Comparison of Effect of Heat Treatment Schedules and Shot Peening Parameters on the Abrasive Wear Behavior of As Received and Quenched & Tempered Medium Carbon Steel

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Abstract - Effect of heat treatment cycles and shot peening on the low stress abrasive wear behaviour of medium carbon (S-31000) steel was studied. For this investigation, As Received (AR) and Quenched & Tempered (QT) steels were selected. Three heat treatment processes namely annealing, inter critical annealing and quenching and tempering were done to obtain different material properties combinations. After heat treatment, the specimen's micro structural analysis and hardness testing were done. The quenched and tempered steel shows maximum hardness than other steels. The annealed steels shows minimum hardness when compared to other heat treated steels. For The quenched and tempered steel the microstructure obtained was tempered martensite. The As received steel has pearlitic and ferrite structure. The peening was done with different shot sizes (0.6 mm, 0.8 mm & 1.0 mm) and different pressures applied (3 bar, 4 bar & 5 bar) on as received and quenched & tempered specimens. Low stress abrasive wear behavior of these steels was investigated by using the dry sand abrasion test rig (TR-50) machine. The wear resistance of the steels was found maximum when subjected to quenching and tempering heat treatment cycle. The As received steel shows very low wear resistance when compared to quenched and tempered steel. After shot peening, wear rate reduced to minimum at a critical shot size peening & applied pressure. The As received steel irrespective of heat treatment schedule provide the minimum wear rate with 0.8 mm shot peeing at 5 bar pressure and quenched & tempered steel exhibits minimum wear rate with 1.0 mm shot peening at 3 bar pressure. At higher pressure intensities the steels suffers higher wear rate. The quenched & tempered steel exhibited relatively more wear resistance than as received steel.

Key words: Microstructure, Heat treatment cycle, shot peening , abrasive wear

1.0 Introduction

Steel is a widely used material for most of the engineering applications not only because of its availability in market but also because of its attaining a wide range of properties, such as hardness, strength, toughness, wear resistance etc., which is not found in any other family of materials **[1].** Steel is used basically in two ways (i.e. untreated and treated) for various applications. Untreated steels have low level of mechanical and tribological properties wheareas treated steels with proper combinations of soaking time, austenitizing temperature and transformation rate provide desired properties as per applications/use. The treated steels are single, dual and multiple phases **[2]**. Properties of dual phase steels such as ferrite – martensite, suit the requirement of agricultural implements as it possess good combination of ductility, strength, toughness and better deformability than other high strength steels. These steels exhibit other inherent specific material properties like, corrosion resistance, wear resistance and machinability **[3]**. Therefore, high strength low alloy dual phase steels are typically used in different engineering applications like power generation equipments, railways, pressure vessels, automobiles, reinforcing rods and bars, welded structure and agricultural applications particularly fast wearing components **[4].** Based on survey of manufacturers of fast wearing components of agricultural implements, it is revealed that majority of manufacturers were using medium carbon steel (55%) followed by high carbon steel (27%), mild steel (12%) and high carbon tool steel (6%) **[5].**

Several researchers **[6-10]** have reported that the wear rate of soil moving, cutting and threshing equipment is very high. It is reported that 50 – 52% of all wear problem in industries are due to abrasion **[11]**. In abrasive wear, chipping of material on a micro scale occurs as a result of rubbing of the other components. The phenomenon of surface wear caused loose abrasives, usually called three-body abrasion is a common wear type encountered in agriculture and industry **[12-14].**

To overcome these problems in agricultural implements, superior wear resistant materials with suitable heat-treatment and surface modification techniques are needed at an affordable cost. Medium carbon steels provide good hardenability, more toughness for equivalent hardness compared to traditional carbon steels and minimum distortion after heat-treatment**[15]**. The shaping and joining of medium carbon steels can be easily accomplished using normal workshop methods. The strength of medium carbon steels after hardening meets the demanding requirement of wear resistant steels. Medium carbon steels can be further strengthened by varying their microstructure, mechanical and tribological properties with suitable heat-treatment processes **[16]**. Annealing, inter-critical annealing and quenching-tempering were opted for observing the microstructure, hardness, wear resistance and wear coefficient of material **[17]**.

Carburizing and hard facing are mostly used for surface modification of fast wearing components in agriculture, as wear is a surface phenomenon. In recent times, many advance surface treatment techniques have come up, which are considered attractive and cost effective for improvement of performance wherein shot peening is one of the most important fields of surface engineering. Shot peening further leads to surface hardening due to initiation of compressive deformation and micro-structural modification on the surface. In a study on Hadfield Steel in China, it is found that the surface hardness of Hadfield Steel has been increased greatly after shot peening **[18-20]**.

Thus, it is expected that synergic effect of heat-treatment cycles, shot peening pressure and shot size would lead to considerable improvement in wear resistance of steel. However, limited attempts have been made to examine the synergic effect of heat-treatment cycles, shot peening pressure and shot size on wear behavior of medium carbon steel **[21-25]**.

2.0 Experimental Procedure

2.1 Material and heat treatment

Specimens for micro structural, mechanical and wear testing were made from medium carbon steel, which contain 0.31 wt% C, 1.00 wt% Cr, 0.61 wt% Mn, 0.027 wt% P, 0.025 wt% S, 0.14 wt% Si, 0.17 wt% V, and rest Fe. The steel was annealed for soaking time of 60 minutes at 870^{0}C and then allowed to furnace cooling. Also the steel was heated at 870^{0}C for 60 minutes and then water quenched, tempering is done at 250^{0}C for two hours and finally the samples were air cooled at room temperature.The steel was inter critically annealed (ICA). This heat-treatment schedule involves soaking the samples for 60 minutes at 875^{0}C, then the samples are allowed for soaking time of 30 minutes at 780^{0}C and after that samples are water quenched. Finally, the samples were kept at 250^{0}C for two hours and allowed for air cooling. Hardness of as received and heat-treated metallographically polished steel samples were tested on Brinell hardness tester at MSME- Testing Station, Govindpura, Bhopal. The hardness of as received, annealed, intercritically annealed and quenched & tempered steels were 150 BHN,138 BHN, 192 BHN and 215 BHN respectively.

2.2 Shot peeing

The shot peening is carried out using Mec shot, Jodhpur make machine at varying shot size and peening pressure maintaining constant peening intensity of 0.27 A. the strips were shot peened, using selected parameters like pressure (bar) and diameter of steel shots of (45 HRC) for 20-120 s for obtaining fixed peening intensity (0.27A).

2.3 Low stress abrasion wear tests

Three body abrasion tests were conducted on as pinned and unpinned samples under differently heat treated conditions. The tests were conducted following ASTM standard tests in a Test rig (Ducom Bangalore, India made). The schematic view of the test procedure is shown in Figure 1(a). The samples of dimensions 75mmx25mmx7mm were used. The sample is hold rigidly against the rubber wheel. The sand particles are feed between sample and rubber wheel. The average size of sand particles is 258.90 μm. The size distribution of these sand particles is shown in Figure 1(b).

The wheel was rotated at a fixed speed of 1.86 m/s and moved up to a distance of 2.6 km and all these tests were conducted at a constant load of 50 N. The wear rate was measured from weight loss measurement using following relation:

$$W_R = \frac{W_i - W_f}{(\rho * D)} \qquad \ldots\ldots \textbf{(1)}$$

Where, W_i is weight of specimen prior to the test, W_f is the final weight of specimen after the wear test, $(W_i - W_f)$ is the weight loss, ρ is density of test specimen and D is siding distance.

