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Development of mathematical model for prediction of abrasive wear behaviour in agricultural grade medium carbon steel

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Reducing the low stress abrasive wear of materials has emerged as a major challenge for researches conducted in the field of engineering for sometime. In this direction, efforts are made for development of prediction model for abrasive wear rate of medium carbon steel like SAE-6150 based on the influencing factors for precise prediction of wear rate and selection of appropriate levels of factors. SAE-6150 steel is tested using dry sand abrasion test rig after heat-treatment (annealing, intercritically annealing and quenched and tempered) and shot peening (ranging 0.17- 0.47 A at an interval of 0.1 A). The hardness and abrasive wear resistance of as-received and annealed steel (ferrito pearlitic structure) are significantly lower in comparison to inercritically annealed (ferrito-martensitic structure) as well as quenched and tempered (tempered martensitic structure) irrespective of peening intensity. The peening intensity reduces the wear rate, if limited to a critical value of 0.17 A. The functional relationship between wear rate and the factors influencing it is found statistically significant and can be used for prediction of abrasive wear at a given level of factors.

Keywords: Predictive model, Wear rate, Heat-treatment process, Peening intensity, Microstructure, Load

Abrasive wear has been emerged as a serious problem in the field of engineering particularly for the metallic surface of working components in machines. It is estimated that about 50% of wear in these components is abrasive in nature[1,2]. Medium carbon low alloying steels are mainly used to overcome abrasive wear-related problems due to their high strength and toughness. Various efforts are going on to reduce abrasive wear rate by changing the chemical composition,[3-7] microstructure[5-12] and mechanical properties[5-7]. Many researchers suggested heat-treatment process as a suitable technique for obtaining combination of properties to resist the abrasive wear[5-12]. The martensitic phase is usually considered for improved wear resistance of steels[8,9]. However, a large number of components with martensitic structure fail at unexpected times and the failure of these parts usually occur due to presence of micro cracks in the martensitic structure[16]. Experimental factors such as applied load[7-9,13,14] and abrasive size[8,9,13-15] also played a crucial role in controlling the abrasive wear behaviour of metals.

For mechanical components several surface alteration techniques like hardfacing[17-21], carborizing[22], nitriding and carbonitriding[22], boriding[22-27] and shot peening[28,29] are used for tailoring the properties to improve the abrasive wear resistance. In all above, the shot peening is considered to be a very fast, economical and energy efficient practice to control the material properties. In shot peening operation, compressive stresses are induced at the surface and sub-surface level of the component. It also prevents crack initiation and propagation. Shot peening reduces the grain size[30] (by refining the microstructure) that makes an improvement in strength and hardness[31] resulting into good wear resistance[32] in engineering components. However, excessive peening makes the surface and subsurface more brittle and as a result micro cracking in material occurs leading to higher wear rate[10,30]. Peening parameters (shot size, pressure, stand-off height, peening duration) are also very crucial for obtaining desired properties of the surface.

Therefore, assessment of abrasive wear behaviour of medium carbon steels such as SAE-6150 under influence of several factors like heat treatment, intensity of shot peening and applied load and their dynamic relationship is very essential. This can be done by developing a functional relationship between the wear rate and the factors influencing it to identify

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Table 1—Heat treatment process, hardness and micro-structural properties

Name of the process	Austenising temperature (°C)	Soaking time (min)	Quenching media	Tempering temperature and duration	Hardness (HV)	Micro- structure
As received	NA	NA	NA	NA	150	86% pearlite 14% ferrite
Annealing	870	60	Furnace Cooling		130	80% pearlite 20% ferrite
Intercritical annealing	870 775	60 30	Water with 8% NaCl	250°C 120 min	471	85% martensite 15% ferrite
Quenching and tempering	870	60	Water with 8% NaCl	250°C 120 min	498	Tempered martensite

appropriate level of influencing factors for reduction of abrasive wear. Development of complex non-linear predictive model[33-35] is a well-established approach to predict the wear rate, which is determined by peening intensity and load factor in the developed model. Therefore, an attempt was made in this study to find out the synergetic effect of different heat treatment process, shot peening intensity and load applied on low stress abrasive wear behaviour of medium carbon steel for enhancing the service life of soil working components of agricultural machineries.

Table 2—Parameters of shot peening[10]

Peening Parameters	Values
Peening pressure (bar)	6
Peening nozzle diameter (mm)	6
Shot size, mm	0.8
Shot hardness (HRc)	45
Stand off hight (mm)	180.0
Exposure time (s)	20-120
Impingement Angle (°)	90
Almen strip used for calibration	ALMEN ‘A’
Peening intensity (ALMEN ‘A’)	0.17-0.47
Surface coverage, %	96-98

Experimental Procedure

Materials and heat-treatment

Rolled sheets of 8 mm thick medium carbon steel (SAE-6150) were used in this study. The investigated steel was observed to have 0.52% carbon, 0.22% silicon, 0.70% manganese, 1.0% chromium, 0.17% vanadium and 0.025% sulphur by weight along with iron as its usual chemical composition. Using three different heat-treatment processes, the specimens were heat-treated as described in Table 1. The hardness of as-received (control) and heat-treated steel samples were tested on Vicker’s hardness tester at a load of 30 kgf. The specimens were metallographically polished and etched with 2% of niatal and then sputtered with gold. The microstructure of polished and etched specimen was examined by using scanning electron microscope (SEM). The heat treatment processes and resulting hardness and microstructure of the specimens are described in Table 1.

