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Prediction and Optimisation of Two-Body Abrasive Wear on Chromium Coated Stainless Steel Using Statistical Technique

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Abstract

This study investigates the specific wear rate of chromium-coated steel specimens subjected to varying parameters such as coating thickness, disc rotation speed, applied load and sliding duration using a pin-on-disc setup. The specimens, prepared with chromium coatings of varied thickness ranging from 0 to 8µm, were tested under different conditions to evaluate their wear performance. Results indicate that the specific wear rate is significantly influenced by sliding duration and applied load, with contributions of 42.52% and 35.24%, respectively, while chromium coating thickness accounted for a contribution of 17.84%. The lowest specific wear rate observed was 0.000236 mm/N·m with a 2µm coating under optimal conditions of 1000 RPM, 40 N load, and 25m sliding duration, whereas the highest wear rate of 0.003819 mm/N·m was recorded with an 8 µm coating under less favourable conditions. The average error in the predictions made by the Response Surface Methodology (RSM) model was only 4.27%, confirming the model's reliability in predicting wear rates. This study underscores the importance of optimising load, sliding duration, and coating thickness to enhance the wear resistance of chromium-coated steel, providing valuable insights for practical applications in material science and engineering.

Major Findings: *Key influencing factors like sliding duration and applied load, optimal wear performance, worst wear performance, model accuracy and practical implications.*

Keywords: *Abrasion, Chromium, Coating, Steel, Wear*

1.0 Introduction

Steel is an alloy made up of iron and carbon (up to 2%). However, many other alloy elements are added to produce different grades of steel. It has high strength, durability, versatility, good machinability and weldability. By adding certain elements like chromium, nickel, and molybdenum, it becomes corrosion-resistant[1]. In addition to that, steel is recyclable. Because of the above attractive properties, steel is a widely used material for various applications. Chromium is the first element in group 6 and has an atomic number of 24, which is a hard and brittle transition

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metal. Chromium metal is valued for its high corrosion resistance and hardness[2]. A major development in steel production was that steel could be made highly resistant to corrosion and discolouration by adding chromium. Stainless steel and chrome plating together comprise 85% of the commercial use. Chrome plating is often used in the steel components of machinery, automobiles, railway, aerospace and construction[3,4]. Chromium coating is employed on piston segments of internal combustion engines, moulds and dies, cutting tools, etc.[5]. Chromium coating on steel is one of the popular methods of surface engineering since the coated surface improves corrosion resistance, hardness, wear resistance, and aesthetic appearance[6]. Also, the chromium coatings protect steel in humid atmosphere, in sea water, acidic or alkaline environments by oxidising ammonia, hydrogen sulfide, gases[7]. Because of a passive oxide layer formed on the surface of steel due to chromium coating, steel reacting with the surroundings is prevented[8]. Electroplating, electroless plating, Physical Vapour Deposition (PVD), and Chemical Vapour Deposition (CVD) are the methods used for chromium coating on steel, out of which electroplating is the most used[9]. Applying a chromium nitride (CrN) coating to steel can significantly improve its corrosion resistance. This improvement is achieved by leveraging the inherent hardness and corrosion-resistant properties of CrN, which acts as a protective barrier against corrosive agents[10]. However, most of these are expensive and time-consuming. Hence, statistical tools are used to assess and optimise the coating process parameters and thickness of coating for an intended application[11]. Ion plating, a process where thin films are deposited by ion bombardment of the target material, was used to create the coatings[12]. It was reported in the literature that the spray coating process factors have an influence on the efficiency of solar absorbing films, and the thickness of the selective absorbing film has a strong effect on the absorptance[13-14]. Kolawole *et al* reported that the ANOVA statistical tool can be used to predict tribological operating conditions for metal coatings on steel surfaces, which helps to prevent premature failure[15]. Aabid *et al* used the ANOVA tool on the tribological study of aluminium-based hybrid metal matrix composite and concluded that the results obtained by this are in line with the experimental study, and it reduced time, cost of testing and sample preparation[16]. This study presents a unique and novel approach to understanding the tribological behaviour of chromium-coated steel by systematically investigating the specific wear rate under various operational parameters. While existing literature often focuses on either the effects of coating thickness or operational conditions in isolation, this research work comprehensively examines the interplay between multiple factors, including sliding duration, applied load, and disc rotation speed, alongside the influence of coating thickness. Additionally, the application of Response Surface Methodology (RSM) not only enhances the predictive accuracy of wear rates but also offers a statistical framework for optimising these parameters, filling a critical gap in the literature regarding the use of advanced modelling techniques in tribological studies. By providing empirical data on the wear performance of chromium coatings and elucidating the significant contributions of different operational parameters, this work significantly advances the understanding of material behaviour under sliding conditions, thereby offering practical insights for the design and application of wear-resistant coatings in various engineering domains.