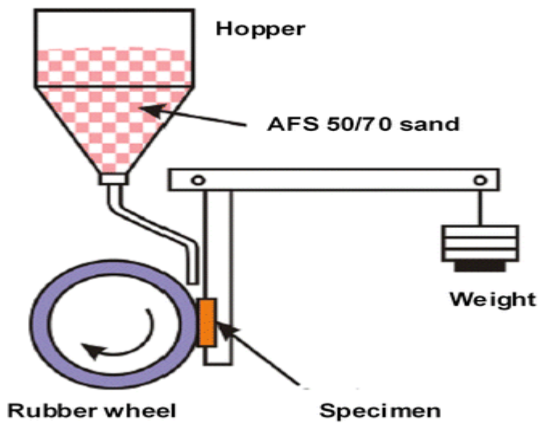


Fig. 1(a) Schematic view of low stress abrasion wear test

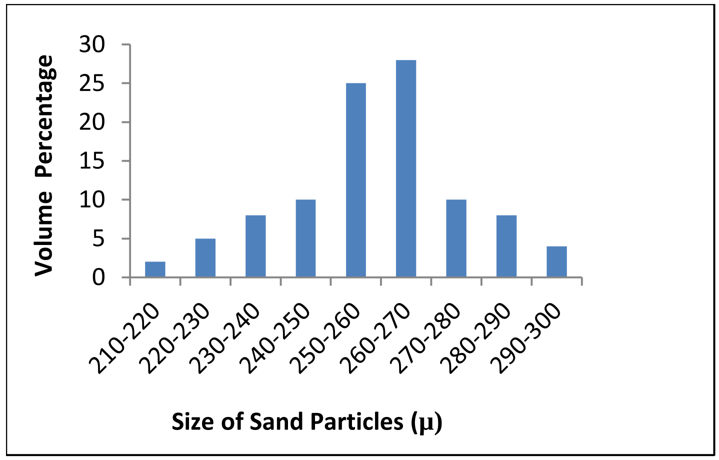
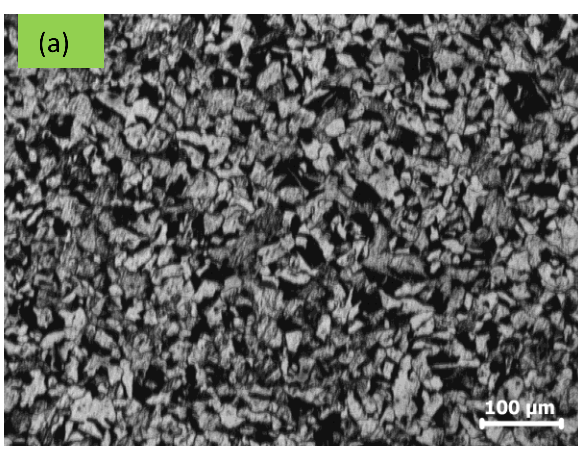


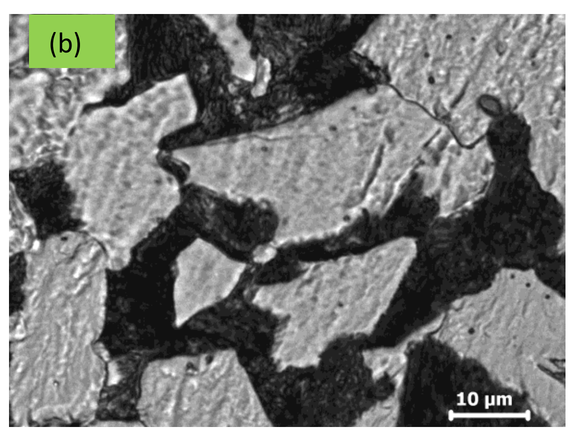
Fig. 1(b) Size distribution of sand particles

2.4 Microstructure of unpeened and peened steel samples

Microstuctures of as received sample at lower magnification is shown in Figure 2(a). It depicts the presence of pearlite patches (black) in the ferrite matrix (white). The average gain size of ferrite is measured to be around 28μm.The volume fraction of pearlite and ferrite is noted to be around 35 and 65% respectively. Higher magnification photograph of the same is depicted in Figure 2(b). It clearly reveals that the ferrite grain size 28- 30 μm and the pearlite lamellas are present primarily at triple point. The phase diagram also states the steel would contain around 32% of pearlite. The inter-lamellar spaces of pearlite are noted to be around 450 μm. The microstructure of quenched & tempered samples at lower magnification is shown in figure 2(c). It shows primarily quenched & tempered martensitic phase. The tempered martensitic phase consists of very fine carbides precipitated in martensite needles/lathes. Higher magnification photograph of QT sample is shown in figure 2(d), which clearly reveals precipitation around the sides of martensite needles.

The microstructure of peened sample is shown in figure 2(e). It shows the presence of spherical dents on the surface.The dents are uniformly distributed.The diameter of the dents are measured to be ~ 170 μm and the average spacing between the dents is noted to be~ 80 μm.In same cases,the dents overlapped. However,the micrograph Figure 2(f) shows quite uniform distribution of dents. The spacing between the dents are lower than the size of dents and thus it is expected that the surface is subjected to more or less uniform deformation due to peening.





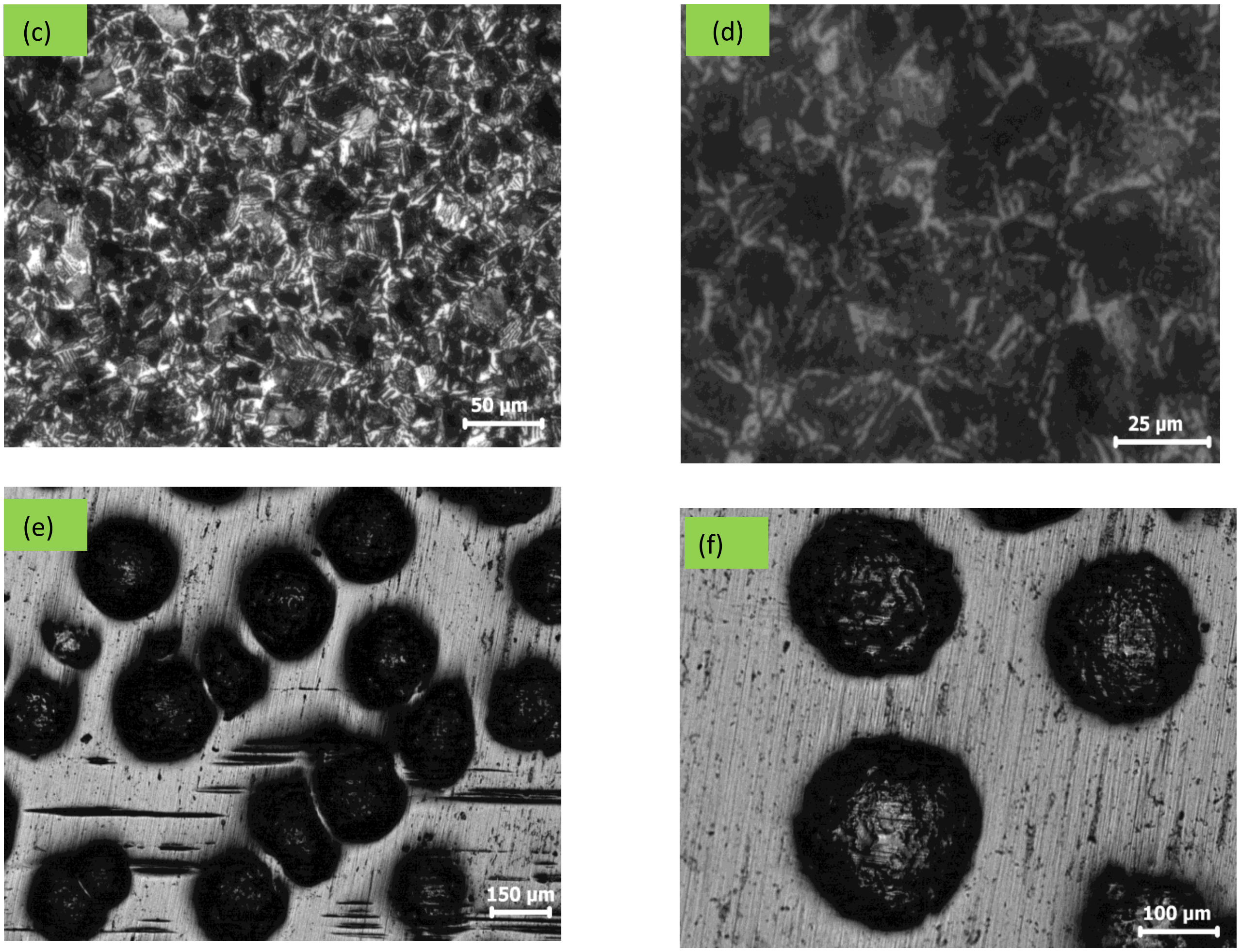


Fig.2 Microstructures of (a) as received sample at lower magnification (b) as received sample higher magnification (c) quenched and tempered sample at lower magnification (d) quenched and tempered sample higher magnification (e) peened sample at lower magnification (f) peened sample at higher magnification.

