Effect of Shot Size and Peening Pressure on the Low Stress Abrasive Wear Behavior of Annealed Medium Carbon Steel

S.L. Ahirwar, D.P. Mondal, Mukesh Pandey, Shyam Birla

Abstract— **The effect of shot size and peening pressure on abrasive wear of annealed medium carbon steel has been studied. The peening pressure was varied between 3-5 bar and shot size in the range of 0.6-1.00 mm at fixed peening intensity of 0.27A.The low stress abrasive wear tests were conducted using dry abrasion test rig TR-38 at an applied load of 50 N. It was noted in general, that the wear rate decreases with increase in sliding distance. It is interestingly noted that the minimum wear rate is observed at 0.8 mm shot size and 4 bar peening pressure. Further, decrease or increase in peening pressure or shot size leads to higher wear rate. This has been understood from the surface and the subsurface microstructures, work hardening and residual stress distribution after shot peening. The wear rate further correlated empirically with peening parameters.**

Index Terms— **Shot peening intensity, Peening parameters, Abrasion, Wear rate, Sliding distance, microstructure**

I. 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, 2]. The As received steel plate may contains inhomogeneous structure which may cause inferior mechanical properties. Therefore, annealing of steel is thought off to get homogeneous structure and uniform and reproducable mechanical properties. But, due to annealing, the steel becomes softer and thus, there is a possibility of reduction in wear resistance [3]. 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 [4, 5]. 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%). Several researchers [6-8] have reported that the wear rate of soil moving, cutting and threshing equipment is very high. This is primarily due to wear, caused by abrasion, because of material surface and soil interaction. The prime cause is that these steels are not properly heat treated or processed.

Wear has been defined as the material removal from solid surfaces, which may cause failure of components. Wear mechanism and wear rate depend extensively on chemical composition, microstructure, surface properties of materials and experimental parameters like load, sliding distance, abrasive particle size and shape etc. [2, 9-11]. It is reported that 80–90% of wear problem in agriculture sectors are due to abrasion. As wear rate is primarily governed by hardness and strength, it is expected that steel component with higher surface hardness and strength should give higher wear resistance in soil engaging components [7, 12]. The wear of material is also related to surface and subsurface cracking. If the extent of cracks increases, the wear resistance will decrease. But the surface cracking can be reduced through generation of compressive residual stresses using shot peening [13-15]. Additionally, shot peening also work hardened the surface and modified subsurface microstructures of the peened specimen [16-18]. Thus, shot peening could improve the wear resistance of steel. It is also reported that steel with higher ductility might achieve better work hardening and surface residual stress [19, 20]. In this context, it is thought that shot peening on annealed steel further improve the wear resistance. But, very limited attempts have been made to examine the effect of shot peening on the low stress abrasive wear behavior of annealed medium carbon agricultural grade steel [2, 21, 22]. Furthermore, the peening parameters were not optimized for getting optimum wear resistance in peened steel. The present paper deals with optimization of peening pressure and shot size to get maximum wear resistance in annealed medium carbon steel.

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II. EXPERIMENTAL PROCEDURE

2.1. Material and heat treatment

Specimens for microstructural, mechanical and wear testing were made from medium carbon steel, which container 0.51 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 which involves soaking the samples for 60 minutes at 875^0C followed by furnace cooling. The hardness of these steels was measured using Vickers hardness tester at an applied load of 50 N. Before hardness measurement, samples are mechanically polished. The tensile tests were conducted using Instron universal test machine (Model: 8801).The hardness and tensile properties of annealed steel are 138 HV and 490 N/mm^2 respectively.

2.2. Shot peening

The shot peening is carried out using Mec shot, Jodhpur make machine at varying shot sizes and peening pressures maintaining constant peening intensity of 0.27 A. The strips were shot peened, using steel shots of (45 HRC) under selected parameters like pressure (3, 4 & 5 bar) and diameter (0.6, 0.8 & 1.0 mm) for 20-120 s to obtain fixed peening intensity (0.27A).