Shot peening

The specimens were ground up to 400 grade emery paper, prior to shot peening. Shot peening of steel samples was conducted on shot peening machine manufactured by M/s Mec Shot, Jodhpur, India. The peening intensities were calibrated using standard ALMEN ‘A’ strip. The strips were shot peened at fixed flow rate, stand off height (distance between nozzle and specimen surface), and peening pressure. However, the time of exposure was varied to obtain different peening intensities. The peening intensity is defined as the deflection at the centre of the strip from its original position. The shot peening parameters used and the peening intensities achieved under varying conditions are given in Table 2. The shot peening intensity varies from 0.17 A to 0.47 A, at an interval of 0.1 A.

Abrasive wear tests

A rubber wheel dry sand apparatus (DUCOM, Bangalore, India make) was used for low stress (three body) abrasion tests as per ASTM G-65 specifications. The diagram of wear test apparatus is shown in Fig. 1. In these tests, a 12.7 mm thick rubber wheel (177.8 mm in diameter) was rotated rubbing the test surface of stationary rectangular specimens (76.2 mm × 25.4 mm and 7 mm thick). Crushed silica sand particles of size 212-300 µm were fed between wheel and specimen at the rate of 370 g/min. The rotational speed of the wheel was set at 100 rpm with test duration of two minutes. Such test was carried out 18 times for each specimen and wear rate was measured after each test, i.e., at an interval of two minutes with three levels of applied load, i.e., 75 N, 200 N and 375 N. The test length covered at the end of experiment was 2592 m for each specimen. The wear rate of the specimens was measured at an interval of 144 m of sliding distance that was covered in each test of two minutes duration. Tests were conducted until the specimens in each case attained steady state wear loss. The specimens were cleaned with acetone and dried with blown air after each test. Wear rate of the specimens were measured by measuring the loss in weight.

Design of experiment and development of mathematical model

Factorial Randomized Complete Block Design (RCBD) with three factors was adopted for conducting the experiment. A total of four treatment, i.e., three heat treatment and one control (as received) were selected as main treatment, five intensities of peening were selected as sub-treatment and three different loads applied were selected as sub-sub-treatment in the experiment. The interaction effects between these factors were also estimated to find out the significance of their influence. Standard error of mean and critical difference (CD) were calculated with the given formula,

Standard error of mean = $\sigma / \sqrt{n}$

CD = Table value of '*t*' at α% and error df × $\sqrt{2 \times M.S.error / n}$

where, σ is standard deviation and *n* is number of observation.

For development of mathematical model, a multiple non-linear (quadratic) equation of the following form was fitted with two factors for the study.

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_1^2 + b_4X_2^2 + b_5X_1X_2$$

where, Y is wear rate, X_1 is intensities of peening; X_2 is load applied; b_1, b_2, b_3, b_4 and b_5 are the regression coefficients and b_0 is the constant intercept.

The experimental data were analysed by MSTAT-C software (version 2.10) of Michigan State University and SYSTAT 10.2 software of SYSTAT Software Inc.

Results and Discussion

Effect of heat treatment

The assessment of wear rate for SAE-6150 steel reveals that the wear rate decreases with gradual increase in sliding distance and reaches to a stable value at the end. It is also noted that the wear rate of 'as received' (AR) and 'annealed' (AN) specimens are comparable (Table 3) due to their almost similar type of micro-structure (a combination of pearlite and ferrite; the amount of ferrite is 6% more in annealed condition) and hardness (150 and 130 Hv for AR and AN respectively). The wear rate is reduced considerably (of about 46%) in 'intercritically annealed' (ICA) and 'quenched and tempered' (QT) specimens. Therefore, the wear rate could be reduced significantly through intercritical annealing or quenching and tempering treatment through generation of ferrito-martensitic structure, or tempered martensitic structures (about 95% tempered martesite and 4-5%retained austenite). The microstructures of ICA and QT exhibit excellent combination of strength and toughness to control the abrasive action by the sand particles. This is the reason behind the reduction in wear rate in case of ICA and QT in comparison to AR and AN specimens.

Effect of peening intensity

The effect of peening intensity on wear rate of SAE-6150 steel indicates that the average rate of

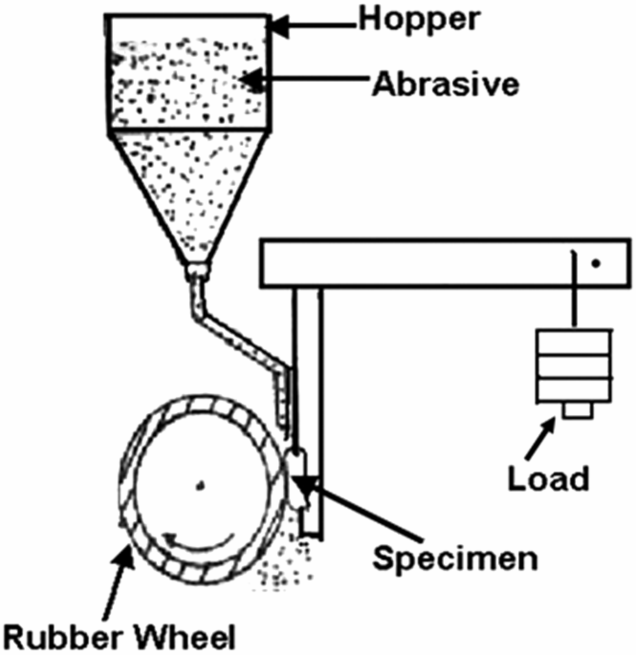

Fig. 1—Diagram of wear test apparatus

wear is reduced significantly with the introduction of shot peening treatment at lower intensity (0.17 A) but it tends to increase again with the increase in intensity of shot peening (Table 3). Significant difference in wear rate was observed in samples subjected to different shot peening intensities, suggesting to restrict the intensity of shot peening at lowest level, i.e., 0.17 A for minimizing the wear rate for SAE-6150 steel. The extent of reduction in wear rate at 0.17 A (mild peening) is due to work hardening of the surface and compressive residual stress developed on the surface which increase the surface hardness and reduce the micro-cracking tendency during wear on the surface. Higher peening intensity makes the