2.5 Microhardness distribution on the surface

The micro-hardness measurements on the surface of the specimens are taken at randomly selected region from the interface of the dents. The distance of the micro-hardness indentors location from interface has been normalized with respect to the distance between the dents.The micro-hardness values are varying in a narrow range between 160 and 185 with an average value of 175 kg/mm^2.This signifies that the surface is more or less uniformly stressed due to shot peening.

3.0 Result and Discussion

3.1 Effect of sliding distance

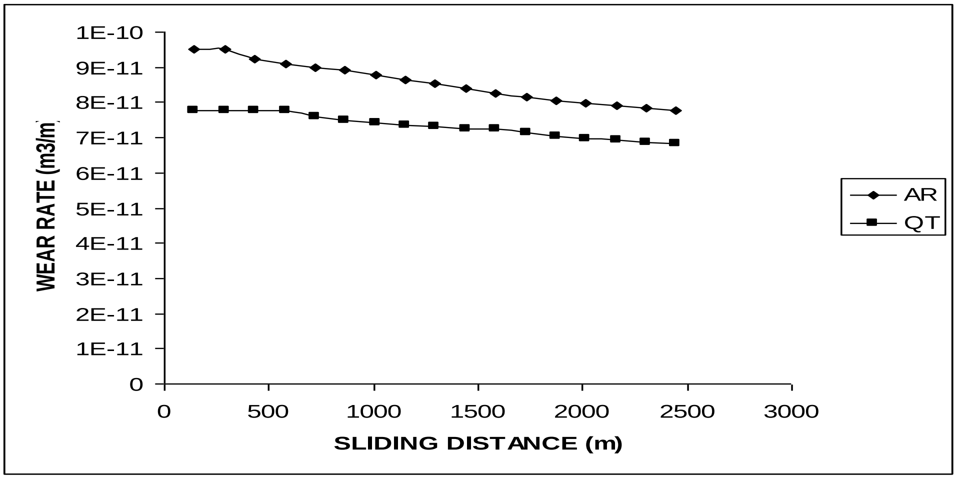


Fig. 3(a) Effect of sliding distance on wear behaviour of as received and quenched & tempered steels without shot peening and pressure.

The heat treated samples were subjected to wear test in dry sand abrasion test Rig TR-50 to know the wear rate and behaviour. The wear rate as a function of sliding distance is plotted for the S-31000 steel. Figure 3(a) represents variation of wear rate as a function of sliding distance at different heat treatment schedules. It is evident from the figure that the wear rate initially decreases with increase in sliding distance and then reaches to a stable value in both the cases. The wear rate decreases sharply in case of quenched and tempered treatment. It is further observed that the wear rate varies significantly with the heat treatment schedules because of different hardness values. The specimen exhibits minimum wear rate when subjected to quenched and tempered because of highest hardness and the maximum in case of as received steel. Decrease in wear rate with sliding distance in both the cases is attributed to the sub surface deformation followed by work hardening. The variation of wear rate with heat treatment schedules is attributed to the variation in microstructures and micro constituents which finally varies the hardness and toughness of the material.

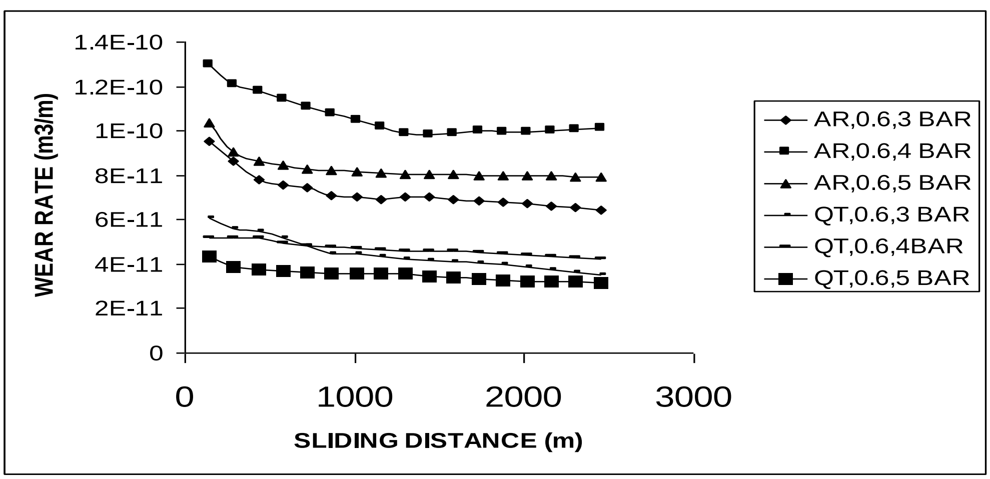


Fig. 3(b) Effect of sliding distance on wear behavior of AR & QT Steels at different pressures applied & 0.6 mm shot peening.

The variation of wear rate with sliding distance for the As Received and Quenched & tempered steel under different heat treatment schedules with 0.6mm shot peening and different pressures applied is shown in figure 3(b).

Above figure indicates that the quenched & tempered steel exhibit least wear rate at 5 bar pressure. As received steel gives higher wear rate as compared with quenched & tempered steel.It is evident from this figure that the wear rate reduces with sliding distance and approaches to a stable value. The as received steel suffers from the highest wear rate whereas the quenched & tempered steel shows the least wear rate. The slight change in the trend of variation between as received and Q&T steels after peening as compares to unpeened samples attributed to the variation in the surface work hardening. The quenched and tempered samples are subjected to more compressive residual stress and work hardening as compared as received steels. It is further to be noted that after shot peening the overall variation in the wear rate due to heat treatment cycles narrowed down significantly. This demonstrates that maximum improvement in wear resistance achieved after shot peening of quenched and tempered samples. This is attributed to the fact that quenched and tempered steels are subjected to greater degree of work hardening/plastic deformation during shot peening.

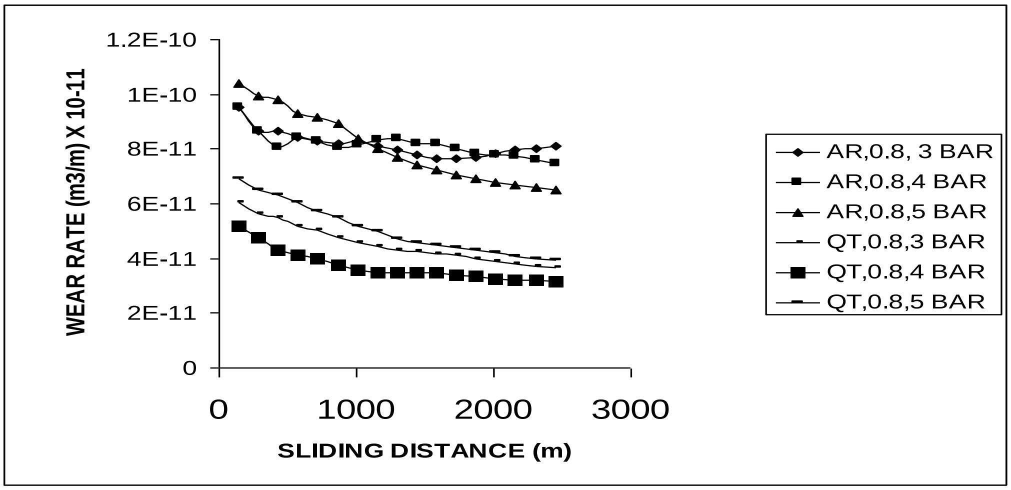


Fig. 3(c) Effect of sliding distance on wear behavior of AR & QT Steels at different pressures & 0.8 mm shot peening. applied & 0.6 mm shot peening.