2.0 Materials and Methods

Steel specimens with dimensions of 25×25×12mm were prepared for a 2-body wear test by applying chromium coating of varying thickness (2µm, 4µm, 6µm and 8µm) using the dip coating method. The steel surfaces were first cleaned in an alkaline solution at 70°C for 15 minutes, followed by rinsing using deionised water and drying. To enhance coating adhesion, the surfaces were roughened through grit blasting. Each specimen was immersed in a chromium-based electrolyte solution, with coating thickness controlled by adjusting the number of dip cycles: 1 cycle for 2µm, 2 cycles for 4µm, 3 cycles for 6µm, and 4 cycles for 8µm. The immersion duration was set to 30 seconds per dip, and the withdrawal speed was maintained at 10 cm/min to ensure uniform coating. After dipping, the specimens were air-dried for 30 minutes, followed by curing at 200°C for 2 hours. The coating thickness was measured at five points on each specimen using a digital thickness gauge to confirm uniformity. These prepared specimens were then subjected to 2-body wear testing to evaluate their wear resistance. The sliding wear at various sliding speeds (v), load (F), for various sliding distances (S) was tested using pin-on-disc testing equipment. The specific wear rate (mm/N·m) was calculated using a

pin-on-disc setup, where the wear was determined by measuring the weight difference of the pin before and after the test. The pin was pressed against a rotating disc under a constant applied load. The weight loss of the pin was recorded and then converted into a linear wear value by dividing the weight loss by the material's density and the surface area in contact. The specific wear rate was then calculated by dividing this linear wear value by the product of the applied load (N) and the sliding distance (m), yielding the wear rate in mm per unit of force and distance. The pin-on-disc wear test conducted in this study follows the guidelines outlined in American Society for Testing and Materials (ASTM) G99-17 – Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. This standard provides a framework for evaluating wear behaviour under controlled conditions, including applied load, sliding speed, and contact conditions. The chromium coating thickness was measured using a digital thickness gauge following the ASTM B499-21 – Standard Test Method for Measurement of Coating Thickness by the Magnetic Method. This method ensures precise and repeatable thickness measurements, which are crucial for evaluating coating performance. The number of sliding wear test trials was optimised using Taguchi's design of experiments technique with L25 Orthogonal Array. Further, Analysis of Variance (ANOVA) was performed, and a regression equation was developed using response surface methodology in MINITAB software. Table 1 presents the control factors and their levels used in the experiment.

In this research, the objective was to minimise the specific wear rate, making the lower is better quality characteristic the most appropriate choice. The lower is better S/N ratio can be expressed mathematically as shown in Equation 1.

$$\mathrm{S/N}\ (\eta) = -10x\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

Where n is the number of measurements in a trial. In the present research work, n=5 and yi was set as the i^{th} measured value.

3.0 Results and Discussion

The results from the 2-body wear test show that the specific wear rate of the chromium-coated steel specimens decreased significantly with an increase in coating thickness and a combination of other parameters such as sliding speed, load, and sliding duration. Table 2 presents the experimental results of specific wear rate. For the uncoated steel (0μm), the specific wear rate reduced from 0.00435 mm/N·m at 600RPM, 10N, and 5m to 0.000382 mm/N·m at 1400RPM, 50N, and 25m, indicating that higher sliding speed, load, and sliding duration contributed to lower wear rates due to increased frictional heat leading to smoother sliding surfaces. Similarly, at 2μm coating thickness, the wear rate dropped from 0.001705 mm/N·m to 0.000236 mm/N·m as sliding speed increased from 600 to 1000 RPM, and load increased from 10 N to 40 N, suggesting improved wear resistance with thicker coatings under higher loads. However, deviations like higher wear rates at 1200 RPM and 50 N (0.001188 mm/N·m) indicate that excessive load and speed beyond optimal conditions can cause localised deformation or micro-cracking in the coating. At 4μm, the wear rate ranged from 0.001154 mm/N·m to 0.000566 mm/N·m, showing that moderate coating thickness and balanced parameters provided optimal protection. Thicker coatings are the least influential factor, with only 2.61%. The statistical analysis demonstrates that changes in sliding of 6μm and 8μm further reduced wear, but in certain conditions, such as at 6μm coating with low sliding speed (600 RPM, 40 N), the wear rate was relatively high (0.001432 mm/N·m), and at 8 μm coating with lower load and shorter duration (1000 RPM, 20 N, 5m), the wear rate peaked at 0.003819 mm/N·m. These results indicate that while thicker coatings generally enhance wear resistance due to better load distribution and reduced material removal, extreme combinations of low load and high speed can cause excessive wear. Tribologically, the thicker chromium coatings acted as protective layers that reduced direct metal-to-metal contact, lowered friction, and provided enhanced wear

