve superior wear and corrosion resistance in marine steel. Future research endeavours should address these gaps to advance the development of eco-friendly and durable solutions for marine steel wear resistance, ultimately contributing to enhanced longevity and reduced maintenance costs of marine structures.

2. EXPERIMENTAL PROCEDURE

2.1 DEPOSITION OF COATING

The study utilized commercially available thermal spray-grade powders, Fe-Cr-B-Mo-Si-Mn-W with a nominal particle size of 50 μm and chemical compositions detailed in Table 1. Coatings were applied onto AH36 steel plates of 5 mm thickness using a Hybrid 2700 HVOF torch (Sulzer Metco, Wohlen, Switzerland) with parameters specified in Table 2. Prior to coating, the marine steel substrate underwent grit-blasting with aluminium oxide (34 mesh grit size).

Composite coatings composed of metallic glass (MG) based on iron (Fe) with and without Mo (P1C and P2C) were developed via HVOF spraying. P2C showed

Table 1. The powder comprises elements

Element	Wt. %
Fe	Rest
Cr	18.4
B	14.4
Mo	8.3
Si	3.0
Mn	1.9
W	1.8

Table 2. HVOF coating spraying parameters

Oxygen flow rate (lpm)	250
Spraying distance (mm)	230
Powder feed rate (gpm)	40
Fuel flow rate (lpm)	60
Carrier gas flow rate (lpm)	15

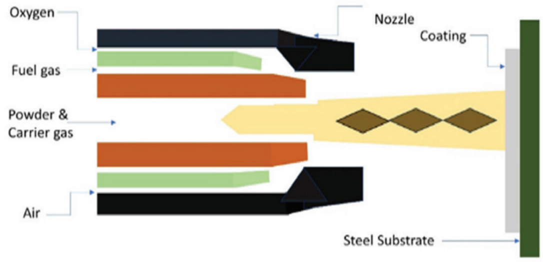

Figure 1. A diagram illustrating the schematic of HVOF coating

enhanced durability against wear and corrosion due to higher amorphous content and effective passivation from Cr- and Mo-oxides, outperforming P1C and even SS316L coatings. This indicates their potential as cost-effective alternatives for high wear and corrosion applications [21]. In previous research amorphous FeCrMnMoWBCSi powder coating of thickness 300mm was engineered for improving wear resistance of mild steel substrate via HVOF thermal spray techniques. Longer amorphous phases correlated with higher Vickers hardness. Low porosity signifies excellent wear resistance. Dry sliding wear tests showed good resistance, with wear rates ranging from (2.81-16.30) x 10(-6) mm3/N m. With properties enhanced by vacuum heat treatment at 650°C, these HVOF coatings exhibit high friction and wear resistance, making them suitable for steel facilities [23]. Another study evaluated coating quality by examining micro and crystal structures, suggesting that Fe-based coatings with the wire arc spraying (WAS) technique could serve as an alternative to Ni-based coatings produced via HVOF method [24]. The Fe-based AMC exhibits higher porosity and lower amorphous content, leading to decreased corrosion resistance and wear resistance [25]. An Fe-based coating was applied onto 304 stainless steels utilizing the HVOF spraying technique to enhance its resistance to wear and corrosion [26]. Schematic diagram of HVOF coating set up is shown in Figure 1.

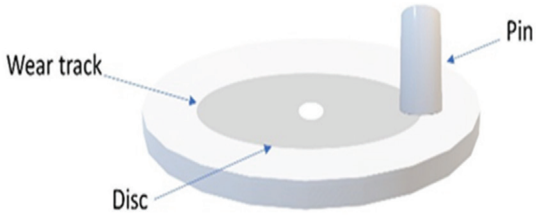

Figure 2. Schematic figure of pin on disc wear set up

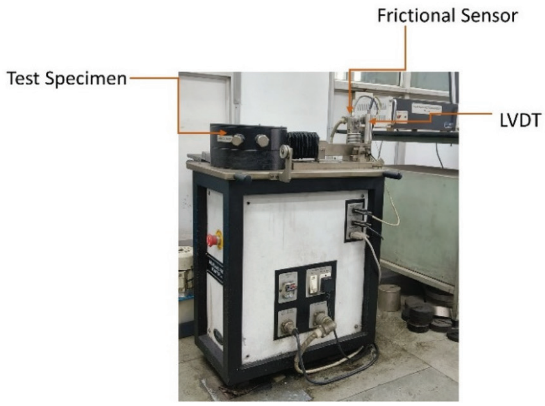

Figure 3. Pin on disc wear test set up

2.2 DRY SLIDING WEAR TEST

In this study, pin-on-disc tests were conducted at dry condition as shown in figure 2 and figure 3 to determine the wear behaviour of a Fe based Coated and uncoated A36 steel pin with dimensions of Ø 10mm × 35 mm.

