

Sliding Wear Analysis of Ultra High Strength Steel Using Full Factorial Design Approach

Varun Sharma¹, Subodh Kumar² and A.S. Shahi³

Department of Mechanical Engineering, Sant Longowal Institute of Engineering & Technology, Longowal, India

Abstract. This study describes multi-factor-based experiments that were applied to investigate the sliding wear behaviour of quenched and tempered wear resistant steel. This study was aimed to evaluate the effect of input parameters (such as applied load, sliding velocity and sliding time) on wear rate. Full factorial design through design of experiments approach was used for investigation by establishing an empirical relationship between wear loss and input parameters and determining the optimal combination of testing parameters for minimum and maximum wear losses. Sliding wear tests were carried out using pin-on-disc type apparatus at room temperature under dry sliding wear conditions. Detailed investigation revealed that applied load was the most significant factor affecting the wear performance followed by sliding velocity and sliding time. The maximum weight loss due to wear was found to be 33.48 mg when experimentation was conducted at maximum levels of input variables and minimum wear loss of 3.12 mg was obtained at the minimum levels of load, sliding velocity and sliding time. The scanning electron microscopy of the worn pin surfaces shows that adhesion and plastic deformation were the dominating mechanisms involved during experimentation that resulted in maximum wear of the pins, and on the other hand no such mechanism persisted when the pins were worn under minimum sliding wear conditions.

1 Introduction

Cost effective and novel materials having high specific mechanical properties have been the favourite research topic of the material scientists all over the world. Among steels the quenched and tempered low alloy abrasion resistant steels or low alloy martensitic steels are currently being considered as new generation steels [1,2]. These steels are being used to manufacture wear plates which presents an effective solution to the sliding wear problems which accounted for approximately 50 % losses due to wear. Owing to high abrasion resistance due to high hardness & ultra high tensile strength backed with good toughness properties, these wear plates are finding their immediate applications in chutes, hoppers, dump truck beds, cutter bars, scraper blades, liner plates, tipper bodies, containers, crushing mills, excavator buckets and loading buckets etc [2,3]. These wear resistant plates are the modern solution in regeneration of worn machines parts & also for producing new parts which connect high wear resistance with cost reduction [4,5].

In order to study the sliding wear performance of the materials, the Pin-on-disc (POD) testing rig has been used extensively by the researchers [6,7]. Individual and combined effects of independent variables such as load, speed, time and other input variables on sliding wear of different material has been studied by number of researchers in the past [8,9,10,11]. In 2004, the effect of

sliding velocity on wear behaviour of different microstructures of Ni-Cr-Mo-V steel was studied by D. Rai and J.P. Pathak using pin-on-disc set up [12]. Wear resistance of various types of sintered steels was studied by Bidulsky R. et.al. in 2010 [13].

The POD experimental set up provides a broad spectrum of controllable parameters with independent variables whose individual and combined effects can be investigated to study the wear performance of different engineering materials. Owing to wide variability of controllable and uncontrollable variables, the researchers used different statistical techniques to have deep insight into the study of wear behaviour [14,15]. In 2010, empirical models were developed by N.S.M. El-Tayeb et.al. using response surface methodology (RSM) to predict the wear characteristics of Ti54 alloy as a function of sliding wear conditions [16]. Gray-Taguchi method was used by Dharmalingam et.al. in 2011 to investigate the optimization of dry sliding performance of aluminium hybrid metal matrix composites under different loads, sliding speeds and varying percentage of molybdenum disulfide [17].

Ravindran et.al. in 2012 applied the factorial techniques to investigate the effect of percentage of reinforcement, load, sliding speed and sliding distance on the wear and sliding friction response of Al hybrid composites [18].

Through detailed literature review, it was found that most of the experimental design techniques were confined to

^a Corresponding author: author@e-mail.org

investigate the sliding wear behaviour of the composites or hard facings. Besides, very few investigations have been carried out to study the combined effect of test parameters or their interactions (i.e. the combined effects of load, speed and time) on the sliding wear behaviour of materials. All published work focused only on the study of the effect of one parameter at a time. Moreover, to the best of the authors' knowledge, none of the past researchers gave attention to investigate the sliding wear behaviour of Q & T ultra high strength steels.