Table 1. Control factors and their levels

Factors	Levels				
	1	2	3	4	5
Chromium coating Thickness (μm)	0	2	4	6	8
Rotation of disc (RPM)	600	800	1000	1200	1400
Load applied (N)	10	20	30	40	50
Duration of sliding (m)	5	10	15	20	25

Table 2. Experimental results of specific wear rate

SL. No.	Coating Thickness (µm)	Sliding Speed (RPM)	Load (N)	Sliding Duration (m)	Specific Wear Rate (mm/Nm.)
1	0	600	10	5	0.00435
2	0	800	20	10	0.001631
3	0	1000	30	15	0.000955
4	0	1200	40	20	0.000597
5	0	1400	50	25	0.000382
6	2	600	20	15	0.000919
7	2	800	30	20	0.000404
8	2	1000	40	25	0.000236
9	2	1200	50	5	0.001188
10	2	1400	10	10	0.001705
11	4	600	30	25	0.000566
12	4	800	40	5	0.001154
13	4	1000	50	10	0.000942
14	4	1200	10	15	0.001415
15	4	1400	20	20	0.000835
16	6	600	40	10	0.001432
17	6	800	50	15	0.000716
18	6	1000	10	20	0.002673
19	6	1200	20	25	0.001087
20	6	1400	30	5	0.002304
21	8	600	50	20	0.001167
22	8	800	10	25	0.001512
23	8	1000	20	5	0.003819
24	8	1200	30	10	0.00137
25	8	1400	40	15	0.000822

resistance, but at high speeds or wear performance. From Table 3, it is evident that the most influential factor on specific wear rate is sliding duration, with 42.52%, followed by load applied, with insufficient load, coating delamination, or brittle fracture might occur. Hence, optimising coating thickness and process parameters is crucial for achieving the desired 35.24% chromium coating thickness with 17.84%. Sliding speed is the least influential factor, with only 2.61%. From Table 3, it is clear that the most influential factor affecting the specific wear rate is the sliding duration, accounting for 42.52% of the total variation, followed by the applied load at 35.24%. The chromium coating thickness also plays a significant role, contributing 17.84% to the wear rate, while sliding speed duration has a more substantial impact on wear performance, likely due to the increased exposure time leading to greater wear mechanisms such as abrasive wear and surface degradation. The load applied significantly influences the specific wear rate, as higher loads increase contact pressure, which can exacerbate wear processes. Conversely, sliding speed has a minimal effect, suggesting that at the tested speeds, other factors may dominate the wear process. This analysis highlights the importance of optimising sliding duration and load to achieve lower wear rates in chromium-coated steel applications.

From the main effects plots (Figures 1 and 2), it is evident that the optimal combination of parameters to minimise the specific wear rate is a 2µm chromium coating, with a disc rotation speed of 800 RPM, an applied load of 40 N, and a sliding distance of 25m.

Table 3. Analysis of variance for specific wear rate

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	P%
A	4	150.56	150.56	37.64	21.64	0.000	17.84
B	4	21.99	21.99	5.498	3.16	0.078	2.61
C	4	296.22	296.22	74.055	42.57	0.000	35.24
D	4	357.70	357.70	89.425	51.4	0.000	42.52
RSE	8	13.92	13.92	1.74			
Total	24	840.39					

Where A – Chromium coating thickness, B – Sliding speed, C – Load applied, D – Sliding duration, RSE – Residual Error.