2.3 DESIGN OF EXPERIMENTS

The study utilized a Taguchi L18 orthogonal array, specifically a mixed 2-3 values with an L18 Taguchi Design. There were four input control parameters, including sliding speed, load, and frequency, each varied across three levels (1, 2, and 3). Additionally, one control factor, surface condition, was varied across two levels (1= coated and 2= uncoated) as mentioned in table 3.

$$S/N = -10 \log \frac{1}{n} \sum y_i^2$$

The signal-to-noise ratio (S/N) for the wear rate is computed based on the repetition number (n). The outcome (Yi) of each experiment's ith trial was documented and recorded accordingly. For Taguchi analysis smaller is better condition was chosen.

3. RESULT AND DISCUSSION

The wear rate was determined by dividing the aggregate amount of volume of the material removed by the product of the load and overall sliding distance. Table 4 lists the computed wear rate values. Table 4 also includes the signal-to-noise (S/N) ratio values derived from Taguchi experimental evaluation.

3.1 PROBABILITY ANALYSIS

Figure 4 presents the probability plot, where it's noted that the values from the experimental results predominantly cluster near the central line, falling within the scope of a normal distribution. The P-value exceeds 0.01[39], indicating that the data is conducive to further analysis and interpretation.

Table 5 illustrates that surface condition is the dominant factor influencing wear rate, followed by load, frequency, and sliding velocity, respectively.

This is visible from table 6 that surface condition is the most dominating factor for influencing wear rate.

Figure 5 and figure 6 demonstrates that specimens with coatings exhibit lower wear rates, and the ideal parameters to reduce the wear rate are a frequency of 10 Hz, a sliding velocity of 1.1 m/s, and a load of 20N.

Table 7 clearly indicates that surface condition is the predominant factor influencing wear.

Table 3. Variables taken for wear test

Factors	L1
Surface	Coated, Uncoated
Frequency	5, 15, 25
Load(P)	10, 15, 20
Sliding velocity (m/s)	0.5, 0.8, 1.1

When a contour plot is generated, considering frequency and sliding velocity for the response parameter wear rate, it becomes apparent from Figure 7 that a reduced wear rate is noticeable at sliding velocities under

Table 4. Experimental values obtained from wear test

	S	F	SV	P	WR	S/N
1.	Uc	5	0.5	10	5.650	-15.04
2.	Uc	5	0.8	15	4.850	-13.71
3.	Uc	5	1.1	20	4.040	-12.12
4.	Uc	15	0.5	10	3.780	-11.54
5.	Uc	15	0.8	15	4.900	-13.80
6.	Uc	15	1.1	20	3.990	-12.01
7.	Uc	25	0.5	15	5.120	-14.18
8.	Uc	25	0.8	20	4.500	-13.06
9.	Uc	25	1.1	10	6.760	-16.59
10.	C	5	0.5	20	2.500	-7.95
11.	C	5	0.8	10	1.980	-5.93
12.	C	5	1.1	15	0.678	3.37
13.	C	15	0.5	15	0.890	1.01
14.	C	15	0.8	20	0.967	0.2915
15.	C	15	1.1	10	0.786	2.09
16.	C	25	0.5	20	0.679	3.36
17.	C	25	0.8	10	0.908	0.83
18.	C	25	1.1	15	1.060	-0.50