The main focus of the current research work is to investigate the relationship between the input independent variables such as load, speed and time on the wear performance of the steel, and to develop mathematical models for the wear behaviour of ultra high strength steel during wear test under dry sliding condition at room temperature.

2 Details of experiment

2.1 Base material

A Japanese grade (JFE EH400) quenched and tempered abrasion resistant steel was used in this wear investigation. The chemical composition and mechanical properties of this steel are given in Table 1 & Table 2 respectively. The optical micrograph of the steel is shown in Figure 1. Wear test specimens were machined from 15 mm thick plate of JFE EH400 grade steel to obtain cylindrical pins possessing diameter of 6 mm and height 25 mm with the hemispherical cross-sectional end.

Table 1. Chemical composition of JFE EH400 quenched and tempered low alloy abrasion resistant steel, % weight

S.No.	Element	Composition (%)
1	C	0.217
2	Si	0.363
3	Mn	0.72
4	P	0.007
5	S	0.002
6	Cr	0.467
7	Ni	0.011
8	Mo	0.006
9	Nb	0.0224
10	Ti	0.0152
11	Al	0.0316
12	V	0.0012

Table 2. Mechanical properties of JFE EH400 quenched and tempered low alloy abrasion resistant steel

Properties	Yield strength	UTS	Elongation	Charpy Impact (J)	Hardness
(Units)	(MPa)	(MPa)	(%)	RT	(HB)
Values	1319.77	1435.47	12.5	249	447

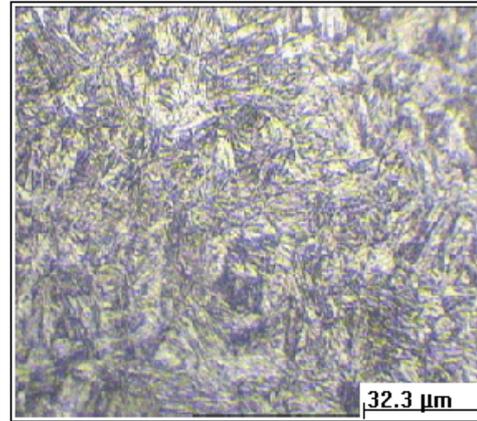


Figure 1. Optical micrograph of the JFE EH400 steel

2.2 Design of Experiment

The experimentation was conducted as per the design of experiments approach by which the number of experiments required, mainly depends on the technique employed through design of experiments. Thus, it is important to have a well designed experiment so that number of experiments required can be minimized [16]. In this study, the design suggested by the full factorial technique has been implemented to analyze the effect of three independent variables for sliding wear i.e. load, sliding velocity and time on wear loss. Table 3 shows the different variables and their levels.

Table 3. Factors and levels of independent variables according to response surface methodology

Factors	Unit	Symbol	Levels	
			-1	1
Load	N	A	20	50
Velocity	m/s	B	1	2
Time	min	C	8	17

The complete design layout for experiments is summarized in Table 4, which shows the experimental combinations of load, velocity and time. As per the design matrix shown in Table 4, a total of sixteen experiments were carried out which constitutes eight factorial points and eight repeated experiments. The software used was Minitab 17.

Table 4. Design matrix and experimental results

Experiments order		Input			Response
Std	Run	A:Load (N)	B:Velocity (m/sec)	C:Time (min)	Wear loss (mg)
	5	1	20	17	5.0
	4	2	50	8	27.4

10	3	50	1	8	9.4
16	4	50	2	17	32.9
9	5	20	1	8	3.4
6	6	50	1	17	14.8
13	7	20	1	17	5.8
2	8	50	1	8	9.1
14	9	50	1	17	14.0
8	10	50	2	17	33.0
15	11	20	2	17	10.5
11	12	20	2	8	4.2
3	13	20	2	8	4.3
7	14	20	2	17	10.2
12	15	50	2	8	28.0
1	16	20	1	8	3.9

2.3 Sliding wear test

A pin-on-disc apparatus shown in Figure 2 was employed to evaluate the wear characteristics of the steel. The wear tests were carried out at room temperature under dry sliding wear conditions in accordance with the ASTM G99-95 standard.