Table 3—Wear rate at various heat treatment, peening intensity and applied load

Name of factors	Average wear rate (10^{-11} m^3 / m)	'*F*' value	Standard error of mean	Critical difference at 5% level
Heat treatment				
As received (Control)	22.321	7268.5386***	0.0679	0.1904
Annealed	21.018			
Intercritically annealed	11.788			
Quenched and Tempered	11.580			
Peening intensity				
0.00 (Control)	20.761	1763.0385***	0.0759	0.2128
0.17 A	12.296			
0.27 A	15.358			
0.37 A	16.551			
0.47 A	18.418			
Load applied				
75 N	8.688	27391.1968***	0.0588	0.1649
200 N	13.824			
375 N	27.519			

*** = significant at 1% level

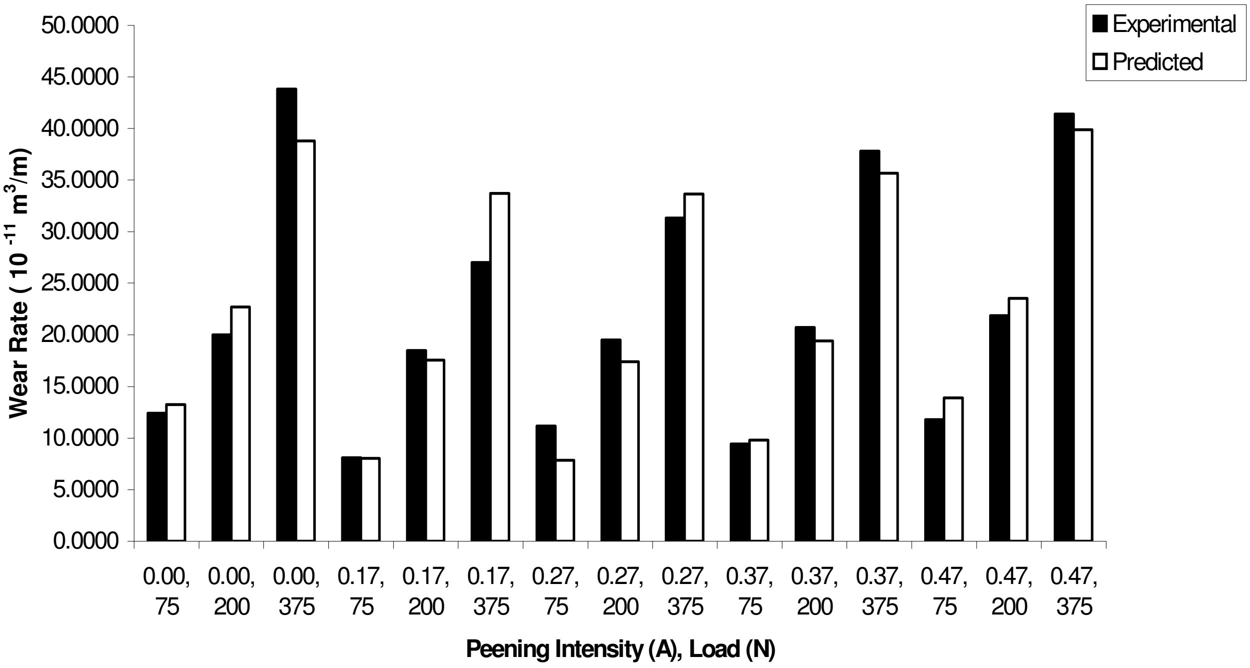

Fig. 2—Experimental and predicted values of wear rate of AR steel

surface work-hardened significantly and cause surface and sub-surface micro cracking. The dents and leaps formed during mild peening gets damaged during the severe peening and thus easily removed. Furthermore, the surface and sub-surface cracks generated during peening, starts growing further and interact with each other leading to delaminating wear in addition to the abrasive type wear.

Effect of load applied

The effect of load applied on wear rate of SAE-6150 steel points out that the wear rate is directly proportional with the load applied because the wear rate of the specimens under investigation increases significantly with the increase in applied load. It is evident from literature that the wear rate increases with increase in applied load[7,13] irrespective of heat-treatment schedule. It is due to the fact that the depth of penetration of sand particles increases with increase in applied load, which leads to more removal of material from the surface. The wear rate observed for AR and AN steels were significantly higher than that of the QT and ICA steels. However, in general, the trend in variation in the wear rate with applied load is almost invariant to the peening intensity. Except in the case of 0.17 A peening intensity, the wear rate increases slowly with load up to 200 N but after that wear rate increases more rapidly. This might be attributed to the greater probability of removal of tips from the boundary of the dents formed after shot peening and interaction of load and saturated surface work-hardening vis-à-vis surface cracks, if any formed due to peening.