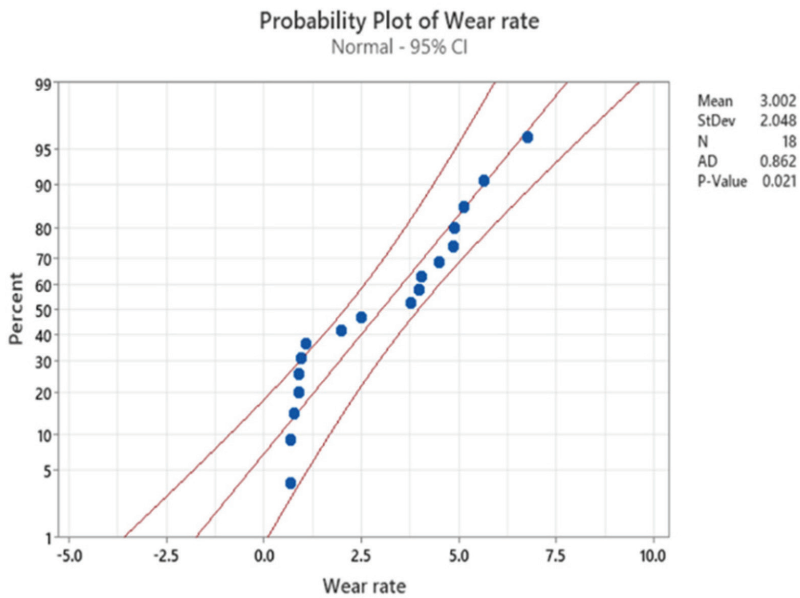

Figure 4. Probability plot for wear rate

0.55 m/s and frequencies falling within the range of 13 Hz to 19 Hz.

When a contour plot is generated for wear rate, with load and frequency as variables, Figure 8 illustrates that a lower wear rate is achieved when the load ranges from 10N to

Table 5. Response table for means for wear rate

Factors	Means				
	L1	**L2**	**L3**	**D**	**R**
S	1.16	4.84	-	3.68	1
F	3.28	2.55	3.17	0.73	2
SV	3.10	3.01	2.88	2.77	4
P	3.31	2.91	2.77	0.53	3

Table 6. Response table for S/N ratio

Factors	S/N Ratio (db.)				
	L1	**L2**	**L 3**	**D**	**R**
S	-0.38	-13.56	-	13.18	1
f	-8.56	-5.66	-6.69	2.90	2
SV	-7.39	-7.56	-5.96	1.60	3
F	-7.69	-6.30	-6.91	1.39	4

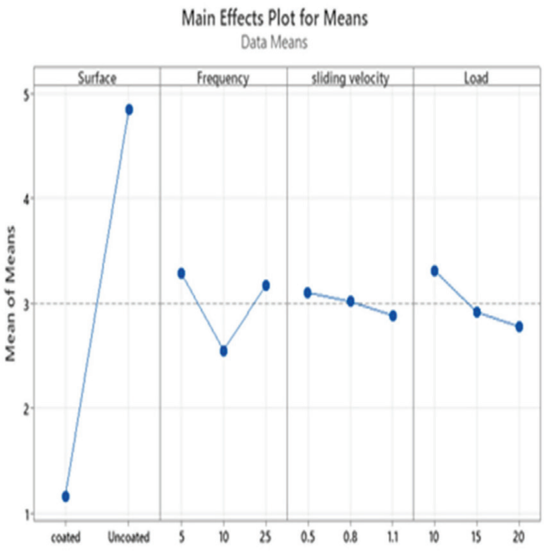

Figure 5. Mean effect plot for means for wear rate

Table 7. Analysis of variation

Source	DF	ADj MS	F value	P value
S	1	61.0218	82.86	<0.0001
f	2	1.8596	1.26	<0.0001
SV	2	0.1441	0.10	<0.0001
F	2	0.9132	0.62	<0.0001
Error	10	7.3646	0.7365	
Total	17	71.3032		