Figure 2. Pin-on-disc test rig

Before the test, the hemispherical ends of pin surfaces were polished with the abrasive paper of 800 mesh grit size and cleaned in acetone, then dried and weighed. The counter material used in this experimentation was EN 31 disc of 8 mm thickness and 100 mm diameter which was hardened to 62 HRC and grounded to the surface roughness of 1.6 Ra. The pin specimens with their hemispherical ends were loaded against metallic disc with the help of a cantilever mechanism. Each test was conducted on a fixed track radius as per the experimental procedure established using full factorial design. After the completion of each test, the wear pin was ultrasonically cleaned in acetone to remove the wear debris, then dried and finally weighed on an electronic balance of 0.0001g measurement accuracy.

3 Full factorial design

Full factorial technique is the compilation of both mathematical and statistical techniques, which are helpful for the modelling and analysis of problems in which a response of interest is influenced by several variables and objective is to optimize the response. In most of the factorial problems, the form of the relationship between the response and the independent variables is unknown. Thus the first step in factorial design is to find a suitable approximation for the true functional relationship between response of interest 'y' and a set of independent variables $\{x_1, x_2, \dots, x_n\}$. If the response is well modelled by a linear function of the independent variables, then the approximating function is the first order model is given as,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \dots + \beta_k x_k + \varepsilon \quad (1)$$

Where, ε represents the noise or error observed in the response y such that the expected response is $(y - \varepsilon)$ and β 's are the regression coefficients [19]. The least square technique is being used to fit a model equation containing input variables by minimizing the residual error measured by the sum of square deviations between the actual and the estimated responses. This involves the calculation of estimates for the regression coefficients. The calculated coefficients or the model equation need to however be tested for statistical significance. So that tests for significance of the regression model, test for significance on individual model coefficients and test for lack-of-fit need to be performed. An ANOVA is commonly used to perform these tests. ANOVA calculates the F-ratio, which is the ratio between the regression mean square and the mean square error. If the calculated value of F-ratio is higher than the tabulated value of F-ratio for roughness, then the model is adequate at desired significance level α to represent the relationship between response and the independent variables. For testing the significance of individual model coefficients, the model is optimized by adding or deleting coefficients through forward addition, backward elimination or stepwise elimination or addition. It involves the determination of P-value or probability of significance. If the P-value is less or equal to the selected confidence level, then the effect of the variable is significant. If the P-value is greater than the selected confidence level, then it is considered that the variable is not significant.

4 Results and discussion

4.1 Metallography

The optical micrograph of the base metal taken at the magnification of 400X and shown in Figure 1, clearly indicates the extra fine microstructure of acicular tempered martensite revealed under high magnification only. The grains consisting of laths of tempered

martensite are clearly identified which are separated by high angle boundaries. Literature shows that the laths of the martensite contain very fine, uniformly distributed coherent carbides. Such a structure results in high yield strength, hardness & toughness of the steels. This structure is responsible for providing the excellent wear resistant properties to these steels.

The results of the 16 experiments conducted as per the experimental plan are shown in Table 4 along with the run order selected at random. These results were input into the Minitab 17 software for further analysis.

4.2 Statistical analysis of variance (ANOVA)

Analysis of variance (ANOVA) is commonly used to perform test for significance of the regression model, model coefficients and lack-of-fit. This analysis was carried out for a significance level of $\alpha = 0.01$, i.e. for a confidence level of 99%. ANOVA test for 23 full factorial model for wear loss is summarized in Table 5. This shows the value of “Prob. > F” for model to be 0.0001 which is less than 0.01, that indicates the model is significant. In the same manner, The value of “Prob. > F” for main effect of load, sliding velocity and sliding time with two-level interaction of load and velocity was less than 0.01, thereby, indicating that these terms are significant model terms. The value of Prob. > F for lack-of-fit is 0.0328, thus greater than 0.01, which indicates that lack of fit is insignificant which is the desirable condition to fit the model.