2.3. Micro-hardness measurement

The micro-hardness values from the surface towards the centre of the specimens are measured. The micro-hardness values are taken at an interval of 20 µm. In all the samples micro-hardness values are taken using applied load of 10gmf. Therefore, in case of ferrite-pearlitic (annealed steel) steel, micro-hardness values are taken in ferrite phase as the indents are the more clear in these phases. The distributions of micro-hardness from the surface towards centers were examined in order to understand the stress distribution the surface of the specimen and also to feel the work hardening and micro structural modification.

2.4. Low stress abrasion wear tests

Three body abrasion tests were conducted on as pinned and unpinned samples under differently heat treated conditions. The schematic view of the test procedure is shown in Figure 1(a). The samples having dimensions 75mmx25mmx7mm were used and are hold rigidly against the rubber wheel. The sand particles are feed between sample and rubber wheel through the hopper. The average size of sand particles is 258.90 ± 20 µm. The size distribution of these sand particles is shown in Figure 1(b).The wheel was rotated at a fixed speed of 1.86m/s and the test is continued up to a distance of 2.6 km. All these wear tests were conducted at a constant load of 50 N. The wear rate was measured from weight loss measurement using the following relation:

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

Where, W_i is weight of specimen prior to the wear 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.

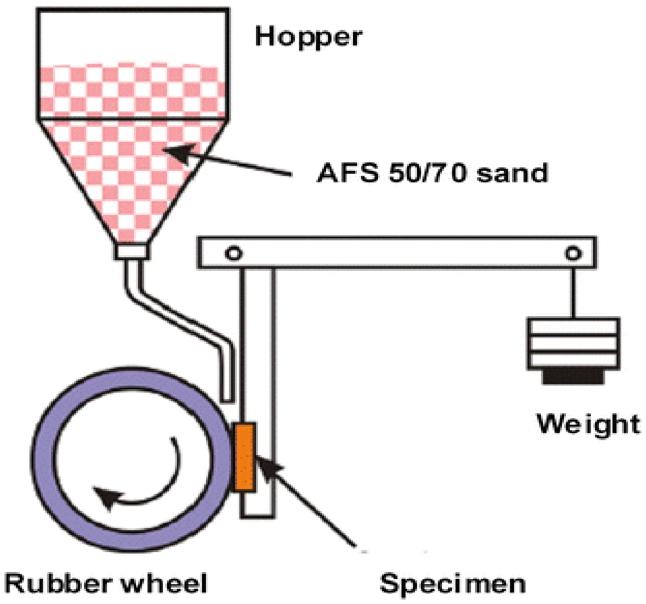

Fig. 1(a) Schematic view of low stress abrasion wear test

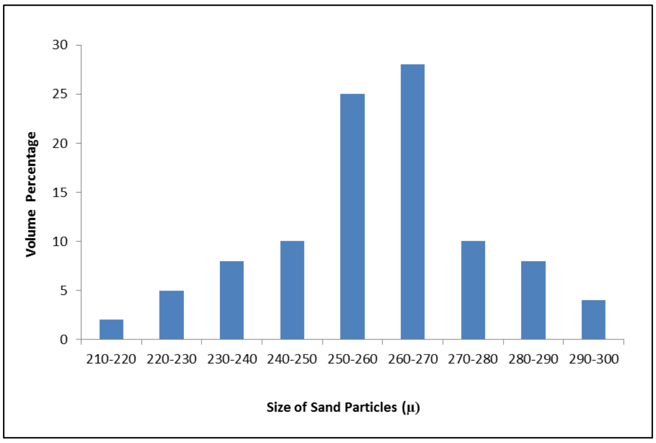

Fig. 1(b) Size distribution of sand particles

III. Result and Discussion

2.5. Material Characteristics

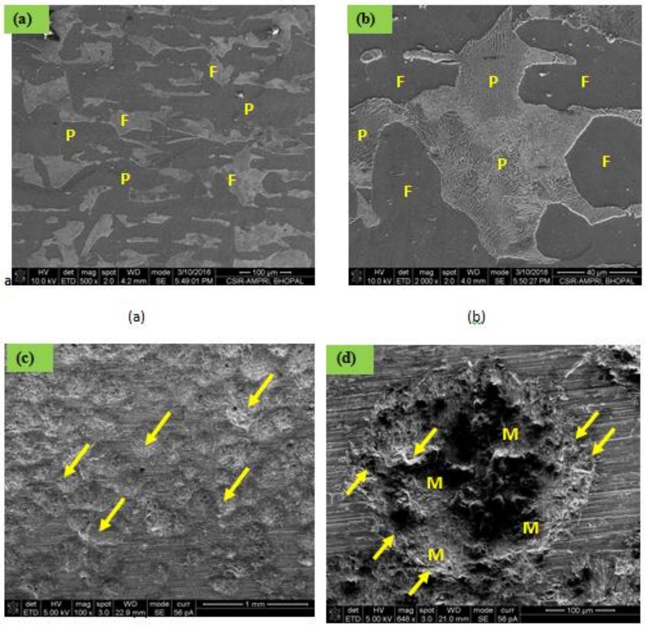

Fig. 2 Microstructure of annealed steel (a) lower magnification and (b) higher magnification (c) shot peened specimen at lower magnification (d) shot peened specimen at higher magnification