Figure 3(c) represents variation of wear rate with sliding distance for the given materials under different heat treatment schedules with 0.8mm shot peening and different pressures applied . It is evident from this figure that the wear rate reduces with sliding distance and approaches to a stable value. The effect of the pressure variation to the material also clearly differentiates by studying the figure. The as received steel shows highest wear rate and quenched and tempered steel shows the lowest wear rate. It is also observed that the wear rate is lower when compared to the steels that are heat-treated and shot peened to 0.6 mm shot peening.

In the above figure, we study that there is a small but a measurable difference in the properties of the heat treated materials. It is observed that there is the measurable difference between the properties of the materials when the pressure raises from 3 bar to 5 bar.

If we compare the both above figures to this figure than we find that there is a appreciable difference in the properties of the heat treated materials when the operating pressure rises from 3 bar to the pressure 5 bar.

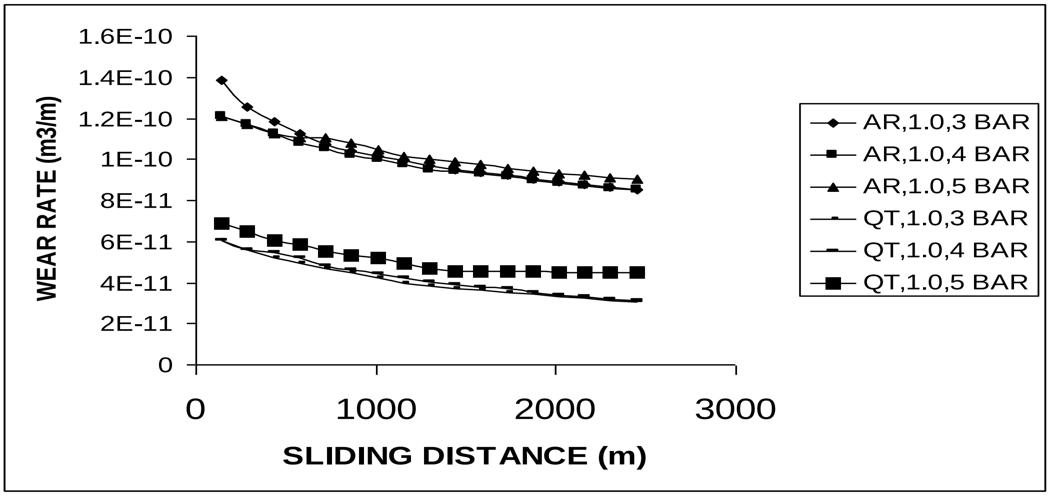


Fig 3(d) Effect of sliding distance on wear behavior of AR & QT Steels at different pressures & 1.0 mm shot peening.

Figure 3(d) exhibits variation of wear rate with sliding distance for the given materials under different heat treatment schedules with 1mm shot peening at different pressures applied. It is evident from this figure that the wear rate reduces with sliding distance and approaches to a stable value. From the study of the figure , we can see that there is a difference in the properties of the as received steel and the quenched & tempered steel.It is also observed that the wear rate is higher when compared to the steels that are heat-treated and shot peened to 0.8 mm shot peening.The least wear rate is shown by the QT steel at 3 bar pressure and the maximum wear rate is given by the AR steel at 5 bar pressure.

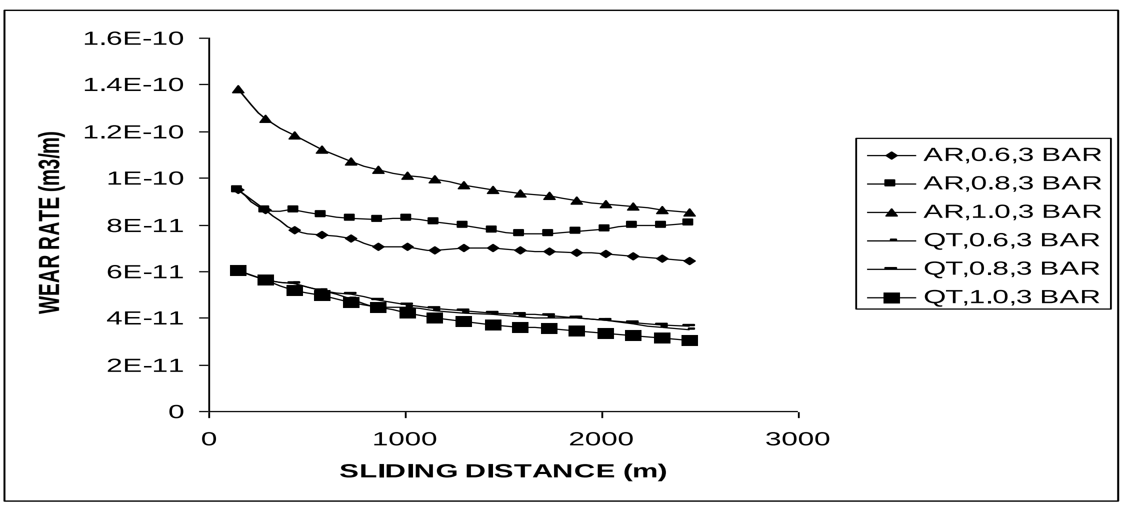


Fig. 3(e) Effect of sliding distance with different shot sizes on the wear behaviour of AR & QT steels at 3 bar pressure.

Figure 3(e) exhibits variation of wear rate with sliding distance for the given materials under different heat treatment schedules with 3 bar pressure and different shot peening. It is evident from this figure that the wear rate reduces with sliding distance and approaches to a stable value. It is evident from the figure that the least wear rate is demonstrated by quenched & tempered steel at 1.0 mm shot peening. The maximum wear rate is indicated by as received steel at 1.0 mm shot peening.

The wear rate is maximum in the quenched and tempered steel as shown in figure and the rapid changes occurs in the properties of as received steel when the shot size increases than the higher heat treated method that is the quenched and

tempered steel. The adverse effect is shown by the as received steel on 0.8 mm shot peening as shown in figure. The as received steel firstly decreases in terms of wear rate and than it increases as the sliding distance is also increases.
If the shot size is changed then there is a little bit difference occurred in the properties of the materials.

