

Effect of Experimental Parameters on the High-Stress Abrasive Wear Behavior of Steels and a Software Package for Its Prediction

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The effect of different experimental factors on the high-stress abrasive wear properties of steels has been studied. A correlation among the factors has been established by linear regression analysis. A computer software in Microsoft Basic language utilizing linear regression analysis has been developed with the capability of predicting the wear response of steels from the experimental factors.

Keywords carbon steel, computer analysis, tribology, wear

1. Introduction

The performance of the steels used for making a number of engineering components under high-stress abrasive wear is an important factor in deciding its tribological performance under actual field conditions (Ref 1, 2). Steels with varying chemical composition and hardness were tested for their high-stress abrasive wear behavior under different experimental conditions. The wear response depends on a number of experimental factors used both independently and jointly. These factors were studied using linear regression analysis. A software has been developed by factorial designing of the experimental data at the maximum and minimum values of the variables. The software can predict the wear response at all intermediate variables within the experimental range.

2. Experiment

2.1 Material Specifications

Five types of steels were chosen for the present study. Their chemical composition, density, and hardness are shown in Table 1.

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2.2 Wear Tests

High-stress abrasive wear behavior was measured on a Suga abrasion tester (Fig. 1) in which a 25 by 35 by 4 mm sample was fixed over a rotating wheel, which was covered with emery paper. Loads of 3, 5, and 7 N were applied on the sample by cantilever methods (Ref 3). The wheel is rotated in strokes, and one complete rotation of the wheel corresponds to 400 strokes and 26 m sliding distance. Weight loss of the sample was measured after every 26 m sliding distance up to 182 m. Fresh emery paper was used after one complete rotation of the wheel. Volume loss was calculated by dividing the weight loss by density.

2.3 Microstructural Examination

Samples from the steels were metallographically polished using conventional techniques and etched in 0.1% nital to reveal the microstructural constituents.

2.4 Factorial Designing and Linear Regression Analysis

The factorial design was based on the P^n type (Ref 4), where P is the number of levels and n is the number of variables. In the present study, two variables, load (X_1) and distance (X_2), were considered. Therefore, $n = 2$. The maximum value of the variables is +1, and the minimum value is –1. There are two levels ($P = 2$). Thus, $P^n = 4$ experimental values (at the maximum and minimum of the load and distance) are to be considered for the regression analysis.

The response variable, Y (volume loss), is expressed as a function of load, distance, and interdependence of these two variables. Thus,

Table 1 Chemical composition and physical properties of steels

	Composition, wt%						Density, 10^3 kg/m^3	Hardness, HV
	C	Si	Cr	Mn	Ni	Fe		
Steel 1	0.39	0.16	0.13	0.05	0.05	Bal	7.86	160
Steel 2	0.30	0.06	0.06	0.05	0.06	Bal	7.85	189
Steel 3	0.44	1.75	0.05	0.10	0.14	Bal	7.77	300
Steel 4	0.50	1.50	0.02	0.06	0.09	Bal	7.74	325
Steel 5	0.65	0.11	…	0.35	0.13	Bal	7.34	460

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_1X_2 \quad \text{(Eq 1)}$$

where a_0 is the response at the base level, a_1 and a_2 are coefficients representing the effects of the variables X_1 and X_2. A positive value of Y means wear (volume) loss; similarly a positive value of any coefficient indicates increase in the volume loss with increase in that particular variable, and a negative variable indicates decreasing trend of volume loss with increase in that variable.