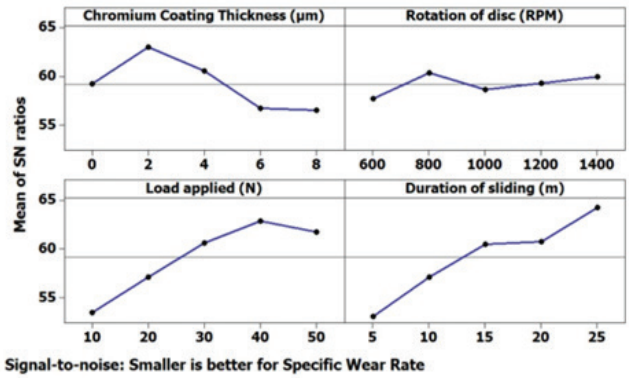


Figure 1. Main effects plot of signal-to-noise ratios.

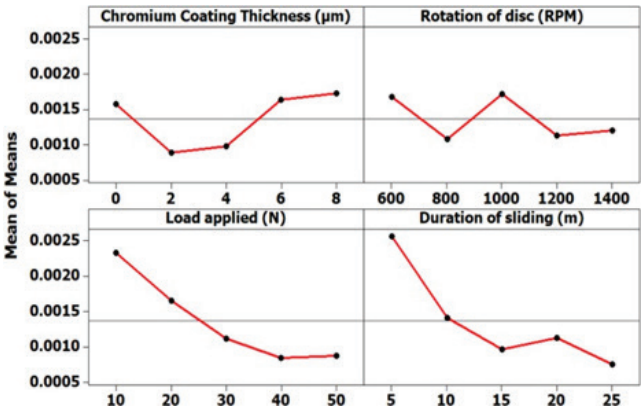


Figure 2. Main effects plot of means.

This specific combination of coating thickness and tribological parameters offers the best balance between load-bearing rate by maximising the protective capacity and wear resistance, reducing the specific wear effect of the chromium coating while minimising material loss. The combination ensures sufficient frictional interaction without causing excessive wear or coating degradation, making it the most effective setup for wear minimisation.

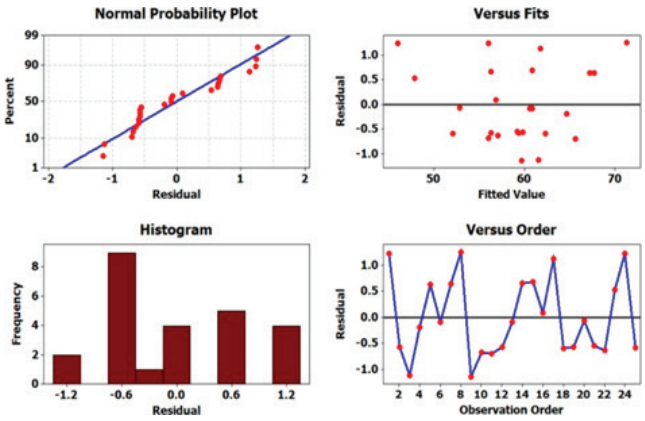


Figure 3. Diagnostic plot of specific wear rate.

The diagnostic plots (Figure 3) indicate that the model fits the data reasonably well. The normal probability plot and the histogram suggest that the residuals are approximately normally distributed, though slight deviations at the extremes hint at possible skew or outliers. The Residuals vs Fits plot shows no clear patterns, implying that the assumptions of linearity and constant variance are likely met. However, the Residuals vs Observation order plot exhibits some patterns, suggesting potential issues with residual independence, which may require further investigation. Overall, the model performs adequately with minor concerns.

Table 4 provides the regression coefficients for developing the second-order polynomial equation, which can be utilised to predict the specific wear rate of the chromium-coated steel specimens. The regression model is further validated through the Analysis of Variance (ANOVA), as shown in Table 5. The F-value of 2.47 from the regression analysis exceeds the critical F-value

(F14,14,0.05), indicating that the model is statistically significant and adequately represents the relationship between the input parameters and the specific wear rate. This confirms the suitability of the regression equation for predicting wear behaviour under varying conditions, making it a reliable tool for optimising wear performance in chromium-coated steel.

From the contour and surface plots (Figure 4), it is evident that specific wear rates in the range of 0.00095 – 0.00112 mm/N·m were achieved with a chromium coating thickness of 4-6μm and applied loads of 25-35 N, indicating optimal wear resistance under moderate loading conditions. Additionally, a wear rate of 0.00108-0.00114 mm/N·m was observed with a very thin 2μm coating thickness, coupled with a sliding duration of 25 minutes, highlighting the importance of sliding time in influencing wear behaviour at lower coating thicknesses. Furthermore, the lowest wear rates, around 0.0008-0.0009 mm/N·m, were achieved with a thinner 1-2μm coating when using a high disc rotation speed of 1400 RPM, indicating that higher speeds may enhance wear resistance under specific conditions. Across these scenarios, the hold values of 1000 RPM disc rotation, 15 minutes sliding duration, and 30 N applied load were maintained, serving as a baseline for comparison. These findings underline the significance of coating thickness, load, and sliding duration in optimising wear performance in chromium-coated steel specimens.