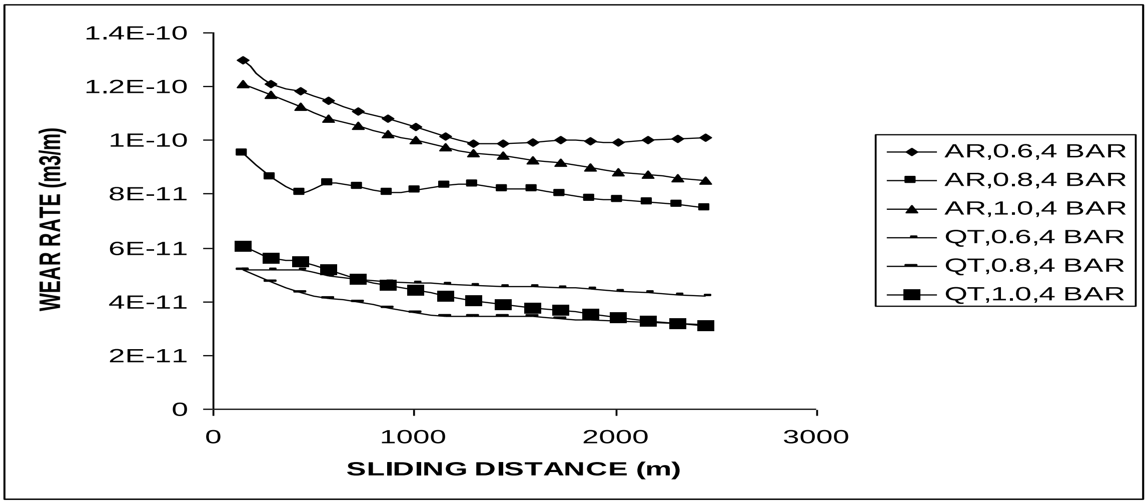


Fig. 3(f) Effect of sliding distance with different shot sizes on the wear behaviour of AR & QT steels at 4 bar pressure.

Figures 3(f) represents variation of wear rate with sliding distance for as received and quenched & tempered steel under different heat treatment schedules with different shot peening size at 4 bar pressure. It is evident from the figure that the wear rate reduces with sliding distance and approaches to a stable value. The QT steel at 0.8 mm shot peening shows the minimum wear rate as compared to the others. The maximum wear rate is represented by the AR steel at 0.6 mm shot peening. The adverse effect is shown by the as received steel at 0.6 mm shot peening as shown in figure. The as received steel firstly decreases in terms of wear rate and than it increases as the sliding distance is also increases. In the above figure, we study that there is a small but a measurable difference in the properties of the heat treated materials .It is observed that there is the measurable difference between the properties of the materials when the shot size raises from 0.6 mm to 1.0 mm.

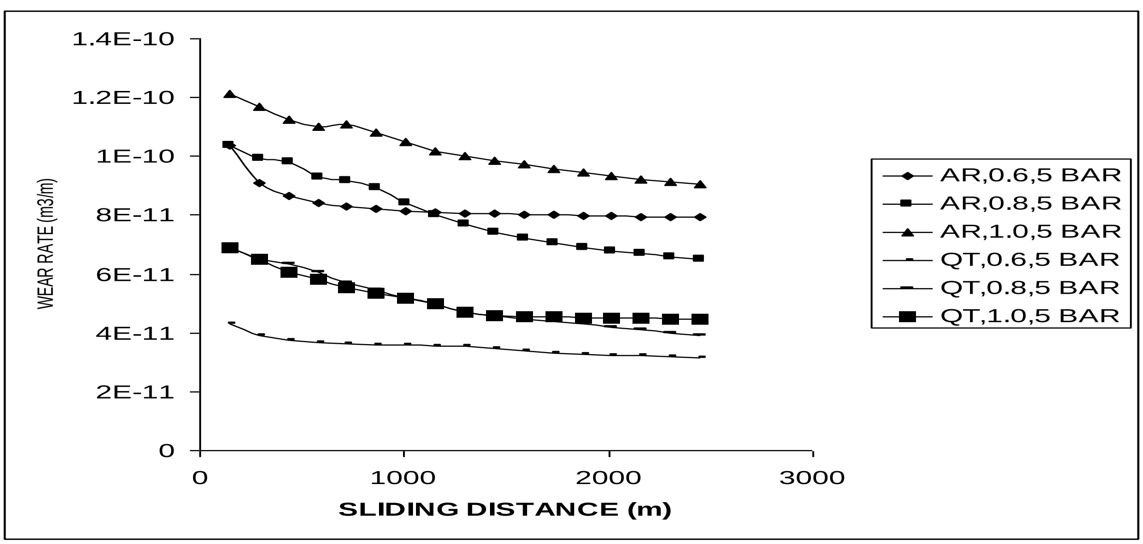


Fig. 3(g) Effect of sliding distance with different shot sizes on the wear behaviour of AR & QT steels at 5 bar pressure. applied & 0.6 mm shot peening.

Figures 3(g) illustrates variation of wear rate with sliding distance for as received and quenched & tempered steel under different heat treatment schedules with different shot peening size at 5 bar pressure. It is evident from the figure that the wear rate reduces with sliding distance and approaches to a stable value. The QT steel at 0.6 mm shot peening shows the minimum wear rate as compared to the others. The maximum wear rate is represented by the AR steel at 1.0 mm shot peening. The adverse effect is shown by the quenched & tempered steel at 1.0 mm shot peening as shown in figure. The quenched & tempered steel firstly decreases in terms of wear rate and than it increases as the sliding distance is also increases. In the above figure, we study that there is a small but a measurable difference in the properties of the heat treated materials .It is observed that there is the measurable difference between the properties of the materials when the shot size raises from 0.6 mm to 1.0 mm.

3.2 Combined Effect of shot size

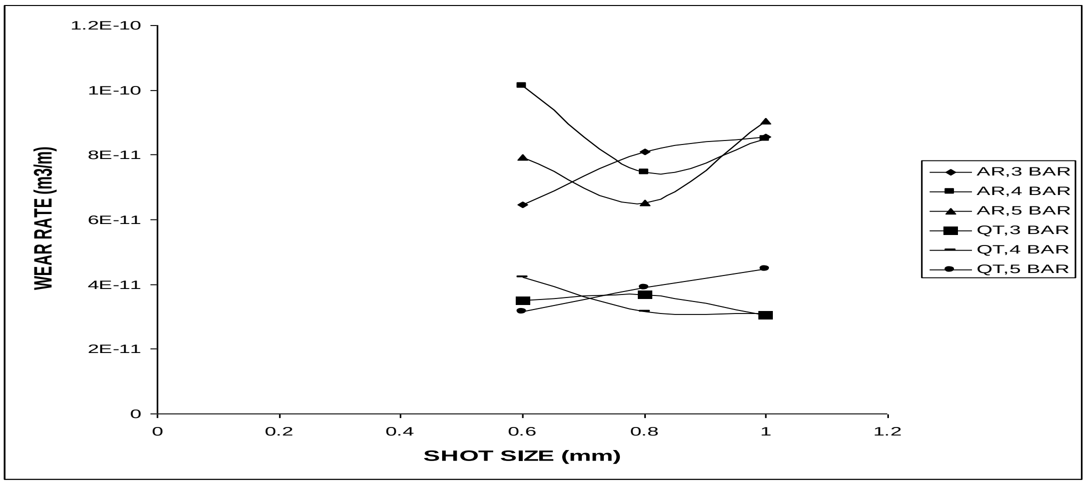


Fig. 3(h) Combined effect of shot size on wear behavior of AR & QT steels

Figures 3(h) illustrates variation of wear rate with shot size for as received and quenched & tempered steel under different with shot size at different pressures applied. The as received steel represents maximum wear rate at 0.6 mm shot peening & 4 bar pressure and minimum at 0.6 mm shot peening 3 bar pressure. The quenched & tempered steel exhibits minimum wear rate with 1.0 mm shot peening at 3 bar pressure and maximum with 1.0 mm shot peening at 5 bar pressure.