Table 2 Software package for predicting high-stress abrasive wear behavior of steels by factorial designing

Main Menu
1. To open data file for the variables, such as load (X_1), distance (X_2), and volume loss (Y)
2. Calculation of the coefficients a_0, a_1, a_2, and a_3
3. To open a data file for intermediate coded values of the material
4. Calculation of predicted values
5. Exit from the program

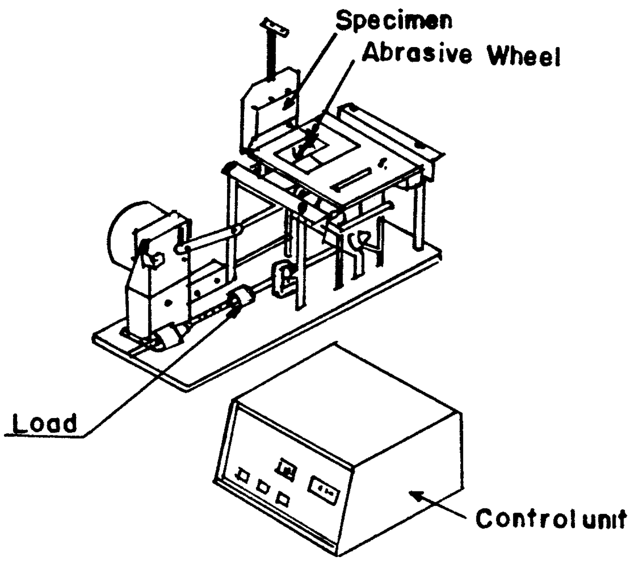


Fig. 1 High-stress abrasive tester

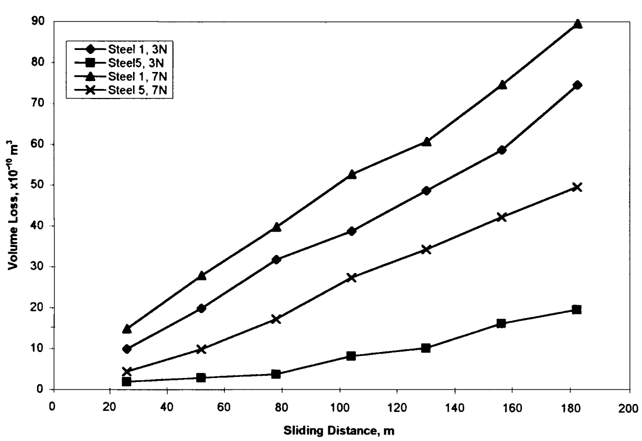


Fig. 2 Variation of volume loss with distance for steels 1 and 5 at different loads

The regression coefficients (a_0 to a_3) were calculated from the experimental values at the maximum and minimum of each level. A +1 level for X means maximum load, whereas –1 means minimum load, similarly +1 and –1 values for X_2 designate maximum and minimum distance, respectively. In the present study, X_1 = +1 corresponds to 7 N and X_1 = –1 corresponds to 3 N; X_2 = +1 corresponds to 156 m and X_2 = –1 corresponds to 26 m.

2.5 Computer Simulation

With the help of Eq 1, a computer software program in Microsoft Basic has been designed. The software is menu driven and consists of four functions (Table 2). Each function is performed by an independent program. The first function consists of entering the data for the variables X_1 (load), X_2 (distance), and Y (volume loss) at X_1 and X_2 equal +1 and –1. The second function calculates the coefficients (a_0, a_1, a_2, and a_3) from the first function. The coefficients are given in a tabular form. These coefficients in the third function help predict the volume loss under different experimental conditions. For prediction, the coded values of the variables X_1 and X_2 are entered in the third function. The final function calculates the predicted values, which are printed in a tabular form.