The microstructure of annealed steel is shown in Figure 2. The microstructure (Fig.2(a)) indicates presence of ferrite grains (marked 'F') and colonies of pearlite(marked 'p') . In this steel the ferrite contains is noted to be lower than of pearlite. The pearlite lamellae are coarser (589 nm) in dimension. This is because the steel is annealed and during annealing a large fraction of pearlite lamellae is subjected to greater growth. The microstructure indicates clearly the ferrite grains and the pearlite lamellae (Fig. 2(a)). The higher magnification micrograph (Fig. 2(b)) clearly reveals the colonies of pearlite as exhibited in Figure 2(b).

The microstructure of shot peened specimen showed that the dents made through shot peening are uniformly distributed on specimen surface as shown in Figure 2(c). The higher magnification micrograph showed that fins are formed within the dents which in due course get fractured (arrow marked) (Fig. 2(d)) it is father noted that within the same dents some minodents [M] are formed. This indicates repetitive peening which also cause fracturing of lips (marked 'arrow') formed in earlier dints At higher peening pressure and coarser shot size, micro cracks are generated as shown in Fig. 2(d).

This is due to greater effective pressure imposed by each individual shots and their repeated peening. Repeated peening cause over hardened the surface and excessive residual strain which synegetically cause cracking of specimen surface at higher peening pressure and coarser shot size.

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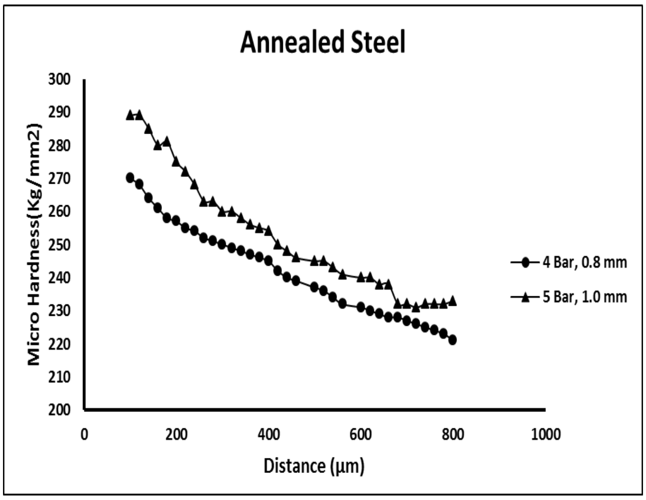

Fig.3 Micro-hardness distribution under selected peening conditions

The micro-hardness distribution under selected peening conditions is shown in Figure 3. It is evident from this figure that micro hardness values are significantly high at the peened surface which gradually reduced with the distance from subsurface and finally reached to the bulk micro hardness of the specimen. Higher microhardness at the surface is due to compressive residual stress generated on the surface and to some extent due to microstructural refinement leading to higher strength. The microhardness changes over the bulk microhardness can be considered to be proportional to the residual stress (σ_{rd}) and can be determined using the following relation [15]:

$$\sigma_{rd} = \frac{\Delta H}{7.1} * 10.0 \qquad \textbf{(2)}$$

ΔH = Hi –Hc, Where Hi is the micro hardness at the i^{th} position from the surface and Hc is the bulk micro hardness at the center. The microhardness values at the surface and center and the residual stress at the surface are shown in Table1.