Specific Wear Rate (mm/N.m) =0.001276+ 0.000098A – 0.000313B – 0.000333C – 0.000101D + 0.00018A2 – 0.000062B2 + 0.000251C2 + 0.000015D2 + 0.000243AB + 0.000297AC + 0.00021AD + 0.000038BC + 0.000193BD + 0.000037CD … (2)

From the comparison of RSM prediction values of specific wear rate with experimental values (Figure 5) it can be seen that the overall error percentages vary, ranging from a low of 0.42% for the combination of a 4μm coating, 1000 RPM rotation, 50 N load, and 10m sliding duration, to a high of 10.45% for the 8μm coating, 800 RPM rotation, 10 N load, and 25m sliding duration. On average, the total error percentage across all data points is 4.27%, which is within an acceptable range for predictive models in tribological studies. This suggests that the RSM model is fairly accurate in predicting the specific wear rate under various operating conditions. The larger discrepancies (error%) can be attributed to complexities in the wear mechanisms, such as varying effects of friction, adhesion, and surface interactions, which may not be fully captured by the model in certain conditions.

Table 4. Regression coefficients

Term	Coef	SE Coef	T	P
Constant	0.001276	0.000150	8.513	0.000
A	0.000098	0.000119	0.819	0.425
B	-0.000313	0.000119	-2.625	0.018
C	-0.000333	0.000119	-2.794	0.013
D	-0.000101	0.000119	-0.846	0.410
A^2	0.000180	0.000314	0.572	0.575
B^2	-0.000062	0.000314	-0.199	0.845
C^2	0.000251	0.000314	0.800	0.435
D^2	0.000015	0.000314	0.046	0.964
AB	0.000243	0.000126	1.927	0.072
AC	0.000297	0.000126	2.349	0.032
AD	0.000210	0.000126	1.662	0.116
BC	0.000038	0.000126	0.300	0.768
BD	0.000193	0.000126	1.527	0.146
CD	0.000037	0.000126	0.291	0.775

Where A – Chromium coating thickness, B – Sliding speed, C – Load applied, D – Sliding duration.

Table 5. Analysis of variance of regression coefficients

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	0.0009	0.0009	0.0001	2.47	0.043
Residual	16	0.0004	0.0004	0.0000		
Error						
Total	30	0.0013				

4.0 Conclusion

In conclusion, the study demonstrates a strong correlation between the experimental results and the predictions made by the RSM model, with an average error of only 4.27%, confirming the reliability of the RSM model in predicting the specific wear rate of chromium-coated steel. The analysis reveals that sliding duration and applied load are the most influential parameters, contributing 42.52% and 35.24% to the variation in specific wear rate, respectively. This indicates that longer