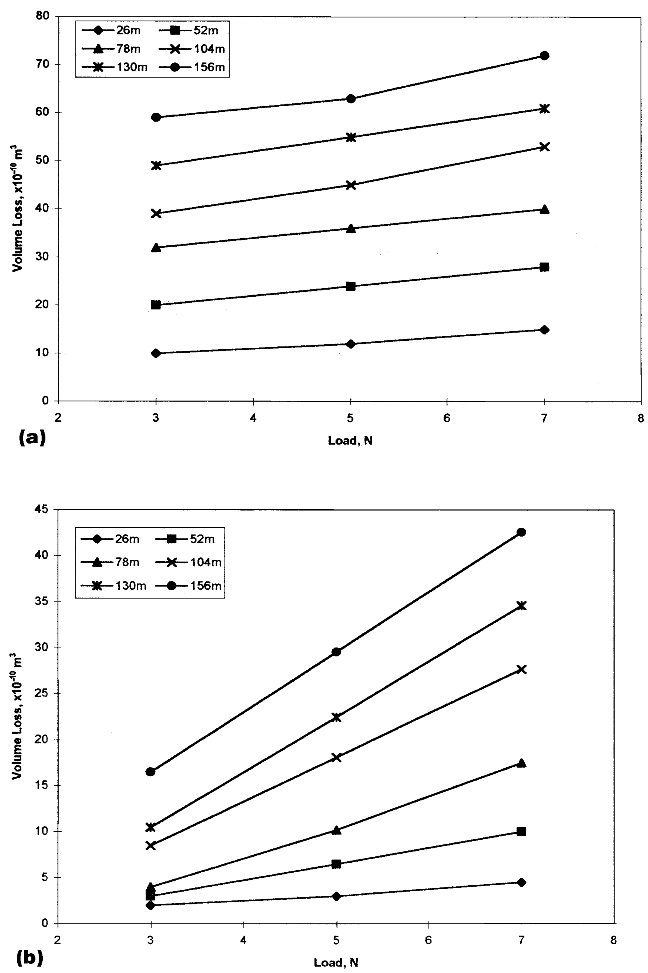


Fig. 3 Variation of volume loss with load for (a) steel 1 and (b) steel 5

Within the selected experimental domain, the software can predict values of volume loss at varying levels of X_1 and X_2 between +1 and –1 using the coded values of the selected experimental parameters.

The coded values of any intermediate level are calculated as follows (Ref 5):

Intermediate (or coded value) =
(selected value – base value)/(difference between base value to upper or lower level) (Eq 2)

In this instance,

Base value = (upper level + lower level)/2 (Eq 3)

For example, when calculating the coded value for 104 m, the base value for distance is (156 + 26)/2 = 91. Therefore, the coded value is (104 – 91)/(91 – 26) = 0.2.

The predicted values from the software have been compared with the experimental values at a number of intermediate or coded values of load and distance.

3. Results and Discussion

3.1 Wear Tests

The variation of volume loss with distance for the steels with the minimum and maximum hardness is plotted in Fig. 2, which shows there is a linear variation up to 156 m. Hence, the linear regression analysis can be carried out from 26 m to 156 m.

The volume loss as a function of load for the above two steels at the minimum and maximum distance exhibits a linear behavior (Fig. 3). Hence, the linear regression analysis can be carried out within the limits of load from 3 to 7 N.

3.2 Microstructural Analysis

The microstructural features of the steels are given in Fig. 4(a-e). For steels 1 and 2, the features are ferrite and pearlite in varying quantity depending on their carbon content (Fig. 4a, b). Hardness values (Table 1) are commensurate with the microstructural features (Ref 6, 7).

For steels 3 and 4, the microstructural features are similar to steels 1 and 2 (Fig. 4c, d). Only the quantity of pearlite is significantly higher because of the higher concentration of carbon (Ref 6, 7).

Steel 5 exhibited basically pearlite structure (Fig. 4e) with a minor quantity of ferrite phase in the microstructure (Ref 6, 7).

3.3 Linear Regression Analysis and Computer Simulation

There is a linear relationship between volume loss and distance from 26 to 156 m and from 3 to 7 N (Fig. 2). Hence, in this situation, when X_1 is +1 the load is 7 N, and when X_2 is –1 the load is 3 N. Similarly, X_1 is +1 at 156 m, and X_2 is –1 at 26 m. The experimental values of volume loss for the combinations of maximum and minimum load and distance for the different steels are given in Table 3.