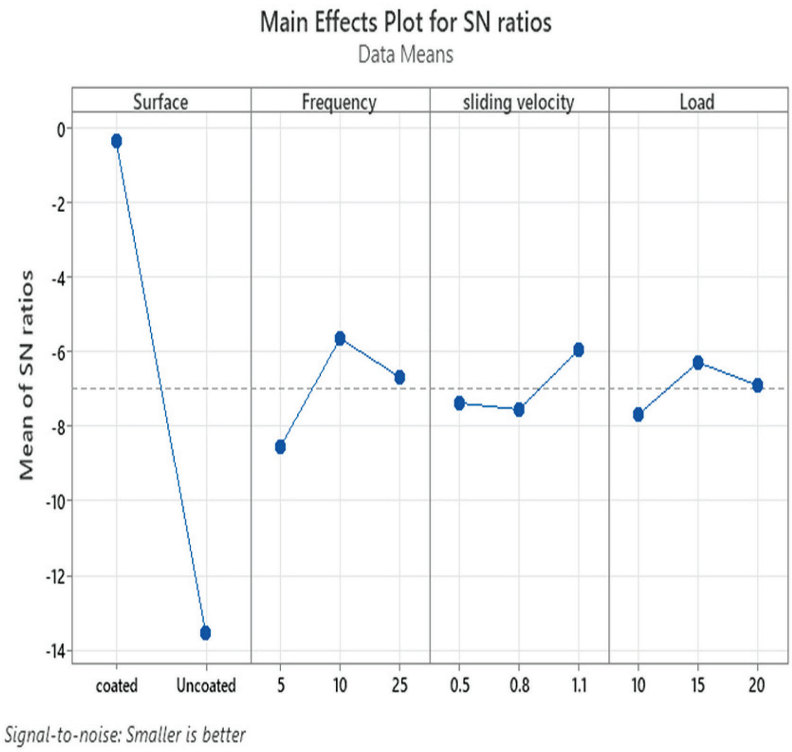

Figure 6. S/N ratio plot for wear rate

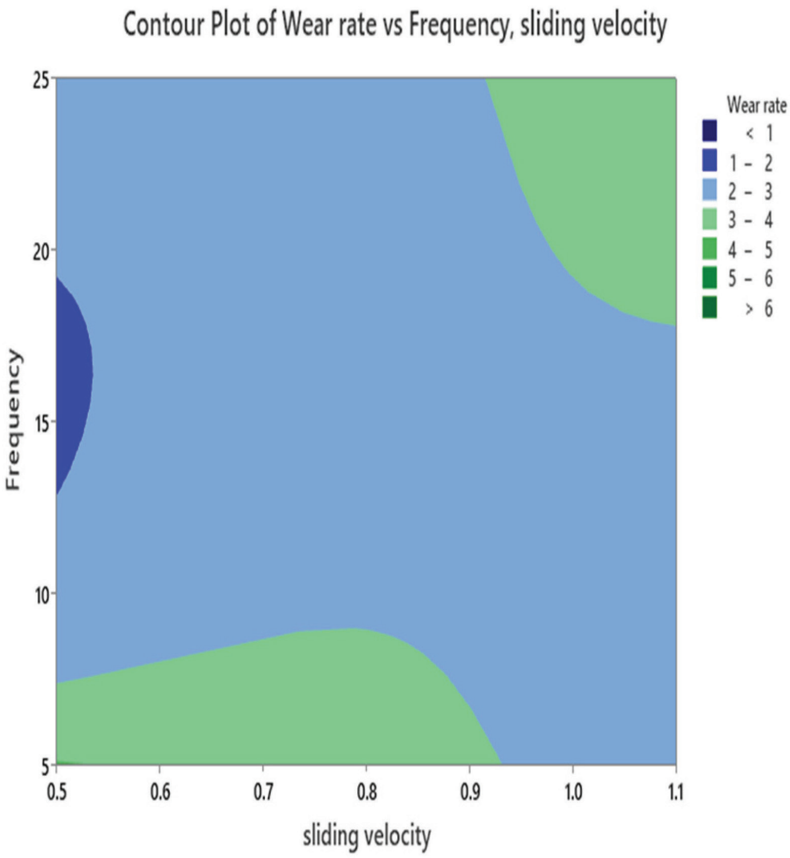

Figure 7. Contour plot of wear rate vs frequency and sliding velocity

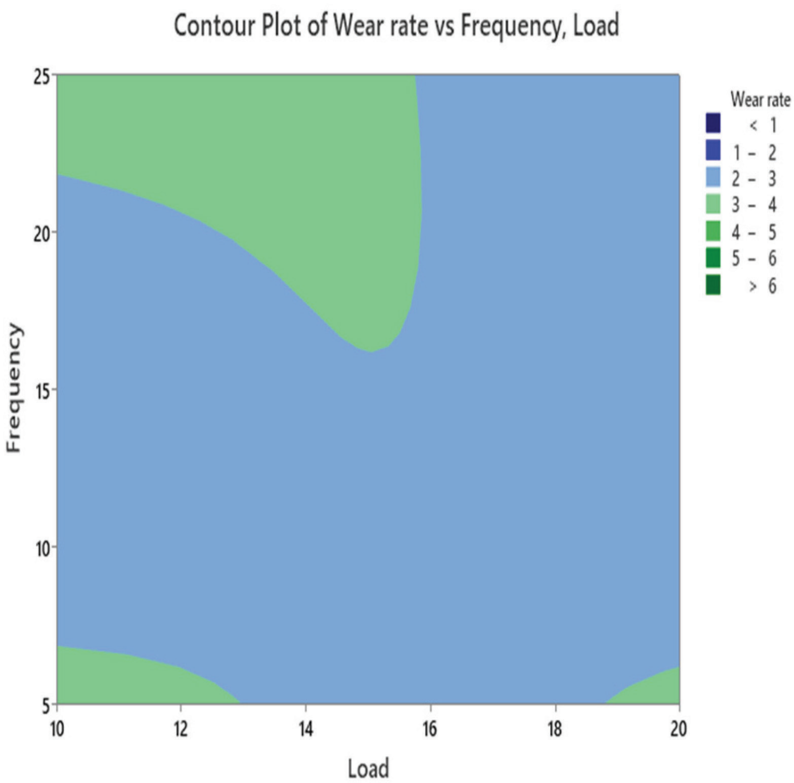

Figure 8. Contour plot of wear rate vs frequency and load

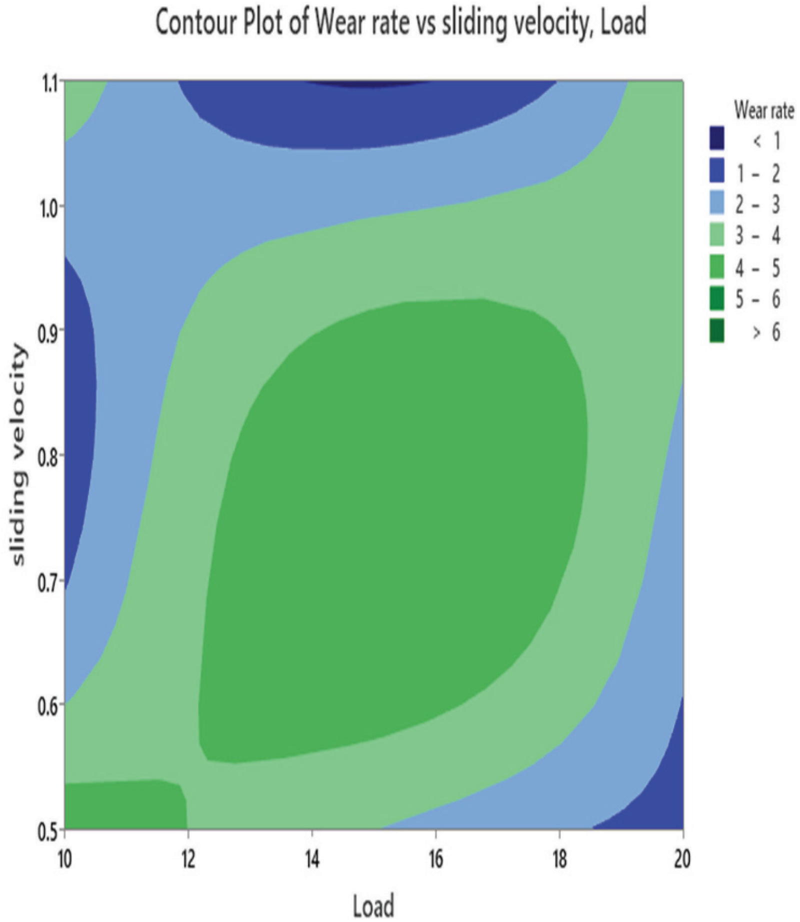

Figure 9. Contour plot of wear rate vs sliding velocity and load

13N or exceeds 19N, and the frequency is less than 6 Hz or between 22 Hz to 25 Hz.

From figure 9, it is apparent that when a contour plot is constructed with the output parameter as wear rate and the input parameters as load and sliding velocity, the minimum wear rate occurs under the following conditions: when the load is below 10 N, or ranges between 12 N to 18 N, or exceeds 19 N, coupled with a sliding velocity between 0.7 m/s to 0.95 m/s, or exceeds 1.05 m/s, or falls below 0.6 m/s.

4. CONCLUSION

This Research clearly illustrate that AH36 steel specimens treated with Fe-based amorphous coatings show significantly lower wear rates. It is further identified that the optimal parameters to achieve the minimum wear rate include a frequency of 10 Hz, a sliding velocity of 1.1 m/s, and a load of 20N. In summary, tackling wear challenges in marine settings requires effective measures like surface treatments and coatings. Optimal load and sliding velocity combinations, along with specific frequency ranges, revealed by contour plots, are crucial for enhancing wear resistance in mechanical systems.

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