Table 5. Resulting ANOVA table for full factorial model

Source	DOF	Adj SS	Adj MS	F-Value	P-Value	
Model	6	1709.35	284.89	461.10	< 0.0001	S
Linear	3	1455.50	485.16	785.25	< 0.0001	S
A	1	919.61	919.60	1488.40	< 0.0001	S
B	1	452.63	452.62	732.59	< 0.0001	S
C	1	83.27	83.26	134.77	< 0.0001	S
Interactions	3	253.85	84.61	136.96	< 0.0001	S
AB	1	247.28	247.27	400.22	< 0.0001	S
AC	1	1.63	1.62	2.63	0.139	NS
BC	1	4.95	4.95	8.01	0.020	NS
Error	9	5.56	0.61			
Lack of Fit	1	4.52	4.51	34.57	0.0328	NS
Pure Error	8	1.05	0.13			
Total	15	1714.91				
Std. Dev.		0.786	R-Squared		99.68%	
Adj R-Squared		99.46%	Pred R-Squared		98.98%	

The total variation in the model can be explained by the R^2 value which is 0.9967 or close to 1, which is the desirable value. The adjusted R^2 value is equal to 0.9946, which is particularly useful when comparing models with different number of terms. The result shows that the

difference between adjusted R^2 value and ordinary R^2 value is within the limit of 20%. The final regression model for wear loss in terms of actual factors is represented in equation (2), and the corrected regression model by eliminating the insignificant terms is shown in equations (3).

$$\begin{aligned} \text{Wear rate (Actual)} \\ = 7.73 - 0.34 \text{ Load} - 10.80 \text{ Velocity} - 0.029 \text{ Time} + 0.52 \text{ Load} * \text{Velocity} + 0.0047 \text{ Load} * \text{Time} \\ + 0.247 \text{ Velocity} * \text{Time} \end{aligned} \quad (2)$$

$$\text{Wear rate (Corrected)} = 7.73 - 0.34 \text{ Load} - 10.80 \text{ Velocity} - 0.029 \text{ Time} + 0.52 \text{ Load} * \text{Velocity} \quad (3)$$

In order to ascertain, that whether the residuals follow a normal distribution or not, the normal probability plot of the residuals is drawn as shown in Figure 3. The figure shows that the residuals generally fall on a straight line implying that the errors are distributed normally. To test the assumption of constant variance, a graph is plotted between residuals and predicted response for wear loss as shown in Figure 4. The presence of random scatter without any geometrical or defined shape signifies that the assumption has not been violated.