3.3 Combined Effect of Peening Pressure

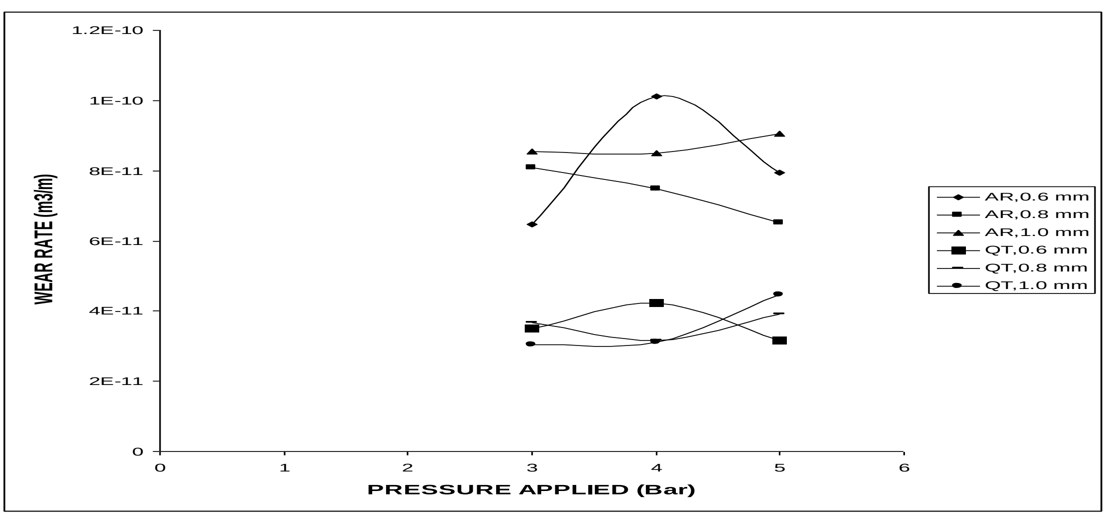


Fig 3(i) Combined Effect of pressures applied on AR & QT steels

Figures 3(i) illustrates variation of wear rate with sliding distance for as received and quenched & tempered steel with different pressures applied at different shot peening size.The as received steel shows maximum wear rate with 4 bar pressure at 0.6 mm shot peening and minimum with 3 bar at 0.6 mm shot peening. The quenched & tempered steel shows maximum wear rate with 5 bar pressure at 1.0 mm shot peening and minimum with 3 bar at 1.0 mm shot peening.

4.0 Wear Resistance of AR & QT Steels

The wear resistance of the material is defined as
Wear resistance = 1/ wear rate.
The wear resistance of AR & QT steel for different heat treatment cycles, different shot peening sizes and different pressures applied is potted as histogram in Figure 4. It is evident from this figure that irrespective of shot peenng intensity and heat treatment cycle the wear rate is increased drastically in comparison with the as received steeel. The highest wear resistance is shown for quenched and tempered steel.

The wear resistance of AR & QT steels for different heat treatment cycles, different shot sizes and different pressure applied is potted as histogram in Figure 4. It is evident from this figure that irrespective of shot size, pressure applied and heat treatment cycle the wear resistance is increased drastically in comparison with the as received steel. The highest wear resistance is shown for quenched and tempered steel with 1.0 mm shot peening at 3 bar.
Quenched and tempered steel with 1.0 mm shot peening at 3 bar shows 2.1 times more resistance when compared to the as received steel.

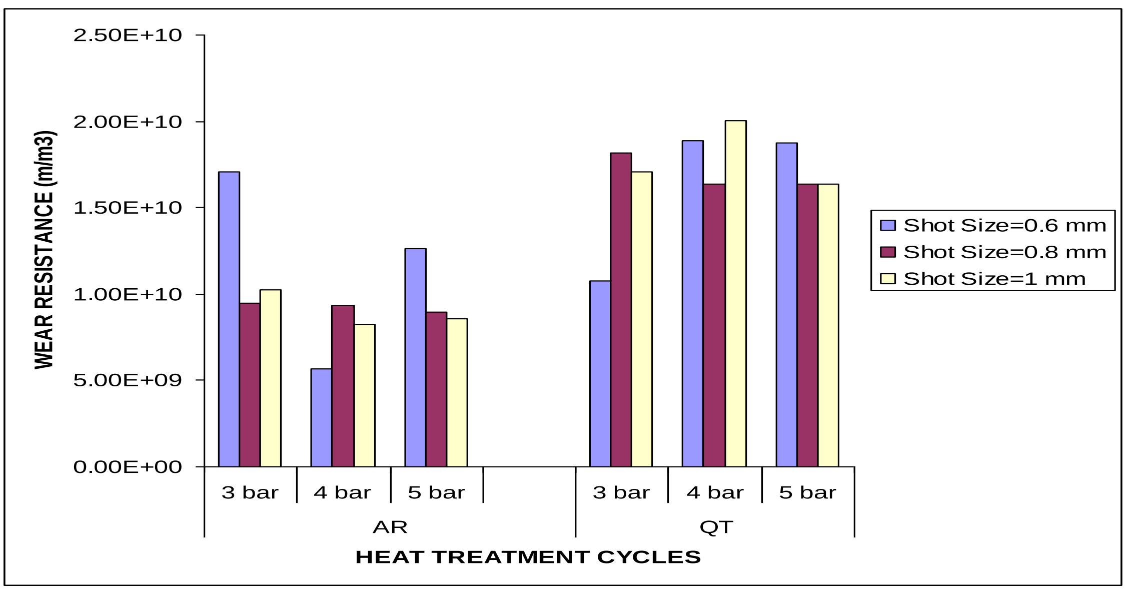


Fig. 4 Effect of heat treatment cycles with various pressures & shot sizes on the wear resistance of AR & QT Steels

5.0 Development of Equations for Correlating Wear Rate, Pressure Applied and Shot Size:

Two levels full factorial design of experiment was used in the present study. Two parameters were varied on two levels, i.e. upper level and lower level. The upper level and lower levels of two parameters, i.e. applied pressure and shot size used in the present study are reported in Table 1.

Table 1. Experimental domains of selected parameters (values in the parenthesis denote the coded value)

S.No.	Experimental Parameter	Upper Level	Lower Level
1	Applied pressure,P (Bar)	5 (+1)	3 (-1)
2	Shot size,S (mm)	1.0 (+1)	0.6 (-1)

This table also includes the coded values of upper and lower levels of each of the parameters in parenthesis.

5.1 Linear Regression Equation

In order to represent the effect of input parameters (i.e. pressure applied and shot size) on wear response (i.e. wear rate), four linear equations were developed for as received steel and quenched & tempered steel. For evaluating these linear equations, 5 & 9 sets of experiment were conducted for each of the steels. The experimental parameters and response variables for these 5 & 9 sets of experiments are shown in Table 2(A)& (B) for as received and quenched & tempered steels respectively. This table also includes the coded values of each experimental parameters used in these trials in parenthesis. Values of pressure applied (p),shot size(s) and wear rate(Wr) for each set of experiment are shown in Table 2(A) & (B). From these tabulated data, matrix (as shown in Table 3) is designed to calculate the coefficients of the linear regression equation representing wear rate as a function of applied pressure and shot size. In present study following type of linear regression equation is assumed:

$W_r = a_o + a_1 x_1 + a_2 x_2 + a_3 x_1 x_2$ ……………………………………………………………… (2)

Where, a_0, a_1, a_2, a_3 are the constants,x_1 and x_2 are the coded values of the parameters: applied pressure and shot size respectively. a_0 is the coefficient indicating the response variable at the base level i.e. p=0(4 Bar) and s=0(0.8 mm) .Values of these coefficients are calculated using the following formulae:

$a_0 = \Sigma W_{Ri} / N$,

$a_1 = \Sigma W_{Ri} (x_1)i / N$,

$a_2 = \Sigma W_{Ri} (x_2)_i / N$,

$a_3 = \Sigma W_{Ri} (x_1 x_2) / N$,

Where i = 1-18, i is the trial number.