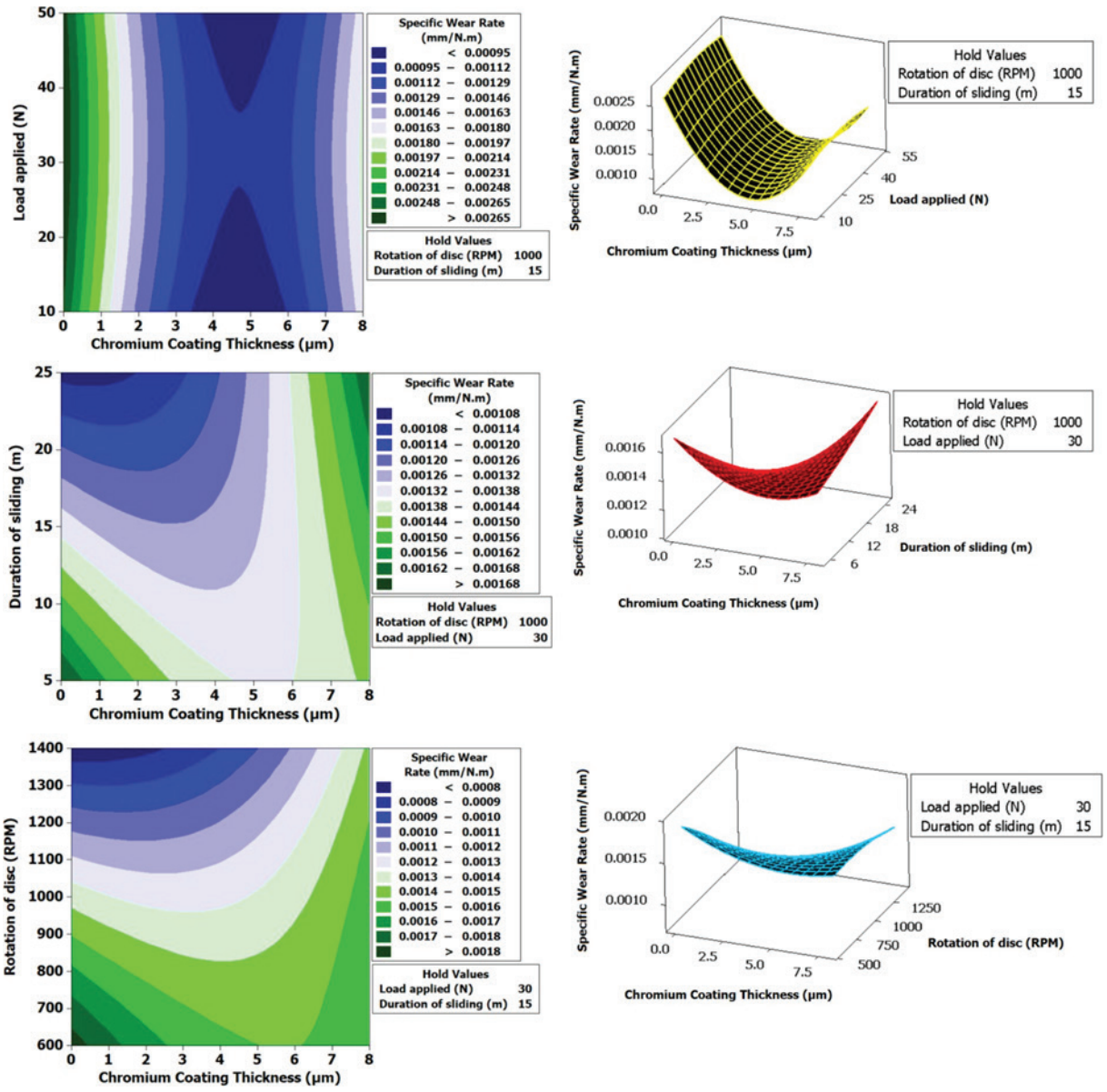


Figure 4. Contour and Surface plots for specific wear rate

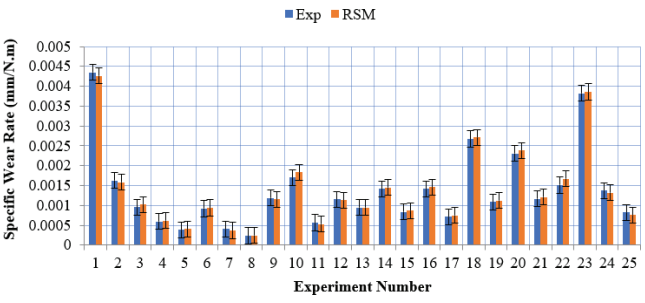


Figure 5. Comparison of RSM prediction values of specific wear rate with experimental values.

sliding durations and higher loads significantly increase material wear, making them critical factors to control for improving wear resistance. Chromium coating thickness, while moderately influential with a contribution of 17.84%, plays a vital role in enhancing wear resistance, particularly when the thickness is optimised in conjunction with load and sliding conditions. The sliding speed, on the other hand, has the least influence on the wear rate, contributing to only 2.61%, suggesting that it has a relatively minor impact on wear compared to other factors. The lowest specific wear rate observed in this

study was 0.000236 mm/N·m, which occurred under the conditions of a 2µm chromium coating, 1000 RPM disc rotation, 40 N load, and 25m sliding duration, showcasing how optimal combinations of load, coating thickness, and sliding conditions can significantly reduce wear. In contrast, the highest wear rate of 0.003819 mm/N·m was observed with an 8µm coating, 1000 RPM disc rotation, 20 N load, and 5m sliding duration, indicating that a thicker coating does not always translate to lower wear, especially under suboptimal loading and sliding conditions.

5.0 References

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