Interaction effect of combined factors on wear rate

Though the analysis on interaction effects of two factors highlighted several combinations of treatments that can significantly reduce the wear rate (Table 4), but the complete picture can only be visible from the analysis of combined interaction effect of all three factor, viz., heat treatment, peening intensity and applied load on wear rate of SAE-6150 steel. The analysis discloses that minimum wear rate of around 5.0 to 5.6 × 10^{-11} m^3/m can be obtained either by intercritically annealing the material with shot peening at 0.17 A to 0.27 A or quenching and tempering the same steel with shot peening at 0.17 A when the applied load is minimum (Table 5). All these treatment combinations give statistically identical wear rate which are minimum amongst all treatment combinations. ICA steels have good combination of mechanical properties, i.e., hardness and toughness. The hardness of ICA steel is about 3-4 times of AR and AN steels and slightly lower than that of QT steel. Because of lower hardness and poor mechanical properties AR and AN steels are unable to sustain higher peening intensities and similarly in case of quenching and tempering, the martensitic structure is brittle in nature and shot peening further increases the phenomena. Due to this, cracking and delamination type wear starts on the surface along with abrasion.

Development of a mathematical model

As the factors like heat treatment process, intensity of shot peening and applied load played a decisive role in determining the wear rate of SAE-6150 medium carbon steel, therefore, the expected wear rate of this metal at any given value of these factors within the domain of experiment can be predicted with sufficient accuracy with the help of a fitted mathematical equation from the experimental data. The experimental data is divided into four sub-groups of heat treatment, as the process of heat treatment being a qualitative factor cannot be quantified for inclusion in the model hence it becomes a basis for segregation. The estimates of the regression coefficients, the test for significance of these estimates, their confidence intervals and their collective influence on the dependent variable have been elaborated below.

The model for prediction of wear rate for AR specimens shows that the influences of peening intensity, load applied and the second degree polynomial of peening intensity were significant on wear rate as apparent in the fitted equation (Table 6a). AR specimens are subjected to pre processed residual stresses due to work hardening and having lower hardness and toughness. The lower hardness allows abrasive sand particles to penetrate easily increasing the wear rate proportionally as the load increases. Therefore, it is obvious that the peening intensity exerts a non-linear influence while the influence of applied load on wear rate follows more or less a straight-line trend. About 94% of the total variation in the dependent variable is elucidated by these factors.

Table 4—Two factors interaction effect of on wear rate

Interaction of two factors	Average wear rate (10^{-11} m^3/m)	'*F*' value	Standard error of mean	Critical difference at 5% level
AR × 0.00 A	25.414	21.8817***	0.1519	0.4257
AR × 0.17 A	17.868			
AR × 0.27 A	20.662			
AR × 0.37 A	22.643			
AR × 0.47 A	25.017			
AN × 0.00 A	25.826			
AN × 0.17 A	15.613			
AN × 0.27 A	20.044			
AN × 0.37 A	20.526			
AN × 0.47 A	23.083			
ICA × 0.00 A	15.728			
ICA × 0.17 A	7.805			
ICA × 0.27 A	10.818			
ICA × 0.37 A	11.640			
ICA × 0.47 A	12.951			
QT × 0.00 A	16.075			
QT × 0.17 A	7.899			
QT × 0.27 A	9.909			
QT × 0.37 A	11.395			
QT × 0.47 A	12.622			
AR × 75 N	10.571	997.8187***	0.1176	0.3297
AR × 200 N	20.111			
AR × 375 N	36.280			
AN × 75 N	10.468			
AN × 200 N	17.452			
AN × 375 N	35.134			
ICA × 75 N	6.869			
ICA × 200 N	9.306			
ICA × 375 N	19.190			
QT × 75 N	6.844			
QT × 200 N	8.426			
QT × 375 N	19.470			
0.00 A × 75 N	10.213	563.7684***	0.1315	0.3687
0.00 A × 200 N	16.008			
0.00 A × 375 N	36.061			
0.17 A × 75 N	6.902			
0.17 A × 200 N	12.150			
0.17 A × 375 N	17.835			
0.27 A × 75 N	8.325			
0.27 A × 200 N	12.700			
0.27 A × 375 N	25.050			
0.37 A × 75 N	8.094			
0.37 A × 200 N	13.547			
0.37 A × 375 N	28.011			
0.47 A × 75 N	9.905			
0.47 A × 200 N	14.713			
0.47 A × 375 N	30.637			