Table 2. Experimental data for as received and quenched & tempered steel

(A) As Received Steel

(a) For four experiments :

Experiment.No.	P(x_1)	S(x_2)	W_r
1	5(+1)	1.0(+1)	9.0551E^{-11}
2	5(+1)	0.6(-1)	7.9359 E^{-11}
3	3(-1)	1.0(+1)	8.5464 E^{-11}
4	3(-1)	0.6(-1)	6.4607 E^{-11}

(b) For next five experiments :

Experiment.No.	P(x_1)	S(x_2)	W_r
1	5(+1)	0.8 (0)	6.5115E^{-11}
2	3 (-1)	0.8 (0)	8.0885 E^{-11}
3	4 (0)	0.8 (0)	7.4781 E^{-11}
4	4 (0)	1.0(1)	8.4955 E^{-11}
5	4 (0)	0.6 (-1)	10.123 E^{-11}

(c) For combined nine experiments:

Experiment.No.	$P(x_1)$	$S(x_2)$	W_r
1	5(+1)	1.0(+1)	9.0551 E^{-11}
2	5(+1)	0.6(-1)	7.9359 E^{-11}
3	3(-1)	1.0(+1)	8.5464 E^{-11}
4	3(-1)	0.6(-1)	6.4607 E^{-11}
5	5(+1)	0.8 (0)	6.5115 E^{-11}
6	3 (-1)	0.8 (0)	8.0885 E^{-11}
7	4 (0)	0.8 (0)	7.4781 E^{-11}
8	4 (0)	1.0(1)	8.4955 E^{-11}
9	4 (0)	0.6 (-1)	10.123 E^{-11}

(B) QUENCHED & TEMPERED STEEL

(a) For four experiments :

Experiment.No.	$P(X_1)$	S(X2)	W_r
1	5(+1)	1.0(+1)	4.4767E-11
2	5(+1)	0.6(-1)	3.154E-11
3	3(-1)	1.0(+1)	3.0523E-11
4	3(-1)	0.6(-1)	3.5101E-11

(b) For next five experiments :

Experiment.No.	$P(x_1)$	$S(x_2)$	W_r
1	5(+1)	0.8 (0)	3.9171 E^{-11}
2	3 (-1)	0.8 (0)	3.6627 E^{-11}
3	4 (0)	0.8 (0)	3.154 E^{-11}
4	4 (0)	1.0(1)	3.1032 E^{-11}
5	4 (0)	0.6 (-1)	4.2223 E^{-11}

(c) For combined nine experiments :

Experiment.No.	$P(x_1)$	$S(x_2)$	W_r
1	5(+1)	1.0(+1)	4.4767 E^{-11}
2	5(+1)	0.6(-1)	3.154 E^{-11}
3	3(-1)	1.0(+1)	3.0523 E^{-11}
4	3(-1)	0.6(-1)	3.5101 E^{-11}
5	5(+1)	0.8 (0)	3.9171 E^{-11}
6	3 (-1)	0.8 (0)	3.6627 E^{-11}
7	4 (0)	0.8 (0)	3.154 E^{-11}
8	4 (0)	1.0(1)	3.1032 E^{-11}
9	4 (0)	0.6 (-1)	4.2223 E^{-11}

Table 3. Matrix to calculate co efficients of the linear regression equation

(A) As Received Steel

$P(x_1)$= Applied Pressure (Bar), $S(x_2)$=Shot Size (mm), Wr = Wear Rate (m^3/m).AR= As Received, QT= Quenched & Tempered.

(a)For four experiments :

x_1	x_2	$x_1.x_2$		**Wr** × E^{-11}	x_1.**Wr**× E^{-11}	x_2.**Wr** × E^{-11}	x_1x_2.**Wr** × E^{-11}
1	1	1		9.0551	9.0551	9.0551	9.0551
1	-1	-1		7.9359	7.9359	-7.9359	-7.9359
-1	1	-1		8.5464	-8.5464	8.5464	-8.5464
-1	-1	1		6.4607	-6.4607	-6.4607	6.4607
			SUM	31.9981	1.9839	3.2049	-0.9665
			AVERAGE	7.9995 (a_0)	0.4960 (a_1)	0.8012 (a_2)	-0.2416 (a_3)

(b) For combined nine experiments :

x_1	x_2	$x_1.x_2$		**Wr** × E^{-11}	x_1.**Wr**× E^{-11}	x_2.**Wr** × E^{-11}	x_1x_2.**Wr** × E^{-11}
1	1	1		9.0551	9.0551	9.0551	9.0551
1	-1	-1		7.9359	7.9359	-7.9359	-7.9359
-1	1	-1		8.5464	-8.5464	8.5464	-8.5464
-1	-1	1		6.4607	-6.4607	-6.4607	6.4607
1	0	0		6.5115	6.5115	0	0
-1	0	0		8.0885	-8.0885	0	0
0	0	0		7.4781	0	0	0
0	1	0		8.4955	0	8.4955	0
0	-1	0		10.123	0	-10.123	0
			SUM	72.6947	0.4069	1.5774	-0.9665
			AVERAGE	8.0772 (a_0)	0.04521 (a_1)	0.1753 (a_2)	-0.1074 (a_3)

(B) Quenched & Tempered Steel

(a) For four experiments :

x_1	x_2	$x_1.x_2$		**Wr** × E^{-11}	x_1.**Wr**× E^{-11}	x_2.**Wr** × E^{-11}	x_1x_2.**Wr** × E^{-11}
1	1	1		4.4767	4.4767	4.4767	4.4767
1	-1	-1		3.154	3.154	-3.154	-3.154
-1	1	-1		3.0523	-3.0523	3.0523	-3.0523
-1	-1	1		3.5101	-3.5101	-3.5101	3.5101
			SUM	14.1931	1.0683	0.8649	1.7814
			AVERAGE	3.5483 (a_o)	0.2671(a_1)	0.2162(a_2)	0.4454(a_3)

(b) For combined nine experiments :

x_1	x_2	$x_1.x_2$		**Wr** × E^{-11}	x_1.**Wr**× E^{-11}	x_2.**Wr** × E^{-11}	x_1x_2.**Wr** × E^{-11}
1	1	1		4.4767	4.4767	4.4767	4.4767
1	-1	-1		3.154	3.154	-3.154	-3.154
-1	1	-1		3.0523	-3.0523	3.0523	-3.0523
-1	-1	1		3.5101	-3.5101	-3.5101	3.5101
1	0	0		3.9171	3.9171	0	0
-1	0	0		3.6627	-3.6627	0	0
0	0	0		3.154	0	0	0
0	1	0		3.1032	0	3.1032	0
0	-1	0		4.2223	0	-4.2223	0
			SUM	32.2524	1.3227	-0.2542	1.7805
			AVERAGE	3.5836 (a_0)	0.1469 (a_1)	-0.0282 (a_2)	0.1978 (a_3)

Positive values of the coefficients signify the increase in wear responses due to increase in associated individual parameters and their interaction. Whereas, the magnitudes of the coefficients signify the extent of influence of the individual parameters or their interaction on the wear responses. For example, positive and higher value of a_1 signifies increase in wear rate with applied load to a greater extent. Similarly very low value of coefficients suggests the effect of associated individual parameters or the interactions is insignificant towards the wear rate of material. The measured wear rate was of the order of $10^{-11} m^3/m$. In the calculation, this multiplication factor is not considered, as it is common to all. Therefore, the coefficients were calculated using the designed matrix.

After calculation, the linear equations generated are as follows:

For AR steel

For four sets of experiments

$Wr = 7.9995 + 0.4960\ x_1 + 0.8012\ x_2 - 0.2416\ x_1 x_2$……………………………………(3)

For nine sets of experiments

$Wr = 8.0772 + 0.04521\ x_1 + 0.1753\ x_2 - 0.1074\ x_1 x_2$…………………………….....(4)

For QT steel

For four sets of experiments

$Wr = 3.5483 + 0.2671\ x_1 + 0.2162\ x_2 + 0.4454\ x_1 x_2$………………………………………..(5)

For nine sets of experiments

$Wr = 3.5836 + 0.1469\ x_1 - 0.0282\ x_2 + 0.1978\ x_1 x_2$…………………………………………………………...(6)

Values of applied pressure,shot size size and wear rate (W_r) for each set of experiment are shown in Table 2 and Table 3. From these tabulated data, matrix is designed to calculate the coefficients of the linear regression equation representing wear rate as a function of applied pressure & shot size.