With the help of the software, the coefficients a_0 to a_3 have been calculated from Table 3 for the different steels. The coefficients obtained are given in Table 4.

The coefficients have a positive value, indicating an increasing trend in the volume loss with increasing distance and load. The coefficient a_0 is maximum for steels 1 and 2, which indicates a higher volume loss for these steels. The minimum value of a_0 is for steel 5. The volume loss decreases with the increase in the hardness of steels under identical experimental conditions. This is commensurate with hardness as it is one of the prime factors in deciding the wear behavior of a steel (Ref 8, 9). In all the situations, the coefficient for distance (a_2) is much higher than that for load (a_1). The coefficients for steel 5 are much less than the other steels, indicating that the increase in volume loss with distance is least.

Coded values at intermediate levels of load and distance are presented in Table 5. From the developed software, the predicted values of all combinations of the coded values can be obtained and are shown in Table 6. Only the load values of 3, 5, and 7 N have been considered, because the experimental setup can measure only these values. This is not a limitation of the software, as it can predict the values as 4 and 6 N also.

Table 3 Experimental values for calculation of coefficients

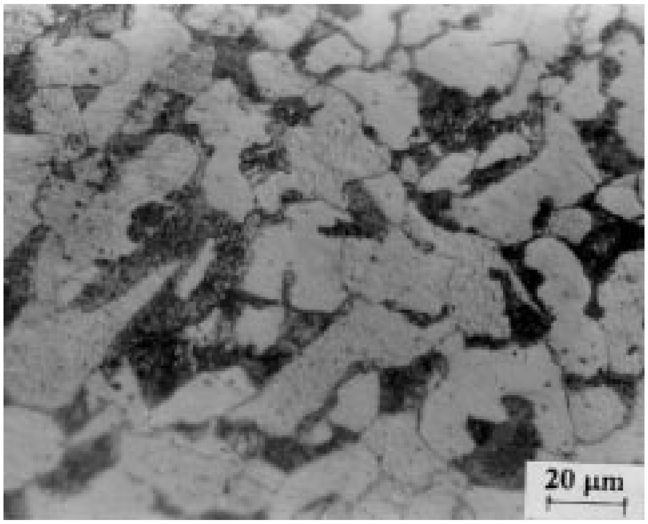
		Volume loss, 10^{-10} m^3				
X_1	X_2	Steel 1	Steel 2	Steel 3	Steel 4	Steel 5
+1	+1	74.5	86.0	51.1	55.6	42.6
+1	–1	58.9	59.0	41.0	43.0	38.4
–1	+1	14.8	13.0	3.5	5.7	4.5
–1	–1	9.0	10.0	7.0	5.6	5.8

Table 4 Linear regression coefficients for steels

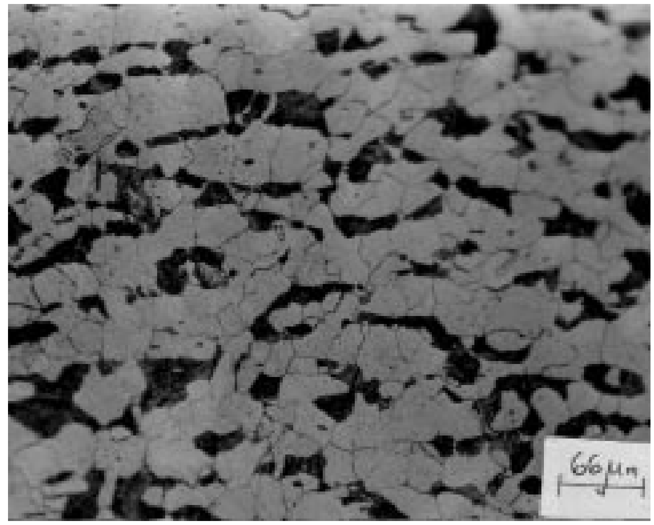
	Linear regression coefficient			
	a_0	a_1	a_2	a_3
Steel 1	39.3	5.35	27.4	2.45
Steel 2	42.0	7.5	30.5	6.0
Steel 3	25.625	1.625	20.375	3.375
Steel 4	27.475	3.175	21.825	3.125
Steel 5	22.825	0.725	17.675	1.375