*** = significant at 1% level

Table 5—Interaction effect of all factors on wear rate of SAE-6150 steel

Interaction of heat-treatment, peening intensity and load	Average wear rate (10^{-11} m^3/m)	'F' value	Standard error of mean	Critical difference at 5% level
AR × 0.00 A × 75 N	12.404	35.4158***	0.2630	0.7373
AR × 0.00 A × 200 N	20.003			
AR × 0.00 A × 375 N	43.835			
AR × 0.17 A × 75 N	8.078			
AR × 0.17 × A 200 N	18.500			
AR × 0.17 A × 375 N	27.025			
AR × 0.27 A × 75 N	11.174			
AR × 0.27 A × 200 N	19.500			
AR × 0.27 A × 375 N	31.312			
AR × 0.37 A × 75 N	9.413			
AR × 0.37 A × 200 N	20.700			
AR × 0.37 A × 375 N	37.815			
AR × 0.47 A × 75 N	11.787			
AR × 0.47 A × 200 N	21.850			
AR × 0.47 A × 375 N	41.413			
AN × 0.00 A × 75 N	11.500			
AN × 0.00 A × 200 N	20.360			
AN × 0.00 A × 375 N	45.618			
AN × 0.17 A × 75 N	8.321			
AN × 0.17 A × 200 N	16.000			
AN × 0.17 A × 375 N	22.517			
AN × 0.27 A × 75 N	11.157			
AN × 0.27 A × 200 N	16.000			
AN × 0.27 A × 375 N	32.975			
AN × 0.37 A × 75 N	9.425			
AN × 0.37 A × 200 N	16.900			
AN × 0.37 A × 375 N	35.252			
AN × 0.47 A × 75 N	11.939			
AN × 0.47 A × 200 N	18.000			
AN × 0.47 A × 375 N	39.310			
IC A × 0.00 A × 75 N	8.632			
IC A × 0.00 A × 200 N	10.140			
ICA × 0.00 A × 375 N	28.412			
ICA × 0.17 A × 75 N	5.602			
ICA × 0.17 A × 200 N	7.500			
ICA × 0.17 A × 375 N	10.312			
ICA × 0.27 A × 75 N	5.040			
ICA × 0.27 A × 200 N	8.500			
ICA × 0.27 A × 375 N	18.914			
ICA × 0.37 A × 75 N	6.830			
ICA × 0.37 A × 200 N	10.090			
ICA × 0.37 A × 375 N	18.001			
ICA × 0.47 A × 75 N	8.242			
ICA × 0.47 A × 200 N	10.300			
ICA × 0.47 A × 375 N	20.311			
Q T × 0.00 A × 75 N	8.317			
Q T × 0.00 A × 200 N	13.530			
Q T × 0.00 A × 375 N	26.378			
Q T × 0.17 A × 75 N	5.610			
Q T × 0.17 A × 200 N	6.600			
Q T × 0.17 A × 375 N	11.486			
Q T × 0.27 A × 75 N	5.930			
Q T × 0.27 A × 200 N	6.800			
Q T × 0.27 A × 375 N	16.997			
Q T × 0.37 A × 75 N	6.710			
Q T × 0.37 A × 200 N	6.500			
Q T × 0.37 A × 375 N	20.974			
Q T × 0.47 A × 75 N	7.652			
Q T × 0.47 A × 200 N	8.700			
Q T × 0.47 A × 375 N	21.515			

*** = significant at 1% level

Table 6a—Predictive model for wear rate of 'as received' SAE-6150 steel

Name of factors	Estimate of coefficient	Standard error of estimates	't' value	95% confidence interval		Coefficient of multiple determination (R^2)
				Lower limit	Upper limit	
Constant Intercept	8.380580	2.452614	3.416995***	3.419689	13.341450	0.935815
Peening intensity	-49.149940	10.596161	4.638467***	-70.582699	-27.717182	
Load	0.060840	0.021579	2.819359***	0.017191	0.104488	
Peening intensity^2	107.193895	19.175806	5.590059***	68.407165	145.980625	
Load^2	0.000054	0.000045	1.201679$^{\text{ns}}$	-0.000037	0.000144	
Peening intensity × Load	0.002875	0.022910	0.125495$^{\text{ns}}$	-0.043464	0.049214	

Table 6b—Analysis of variance for 'as-received' SAE-6150 steel

Source	Degree of freedom	Sum of squares	Mean sum of square	'F' ratio
Regression	6	27783.70	4630.62	491.05***
Residual	39	367.92		
Total	45	28151.62		

*** = significant at 1% level; ns = not significant

Table 7a—Predictive model for wear rate of 'annealed' SAE-6150 steel

Name of factors	Estimate of coefficient	Standard error of estimates	't' value	95% confidence interval		Coefficient of multiple determination (R^2)
				Lower limit	Upper limit	
Constant Intercept	11.464665	2.997683	3.824509***	5.401278	17.528052	0.90511
Peening intensity	-54.862624	12.951052	4.236152***	-81.058600	-28.666649	
Load	0.019691	0.026375	0.746565$^{\text{ns}}$	-0.033658	0.073039	
Peening intensity^2	120.941551	23.437438	5.160186***	73.534857	168.348246	
Load^2	0.000151	0.000055	2.761887***	0.000040	0.000261	
Peening intensity × Load	-0.020429	0.028001	0.729588$^{\text{ns}}$	-0.077067	0.036208	

Table 7b—Analysis of variance for 'annealed' SAE-6150 steel

Source	Degree of freedom	Sum of squares	Mean sum of square	'F' ratio
Regression	6	25122.12	4187.02	297.1201***
Residual	39	549.62	14.09	
Total	45	25671.74		

*** = significant at 1% level; ns = not significant

The predictive model for forecasting of wear rate of AN specimens show that the peening intensity and the second degree polynomial of peening intensity as well as applied load are having significant influence on wear rate as manifested in the fitted equation (Table 7a). AN specimen contains more homogeneous structure, free from pre-process residual stresses and higher ductility; all these make it more resistant towards abrasive wear after shot peening. Greater ductility and lower hardness of this steel assists in holding wear debris and entraps fine particles for longer duration leading to considerably reduction in wear rate. Hence, both the peening intensity and applied load compulsorily follow a non-linear relationship with wear rate diminishing the linear influence of applied load on wear rate. About 91% of the total variation in the dependent variable is explained by these factors.