5.2 Validity of Linear Regression Equation

Validity of the above equations was tested by conducting a series of tests at randomly selected experimental parameters such as applied pressure (P) and shot size (S) . The calculated values under such selected experimental parameters are compared with experimental values.

It is to be noted that during calculation of wear rate under selected experimental conditions, the coded values of experimental parameters are considered. The coded value is defined as follows:

$$CV = \frac{AV-BV}{BV-ULV \text{ or } LLV} \qquad \ldots\ldots(7)$$

Where AV is the actual value, BV, ULV and LLV are the values of the selected parameters in the base value, upper level value and lower level value respectively. For example the coded value of 0.6 mm shot peening at 3 bar pressure is equal to (0.6-0.8)/(0.8-0.6) = - 1.

The experimental values along with the calculated values of wear rate from Eq. (I), (II),(III) & (IV) are reported in Table 2 (a & b)and Table 3 (a & b), for As Received steel and Quenched & Tempered steel respectively.

Table 4. Comparison of wear rates for As Received steel
(a)For randomly taken five sets

Pressure (Bar) , x_1	Shot Size (mm), x_2	Wear Rate Wr× 10^{-11} (m^3/m). experimental	Wear Rate Wr× 10^{-11} m^3/m). calculated	Difference (W_{rexp} –W_{rcal})
5(+1)	0.8 (0)	6.5115	8.4955	-1.984
3 (-1)	0.8 (0)	8.0885	7.5035	0.585
4 (0)	0.8 (0)	7.4781	7.9995	-0.5214
4 (0)	1.0(1)	8.4955	8.8007	-0.3052
4 (0)	0.6 (-1)	10.123	7.1983	2.9247

(b) For combined nine sets

Pressure (Bar) , x_1	Shot Size (mm), x_2	Wear Rate Wr× 10^{-11} (m^3/m). experimental	Wear Rate Wr× 10-11 m3/m). calculated	Difference (W_{rexp} –W_{rcal})
5(+1)	1.0(+1)	9.0551	8.19031	0.86479
5(+1)	0.6(-1)	7.9359	8.05451	-0.11861
3(-1)	1.0(+1)	8.5464	8.31469	0.23171
3(-1)	0.6(-1)	6.4607	7.74929	-1.28859
5(+1)	0.8 (0)	6.5115	8.12241	-1.61091
3 (-1)	0.8 (0)	8.0885	8.03199	0.05651
4 (0)	0.8 (0)	7.4781	8.0772	-0.5991
4 (0)	1.0(1)	8.4955	8.2525	0.2430
4 (0)	0.6 (-1)	10.123	8.1983	1.9250

Table 5 Comparison of wear rates for Quenched & Tempered steel

(a) For randomly taken five sets

Pressure (Bar) , x_1	Shot Size (mm), x_2	Wear Rate Wr× 10^{-11} (m^3/m). experimental	Wear Rate Wr× 10-11 m3/m). calculated	Difference (W_{rexp} –W_{rcal})
5(+1)	0.8 (0)	3.9171	3.8154	0.1017
3 (-1)	0.8 (0)	3.6627	3.2812	0.3815
4 (0)	0.8 (0)	3.154	3.5483	-0.3943
4 (0)	1.0(1)	3.1032	3.7645	-0.6613
4 (0)	0.6 (-1)	4.2223	3.3321	0.8902

(b) For combined nine sets

Pressure (Bar) , x_1	Shot Size (mm), x_2	Wear Rate Wr× 10^{-11} (m^3/m). experimental	Wear Rate Wr× 10-11 m3/m). calculated	Difference (W_{rexp} –W_{rcal})
5(+1)	1.0(+1)	4.4767	3.9001	0.5766
5(+1)	0.6(-1)	3.154	3.5609	-0.4069
3(-1)	1.0(+1)	3.0523	3.2107	-0.1584
3(-1)	0.6(-1)	3.5101	3.6627	-0.1526
5(+1)	0.8 (0)	3.9171	3.7305	0.1866
3 (-1)	0.8 (0)	3.6627	3.4367	0.2260
4 (0)	0.8 (0)	3.154	3.5836	0.4296
4 (0)	1.0(1)	3.1032	3.5554	-0.4522
4 (0)	0.6 (-1)	3.8123	3.3321	0.4802

Table 4 and Table 5 shows that the experimental values of wear rates at the randomly selected experimental parameters are in good agreement with the calculated values of wear rate from Eq. (3),(4),(5) & (6) using the coded values of the experimental parameters.

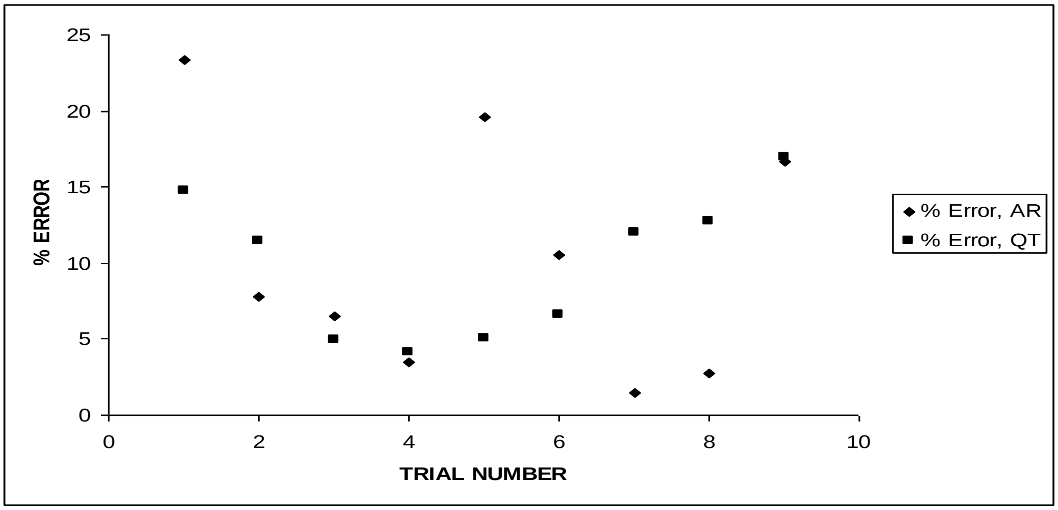


Fig. 5 %Error Vs Trial No. plot

Figure 5 shows the plot between %error and number of trials chosen for validity. Out of these nine trials only one trial value crosse over 20% error mark and only three values of trials crosses 15% error mark. Other then these trial values, five trial values are well below the 15% error mark. From this plot it is clear that the empirical equations developed hold good for prediction of wear behaviour as a function of applied pressure and shot size.

6.0 Conclusions:

The following conclusions could be drawn from the present study:

1) The wear rate of quenched & tempered (QT) steel is less than the as received (AR) steel. However QT steel exhibits higher wear resistance as compared to AR steel.
2) The As received steels depicts the presence of pearlite patches in the ferrite matrix and the pearlite lamelaes are present primarily at triple point
3) The tempered martensite phase consists of very fine carbides precipitated in martensite needles in QT steel.
4) After shot peening, the wear rate of both the steels are different.
5) After shot peening, there is improvement in wear resistance in both steels. But the overall wear resistance of the steels is more when the steel is subjected to QT.
6) The wear rate is minimum when both the steels were shot peened. However in as received steel the minimum wear rate was observed at 5 bars with 0.8 mm shot size. In case of QT the minimum wear rate was observed at 3 bars pressure with 1.0 mm shot size.
7) The wear rate reduced to minimum at a critical shot peening. The AR & QT steels, irrespective of heat treatment schedule, provide the minimum wear rate at 4 bar pressure. At higher pressure the steel suffers from higher wear rate.
8) The microstructure of peened sample shows the presence of spherical dents on the surface and they are uniformly distributed.
9) The distance of the microhardness indentors location from interface has been normalised with respect to the distance between the denters.

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