Table 5 Coded values at intermediate levels of load and distance

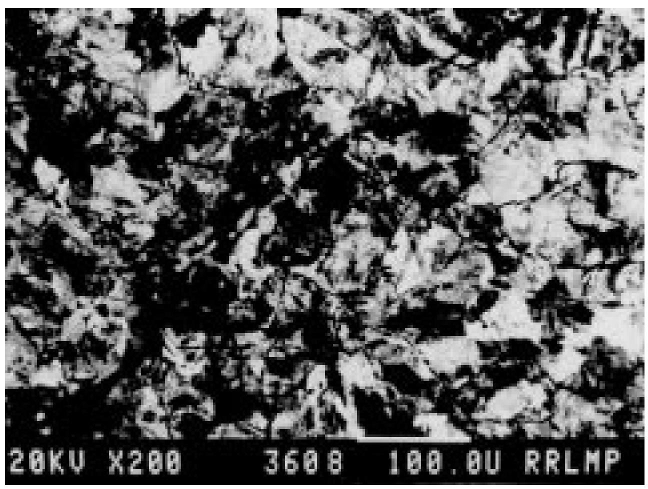
Actual value	Coded value
Load	
3 N	–1
4 N	–0.5
5 N	0
6 N	+0.5
7 N	+1
Distance	
26 m	–1
52 m	–0.6
78 m	–0.2
104 m	+0.2
130 m	+0.6
156 m	+1



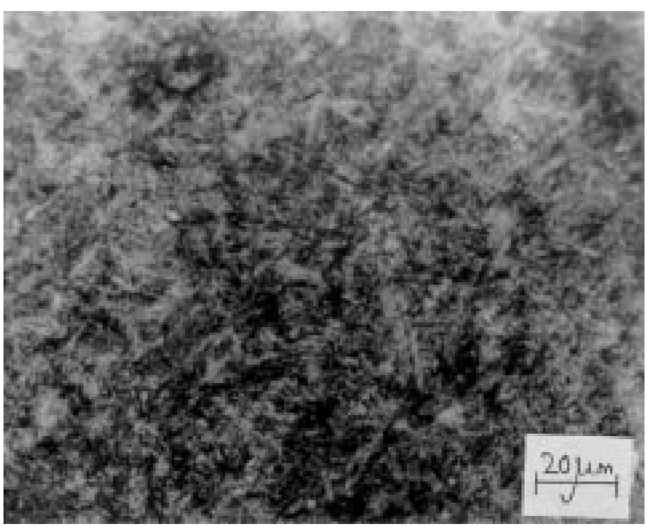
(a)



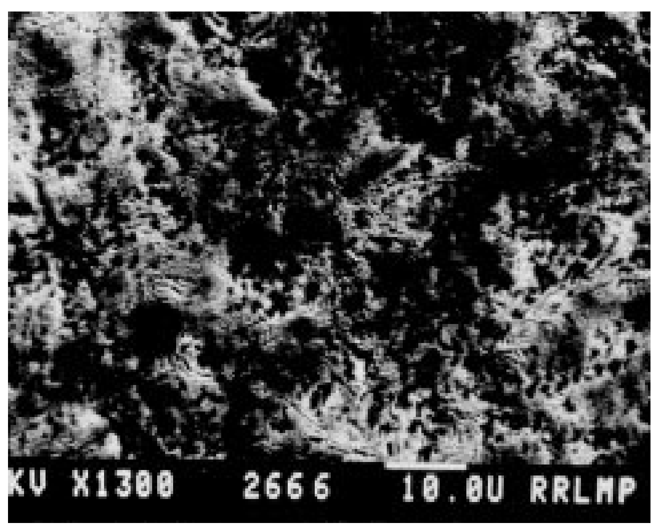
(b)