The predictive model developed for assessment of wear rate in ICA specimens shows that the peening intensity and second degree polynomial of peening intensity and applied load are having significant influence on wear rate (Table 8a). ICA annealed steel has excellent combination (85% tempered martensite and 15% ferrite) of mechanical properties. Tempered martensitic structure is very capable to resist the abrasive wear of sand particles. Work hardening during mild peening further improves the wear resistance. As a consequence, it resists the abrasive wear, which is observed to grow up at a slower rate with the applied load. Accordingly, both the peening intensity and applied load are wielding a significant non-linear influence on wear rate however; the interaction of these two factors does not exert any

Table 8a—Predictive model for wear rate of intercritically annealed SAE-6150 steel

Name of factors	Estimate of coefficient	Standard error of estimates	'*t*' value	95% confidence interval		Coefficient of multiple determination (R^2)
				Lower limit	Upper limit	
Constant Intercept	8.475316	2.206520	3.841033***	4.012209	12.938424	0.8370
Peening intensity	-37.394278	9.532946	3.922636***	-156.676482	-18.112074	
Load	-0.004592	0.019414	0.236544^{ns}	-0.043861	0.034676	
Peening intensity^2	90.882337	17.251714	5.268018***	55.987452	125.777222	
Load^2	0.000123	0.000040	3.072106***	0.000042	0.000204	
Peening intensity × load	-0.038344	0.020611	1.860389^{ns}	-0.080034	0.003345	

Table 8b—Analysis of variance for intercritically annealed SAE-6150 steel

Source	Degree of freedom	Sum of squares	Mean sum of square	'*F*' ratio
Regression	6	7782.67	1297.11	170.0013***
Residual	39	297.79	7.63	
Total	45	8080.46		

*** = significant at 1% level; ns = not significant

Table 9a—Mathematical model for prediction of wear rate for 'quenched and tempered' SAE-6150 steel

Name of factors	Estimate of coefficient	Standard error of estimates	'*t*' value	95% confidence interval		Coefficient of multiple determination (R^2)
				Lower limit	Upper limit	
Constant intercept	12.012835	1.883735	6.377136***	8.202621	15.823049	0.8868
Peening intensity	-49.556631	8.138402	60.89234***	-66.018104	-33.095159	
Load	-0.031871	0.016574	1.922953^{ns}	-0.065395	0.001653	
Peening intensity^2	98.897019	14.728016	6.714892***	69.106805	128.687253	
Load^2	0.000168	0.000034	4.908719***	0.000099	0.000237	
Peening intensity × load	-0.006712	0.017596	0.381433^{ns}	-0.042302	0.028879	

Table 9b—Analysis of variance for 'quenched and tempered' SAE-6150 steel

Source	Degree of freedom	Sum of squares	Mean sum of square	'*F*' ratio
Regression	6	7734.90	1289.15	231.6948***
Residual	39	217.04	5.57	
Total	45	7951.94		

*** = significant at 1% level; ** = significant at 5% level; ns = not significant influence on wear rate. About 84% of the total variation in the dependent variable is explicated by these factors.

The prediction model developed for wear rate of QT specimens shows that all the variables except applied load and the interaction effect of peening intensity and load applied are having significant influence on wear rate (Table 9a). Because, tempered martensitic structure with about 4-5% retained austenite gives more hardness and wear resistance. During shot peening, the fraction of grain boundaries is increased due to reduction in grain size at lower