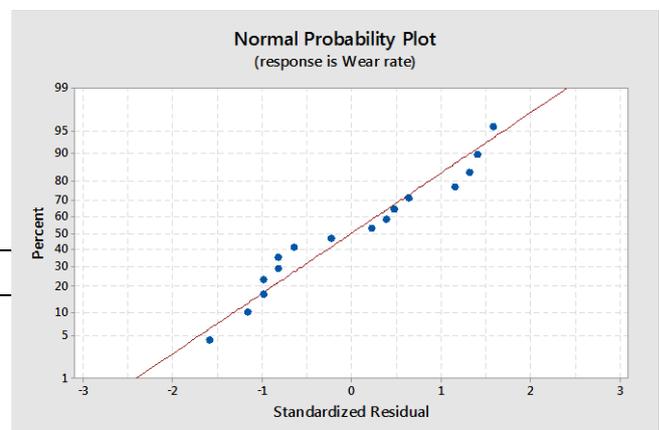


Figure 3. Normal probability plot of residuals

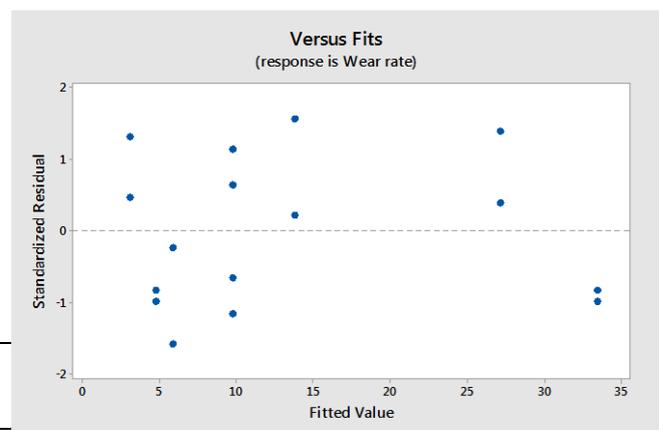


Figure 4. Plot of standardized residuals vs. fitted values

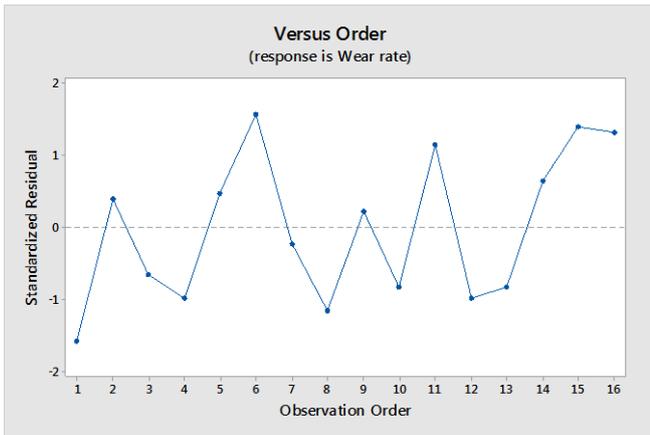


Figure 5. Plot of standardized residuals vs. run order

The randomization of the experimental runs resulted in reducing systematic experimental error and is clearly evident from the graph plotted between standardized residuals and the observation runs shown in Figure 5 the graph shows the significant fluctuation of the error values across the mean value of the standardized residuals.

The Figure 6 shows the effect of load, velocity and time on the wear rate of performance of the base metal. The graphs show that all the factors had an increasing positive influence on the wear rate. However variation in slope of the curves indicates that the load had the maximum influence on the wear loss of the material followed by velocity and time.

The combined effects of input parameters on wear rate are depicted as interactions and are shown in Figure 7. No observable interaction has been observed for the combined effect of load and time, and velocity and time. However a strong interaction effect has been observed for the combined effect of load and velocity. A significant divergence between load and velocity curves has been observed with an increase in load from minimum to the maximum value and maximum curve divergence occurred at the maximum value of load.

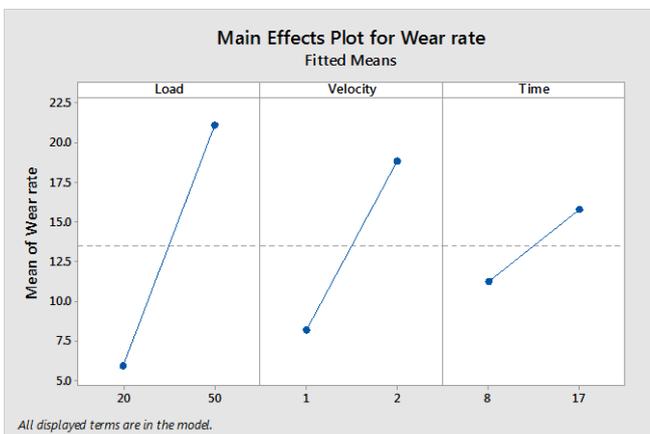


Figure 6. Single factor plots of load, velocity and time for wear rate

The 3D surface graph shown in Figure 8 shows the interaction effect of load and sliding velocity on the wear loss of the specimen pins when the pins were subjected

for 12.5 minutes sliding wear. Figure clearly shows that wear loss is following a linear relationship with load and sliding velocity. Higher slope of surface w.r.t. load illustrates its stronger effect on wear loss in comparison to sliding velocity.

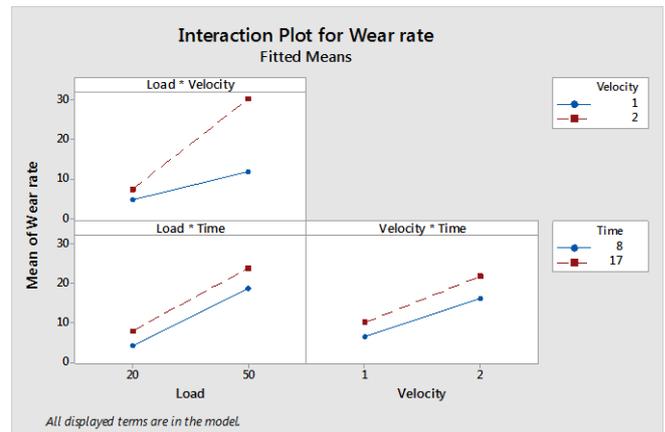


Figure 7. Combined graph illustrating the influence of interactions on the wear rate

From the 3D surfaces it can be clearly inferred that the minimum wear loss was achieved at lowest level of load and sliding velocity. Similarly, the maximum weight loss occurred for the conditions when load and sliding velocity were at their maximum levels. The flat profile of 3D surfaces for wear loss shows that the best fitted model is linear in nature.