(c)



(d)



(e)

Fig. 4 Microstructure of steels. (a) Steel 1. (b) Steel 2. (c) Steel 3. (d) Steel 4. (e) Steel 5

Table 6 Predicted values of high-stress abrasive wear at intermediate levels

		Volume loss, $10^{-10}m^3$				
X_1	X_2	Steel 1	Steel 2	Steel 3	Steel 4	Steel 5
+1	1	74.5	88	59	55.6	42.6
0	1	66.7	72.5	49.5	49.3	48.5
–1	1	58.9	65	40	43	38.4
+1	0.6	62.56	67.6	49	45.62	34.98
0	0.6	55.74	60.3	41	48.57	33.43
–1	0.6	48.92	52	33	35.52	31.88
+1	0.2	58.62	55.6	39	35.64	27.36
0	0.2	44.78	48.1	32.5	31.54	26.36
–1	0.2	38.94	40.6	26	28.84	25.36
+1	–0.2	38.68	43.4	29	25.66	19.74
0	–0.2	38.62	35.9	24	23.11	19.29
–1	–0.2	28.96	28.4	19	20.56	18.84
+1	–0.6	26.74	31.2	19	15.68	12.12
0	–0.6	22.86	23.7	15.5	14.38	12.22
-1	–0.6	16.98	16.2	12	13.88	12.32
+1	–1	14.8	19	9	5.70	4.50
0	–1	11.9	11.5	7	5.65	5.15
–1	–1	9.00	4.0	5	5.60	5.80

Table 7 Comparison of experimental and predicted values for high-stress abrasive wear

		Volume loss, $10^{-10}m^3$									
		Steel 1		Steel 2		Steel 3		Steel 4		Steel 5	
X_1	X_2	Experimental	Predicted	Experimental	Predicted	Experimental	Predicted	Experimental	Predicted	Experimental	Predicted
+1	0.6	61.0	62.5	58.0	67.8	50.0	49.0	47.0	45.6	34.6	34.9
0	0.6	53.0	54.0	50.0	50.6	42.0	42.3	38.2	38.8	28.6	29.2
–1	0.6	49.0	48.9	46.0	52.0	33.0	33.0	30.5	35.5	10.5	31.8
+1	0.2	53.0	50.6	50.5	55.6	42.0	39.0	40.0	35.6	27.7	27.3
–1	0.2	39.0	38.9	37.0	40.6	30.0	27.0	22.0	25.4	17.5	25.3
+1	–0.2	40.0	38.6	37.0	43.4	30.0	29.0	22.0	25.6	17.5	19.7
+1	–0.6	28.0	26.7	27.0	31.2	20.0	19.0	19.0	15.6	10.0	12.1
0	–0.6	13.0	22.8	13.2	23.7	8.0	15.5	7.2	14.3	10.2	12.2
–1	–0.6	20.0	18.9	19.0	16.2	12.5	12.0	10.7	13.0	8.0	12.3

Experimental values obtained at a number of intermediate levels were matched with the predicted values obtained from the software. The comparative values are given in Table 7. There is a close match between the experimentally observed and predicted values. In most cases, the deviation is within ±10%. Any greater deviation may be attributed to experimental error, because these lines do not follow a linear relationship.

4. Concluding Remarks

The high-stress abrasive wear properties of steels is dependant on a number of experimental parameters, such as load and sliding distance, and on material properties, such as hardness.

A linear regression analysis was carried out within the experimental range where there is a linear relationship between the wear (volume) loss with load, hardness, and sliding distance.

A computer software in Microsoft basic language has been developed, which considers the limits of the experimental range of load and sliding distance where there is a linear variation with volume loss. The software can predict the volume loss at all intermediate levels within an accuracy of ±10%.

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