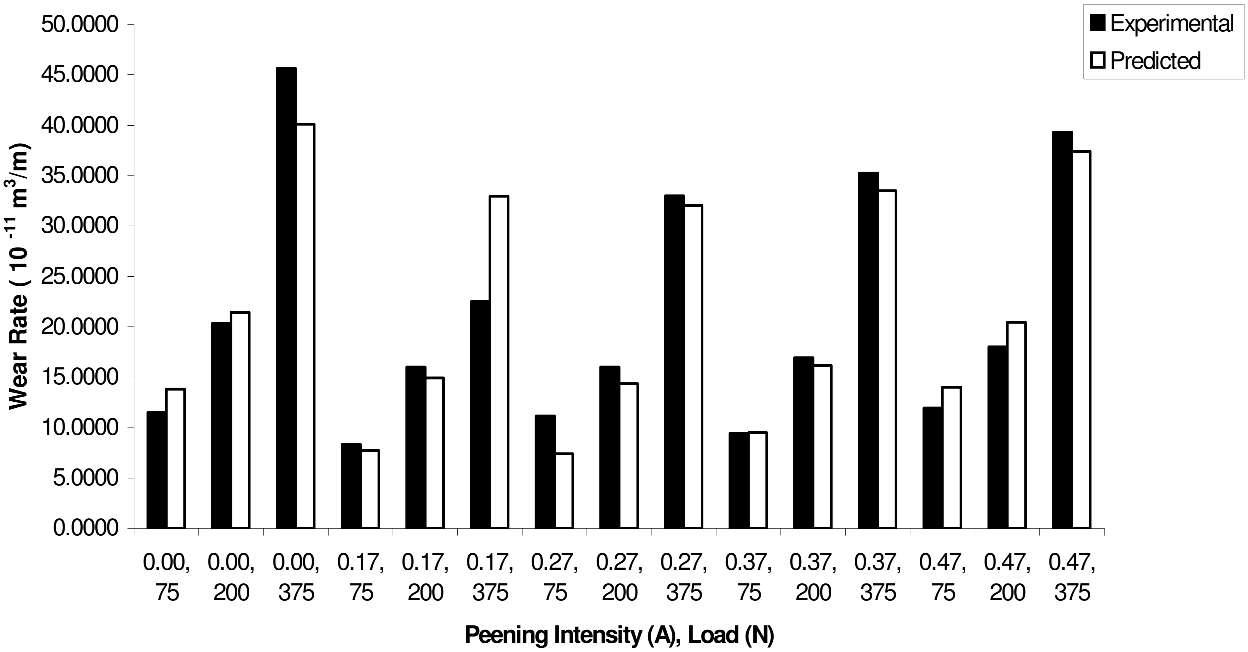

Fig. 3—Experimental and predicted values of wear rate of AN steel

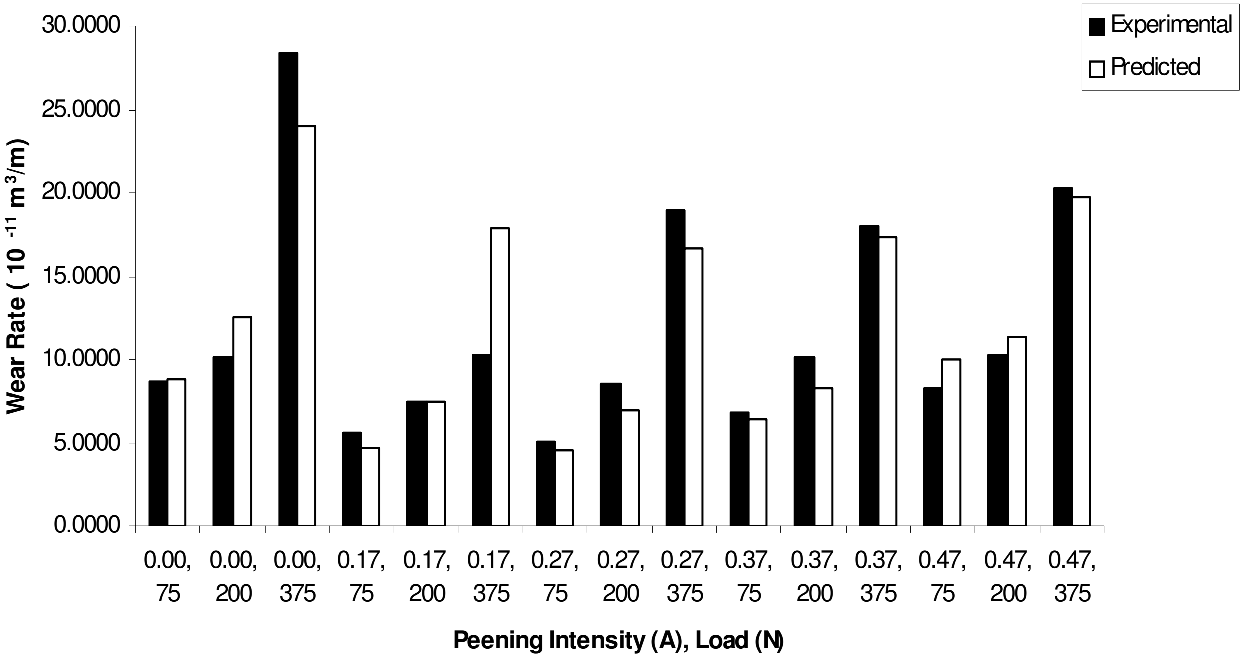

Fig. 4—Experimental and predicted values of wear rate of ICA steel

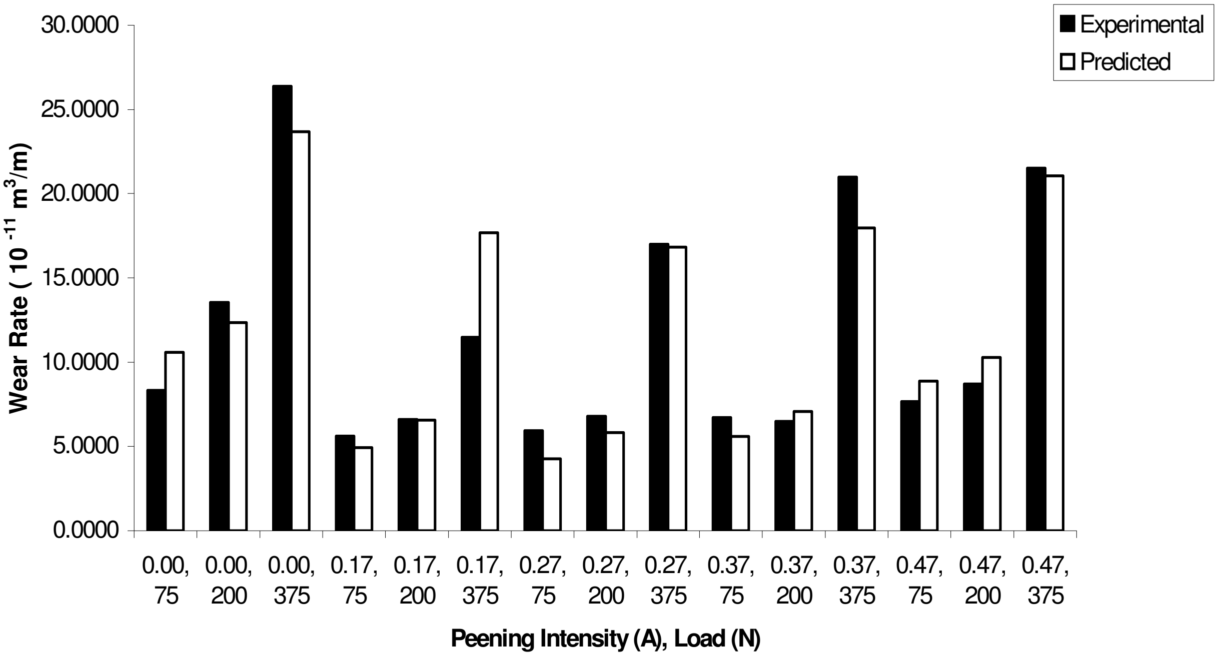

Fig. 5—Experimental and predicted values of wear rate of QT steel

peening intensity (refinement in microstructure). As a result, it reduced the wear rate by restricting the penetration of abrasive sand particles. Therefore, it becomes obvious that both the factors certainly have a significant non-linear influence on wear rate. About 89% of the total variation in the dependent variable is explained by these variables.