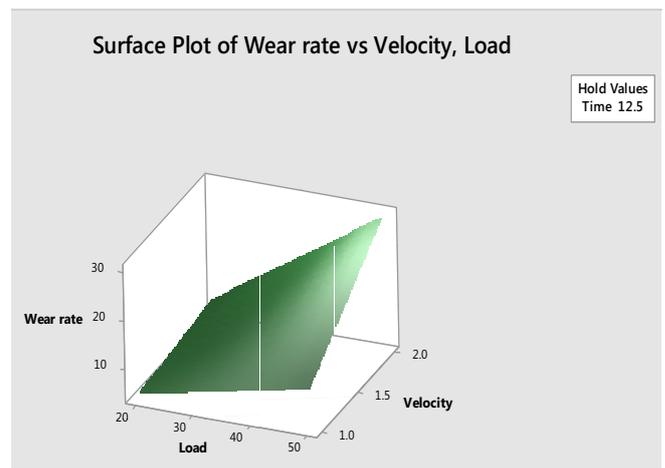


Figure 8. Three-dimensional surface plot for wear loss for a time period of 12.5 min

Figure 9 represents the cube plot which shows the simultaneous effect of load, velocity and time on the wear loss. It can be figure out from the cube that the minimum wear loss of 3.118 mg occur when load was 20 N, sliding velocity was 1 m/s and sliding time for 8 min. Similarly, the maximum weight loss of 33.48 mg occur when the pins were loaded against the disc for 17 minutes, subjected to maximum load of 50 N and exposed for maximum sliding velocity of 2 m/s.

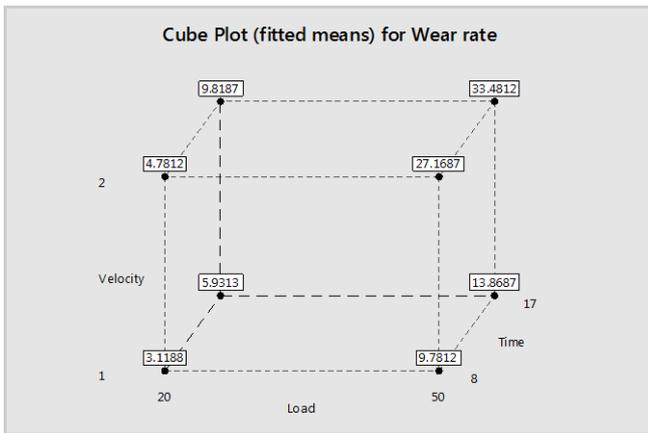


Figure 9. Cube plot for wear loss

4.3 Wear optimization

The current research problem was aimed at finding the optimal values of input variables in order to ascertain the minimum and maximum wear loss, the optimal solutions of which are reported in Table 6.

Table 6. Optimization results of sliding wear

Wear condition	Solution no.	Load (N)	Velocity (m/s)	Time (min)	Wear (mg)	Remarks
Minimum	1	20	1	8	3.12	Select
	2	21.27	1	8	3.40	
Maximum	1	50	2	17	33.48	Select
	2	50	1.97	17	33.00	

4.4 Confirmation experiments

The mathematical model in the form of regression equation that was statistically developed for wear loss and given by equation (3) was found to be significant and was validated through F-tests and lack-of-fit test. The coefficient of variation (R^2) for model was found to be 0.9968, which indicates its effectiveness of making predictions. This conclusion is further supported through the confirmation runs. A set of confirmation runs were performed to verify the prediction ability of the developed wear model. The details of the confirmation runs are given in Table 7. The percentage error between the experimental and the predicted values was found to be less than 6%, which clearly demonstrates the accuracy of the models developed in this study.

Table 7. Plan of confirmation experiments and results

Wear condition	Test conditions			Wear loss (mg)		Error (%)
	Load (N)	Velocity (m/s)	Time (min)	Predicted	Experimental	
Minimum	20	1	8	3.12	3.28	5.1
Maximum	50	2	17	33.48	35.09	4.8

4.5 Worn Surface observations

Experiments were conducted using the optimal sets of input variables to obtain the minimum and maximum wear conditions as shown in Table 7. The worn out ends

of the wear pins were sectioned and their surface morphology was examined using scanning electron microscopy. The surface morphology of worn out pins under minimum wear condition and maximum wear condition are shown in Figure 10 and Figure 11 respectively.

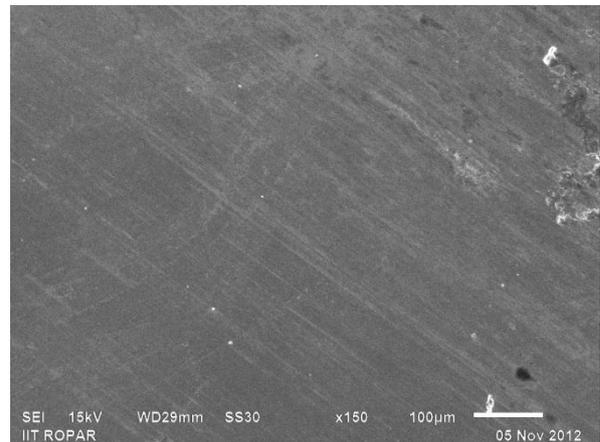


Figure 10. SEM micrographs of worn out pin at the magnification of 150X. under minimum wear condition when load is 20 N, velocity is 1 m/s, time is 8 min.

The SEM macrograph of the worn out surface of the pin worn under minimum wear testing conditions is shown in Figure 10. At the minimum wear conditions (load of 20 N, sliding velocity of 1 m/s and time 8.04 minutes), mild wear occurred. No adhesion or oxidation marks have been observed on the surface.

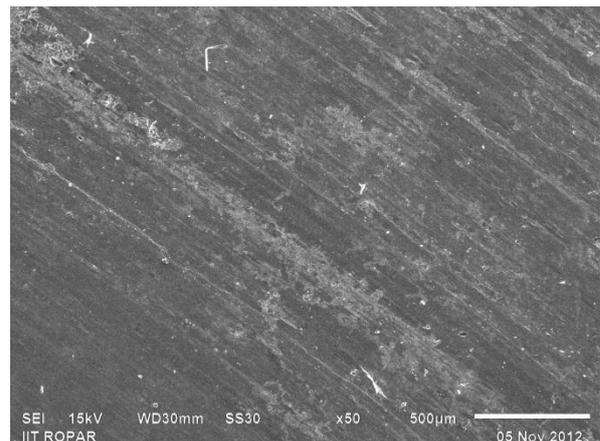


Figure 11. SEM micrographs of worn out pins at the magnification of 50X under maximum wear condition when load is 50 N, velocity is 2 m/s and time is 17 min.

However at the maximum wear testing condition (load is 50 N, velocity is 2 m/s and time is 17 minutes), adhesion arises as the most damage mechanism together with intense plastic deformation, which becomes more evident from the SEM micrograph shown in Figure 11. The figure shows the presence of adhesion marks and attached debris to the worn surface owing to the oxidation and excessive heating of the pin surface under maximum wear testing conditions. Similar worn surface morphology has been reported by C.C. Viafara et.al. for

the unlubricated sliding wear of pearlitic and bainitic steels [20].

5 Conclusions

The present investigation has been carried out to develop the mathematical relationship between wear rate as response and input variables namely applied load, sliding velocity and sliding time using 23 full factorial design. Through this study an attempt has been made to identify the most significant factor that affects the wear performance of the quenched and tempered low alloy abrasion steel. The results reveals that applied load was found to be the most significant factor with the percentage contribution of 53.79% followed by sliding velocity (26.48% contribution) and sliding time (4.87% contribution). Further, the maximum weight loss due to wear was found to be 33.48 mg when load was 50 N and disc was rotated at a sliding velocity of 2 m/s for 17 minutes. Similarly, the minimum wear of 3.12 mg was found at 20 N load when disc loaded for 8 minutes at a sliding velocity of 1 m/s. Furthermore the prediction ability of the mathematical model was verified through confirmation experiments and the percentage error between the experimental and the predicted values of wear loss were found to be less than 6 %. This shows the excellent predicting ability of the developed mathematical model within the ranges of tested parameters.