It was also apparent that the quadratic regression equations of the model surface to be best fitted, as the regression equation was highly significant (Tables 6b-9b). Thus, the fitted mathematical equation gives very accurate prediction of wear rate for SAE-6150 steel as depicted in Figs 2-5.

Conclusions

The following conclusions have been drawn from the present study:

(i) The wear rate of ICA and QT specimens are much lower than that of AR and AN specimens due to formation of ferreto-martensitic, and tempered martensitic structure respectively during heat-treatment process.

(ii) Wear rate follows a non-linear relationship with peening intensity as at first it is reduced up to a peening intensity of 0.17 A, then increases again with the increase in peening intensity due to increase in brittleness of the specimen with the peening intensity.

(iii) The wear rate is directly proportional to the applied load, however the rate of growth may vary according to heat treatment applied to the material.

(iv) The complex relationship between the influencing factors and wear rate can be illustra-ted by fitting a mathematical equation of quad-ratic form which shall help in prediction of wear rate accurately as the corresponding regression coefficients and the model are found to be highly significant.

References

1 Eyre T S, *Tribol Int,* 9 (5) (1976) 203-212.
2 *WTIA, Technical Note 4: WTIA, TN, 4-96,* Welding Technology Institute of Australia, Sydney, Australia, (1996 b) ISBN 090539596.
3 Dasgupta R, Mondal D P & Roy A, *Wear*, 231 (1999) 235-241.
4 Ueda, M, Uchino K & Kobayashi A , *Wear,* 253 (7) (2002) 107-113.
5 Bhakat A K, Mishra A K, Mishra N S & Jha S, *Wear,* 257 (3-4) (2004) 338-346.
6 Gupta A K, Jesudas D M, Das P K & Basu K, *Biosyst Eng,* 88 (1) (2004) 63-74.
7 Moore M A, *Wear,* 28 (1974) 59-68.
8 Modi O P, Pandit P, Mondal D P, Prasad B K, Yegneswaran A H & Chrysanthou A, *Mater Sci Eng A***,** 458 (2007) 303-311.
9 Modi A P, *Tribol Int,* 40 (3) (2007) 490-497.
10 Singh D, Mondal D P, Modi O P & Sethi V K, *Indian J Eng Mater Sci*, 17 (2010) 208-218.

11 Modi O P, Mondal D P, Prasad B K, Singh M & Khaira H K, *Mater Sci Eng A*, 343 (1-2) (2003) 235-242.

12 Jha A K, Prasad B K, Modi O P, Das S & Yegneswaran A H, *Wear*, 254 (1) (2003) 120-128.

13 Wirojanupatump S & Shipway P H, *Wear,* 239 (11) (2000) 91-101.

14 Mondal D P, Singh D, Kumar N, Ahmed S & Sethi V K, *Indian J Tribol*, 4 (1) (2009) 14-24.

15 Bahrami A, Anijdan S H M, Golozar M A, Shamanian M & Varahram N, *Wear,* 258 (5-6) (2005) 846-851.

16 Xu L and Kennon N F, *Wear,* 148 (1991) 101-112.

17 Raval A H & Kaushal O P, *Agricultural Mechanization in Asia Africa and Latin America (AMA),* 21 (2) (1990) 46-48.

18 Moore M A, McLees V A & King F S, *The Agricultural Engineer* (Spring), (1979) 15-19.

19 Buchely M F, Gutierrez J C, Leon L M & Toro A, *Wear*, 259 (2005) 52-61.

20 Kumar S, Mondal D P, Khaira H K & Jha A K, *J Mater Eng Performance,* 8 (6) (1999) 711-715.

21 Kumar S, Mondal D P & Jha A K, *J Mater Eng Performance,* 9 (6) (2000) 649-655.

22 Moore M A, *J Agric Eng Res,* 20 (1975) 167-179.

23 Atik E, *Mater Struct,,* 31 (1998) 418-422.

24 Meric C, Sahin S, Backir B & Koksal N S, *Mater Des*, 27 (2006) 751-757.

25 Allaoui O, Bouaouadja N & Saindernan G, *Surf Coat Technol,* 201 (2006) 3475-3482.

26 Bejar M A & Moreno E, *J Mater Process Technol*, 173 (2006) 352-358.

27 Bourithis L & Papadimitriou G, *Mater Lett,* 57 (12) (2003) 1835-1839.

28 Sharma M C & Mubee A, *J Mech Work Technol*, 8 (2-3) (1983) 155.

29 Sharma M C & Mubee A, *J Mech Working Technol*, 8 (4) (1983) 399.

30 Yan W, Fang L, Sun K & Xu Y, *Mater Sci Eng A*, 460-461 (2007) 542-549.

31 Tang J S C & Koch C C, *Acta Metall Mater*, 24 (1990) 1599-1604.

32 Takagi M, Ohta H, Kawamura Y & Inoue A, *Scripta Mater*, 44 (2001) 2145-2148.

33 Ginta T L, Nurul Amin A K M, Mohd Razdi H C D & Lajis M A, *Eur J Sci Res*, 28 (4) (2009) 533-541.

34 Sivasakthivel P S, Vel Murugan V & Sudhakaran R, *Int J Eng Sci Technol*, 2 (6) (2010) 1780-1789.

35 Alauddina M, El Baradie M A & Hashmi M S J, *J Mater Process Technol*, 71 (3) (1997) 456-465.