References

1. Y. Murota, M. Hashimoto and T. Abe, "High performance steel plates for construction and industrial machinery use", JFE Technical Report, pp.60-65, 2005.
2. Buglachi, H.; Smajdor, M. Mechanical properties of abrasion resistant Hardox 400 steel and their welded joints. *Advances in Material Science* 2003, 4 (2), 5-8.
3. R.S. Parmar, "Welding Engineering and technology", 2nd Ed. New Delhi, Khanna Publishers, 2003.
4. JFE Steel Plate, A Manual, 1-36 pp. 2010.
5. M. Adamiak, J. Gorka, T. Kik, "Comparison of abrasion resistance of selected constructional materials", *Journal of Achievements in Materials and Manufacturing Engineering*, Vol. 37, issue 2, pp. 375-380, 2009.
6. Ruff, A.W.; Bayer, R.G. *Tribology: Wear Test Selection for Design and Application*; American Society for Testing and Materials, Philadelphia, PA, 1993; 94-99 pp.
7. Riyadh A. Al-Samarai, Haftirman, Khairil Rafezi Ahmed, Y. Al-Douri, "Effect of load and sliding speed on wear and friction of Al-Si casting alloy", *International Journal of Scientific and Research Publications*, Vol. 2, issue 3, pp. 1-4, 2012.
8. H.A. Ameen, K.S. Hassan, E.M.M. Mubarak, "Effect of loads, sliding speeds and times on the wear rate for different materials", *American Journal of Scientific and Industrial Research*, Vol. 2(1), pp. 99-106, 2011.
9. F.U. Ozioko, "Synthesis and study on effect of parameters on dry sliding wear characteristics of Al-Si alloys", *Leonardo Electronic Journal of Practices and Technologies*, Issue 20, pp. 39-48, 2012.
10. R. Tyagi, S.K. Nath, S. Ray, "Effect of martensite content on friction and oxidative wear behavior of 0.42 pct carbon dual-phase steel", *Metallurgical and Materials Transactions A*, Vol. 33A, pp. 3479-3488, 2002.
11. H. So, "Characteristics of wear results tested by pin-on-disc at moderate to high speeds", *Tribology International*, Vol. 29 (5), pp. 415-423, 1996.
12. D. Rai, J.P. Pathak, "Influence of sliding velocity on wear behavior of different microstructures of Ni-Cr-Mo-V steel", *Indian Journal of Engineering & Materials Sciences*, Vol. 11, pp. 113-120, 2004.
13. R. Bidulsky, M. Actis Grande, A. Zago, Z. Brytan, J. Bidulska, "Wear resistance of various type sintered steels", *Archives of Metallurgy and Materials*, Vol. 55, issue 3, pp. 623-629, 2010.
14. R. Shanmugam and N. Murugan, "Optimization and sensitivity analysis of wear model of satellite 6 hardfacing by gas tungsten arc welding process", *IE (I) Journal-MM*, Vol. 85, pp. 65-70, 2004.
15. Y. Sahin, "Optimal testing parameters on the wear behavior of various steel", *International Journal of Materials and Design*, Vol. 27, pp. 455-460, 2006.
16. N.S.M. El-Tayeb, T.C. Yap, P.V. Brevern, "Wear characteristics of titanium alloy Ti54 for cryogenic sliding applications", *Tribology International*, Vol. 43, pp. 2345-2354, 2010.
17. S. Dharmalingam, R. Subramaniam, V. Somasundara, B. Anandavel, "Optimization of tribological properties in aluminium hybrid metal matrix composites using gray-taguchi method", *Journal of Materials Engineering and Performance*, Vol.20, pp. 1457-1466, 2011.
18. P. Ravindran, K. Manisekar, P. Narayanasamy, N. Selvakumar, R. Narayanasamy, "Application of factorial techniques to study the wear of Al hybrid composites with graphite addition", *Materials and Design*, Vol. 39, pp. 42-54, 2012.
19. D.C. Montgomery, "Design and Analysis of Experiments", 5th ed., Wiley, New York, 2001.
20. C.C. Viafara, M.I. Castro, J.M. Velez and A. Toro, "Unlubricated sliding wear of pearlitic and bainitic steels", *Wear*, Vol. 259, pp. 405-411, 2005.