Table1: Peening depth and compressive residual stress

Heat Treatment	Peening Parameters		Micro Hardness at Surfaces (Hv)	Peening Depth (µm)	Residual Stress (MPa)
	Peening Pressure (bar)	Shot Size (mm)			
AN	3	0.6	295	620	77.46479
		0.8	310	640	98.59155
		1	320	640	112.6761
	4	0.6	305	640	91.5493
		0.8	315	700	105.6338
		1	325	800	119.7183
	5	0.6	315	680	105.6338
		0.8	325	720	119.7183
		1	330	800	126.7606

It is noted that the residual stress (microhardness) increases with increase in shot size and peening pressure. This is because of greater over all energy imposed on the specimen surface through peening. However, the increase of microhardness or residual stress is marginal when shot size changed from 0.8 to 1.0 mm and peening pressure changes from 4 bar to 5 bar. This might be due to surface micro cracking under high pressure and coarser shot size and also greater extent of rebounding action of shots leading to reduction in effective speed of shots over the specimen. The microcracking of surface and greater heat generated also cause release of residual stress to some extent.

2.6. Wear behavior of annealed steel

2.6.1. Effect of sliding distance

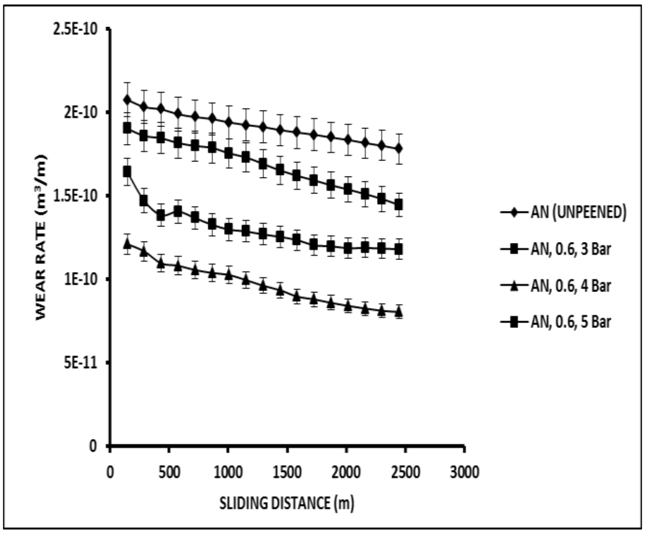

Fig. 4(a) Comparison of wear rate with sliding distance at fixed shot size of 0.6 mm for different peening pressures with unpeened annealed steel

Figure 4(a) represents the variation of the wear rate with sliding distance for the given materials peened with 0.8 mm shot peening and different peening pressures. It is evident from this figure that the wear rate reduces with sliding distance and approaches to a stable value. The annealed steel shows lowest wear rate at 0.6 mm shot size when the peening pressure is 4 bar throughout the sliding distance. For example, the wear rate at sliding distance of 720 m for peening pressure of 3 bar, 4 bar and 5 bar are 1.7988E-10 m^3/m, 1.0032E-10 m^3/m and1.3664E-10 m^3/m respectively. Similarly, at sliding distance of 1440 m, the wear rate for peening pressure of 3 bar, 4 bar and 5 bar are 1.6518E-10 m^3/m, 9.5129E-11 m^3/m and 1.254E-10 m^3/m respectively. At steady state (i.e. at 2448 m sliding distance) the wear rate for peening pressure of 3 bar, 4 bar and 5 bar are 1.4447E-10 m^3/m, 8.6481E-11 m^3/m and 1.1802E-10 m^3/m respectively.

Figure 4(a) also included the wear rate data of unpeened sample. When the wear rate is compared with the unpeened sample, it is noted that the peened sample exhibited much better wear resistance (Fig. 4(a)) especially at peening pressure of 4 bar. It is further noted that the wear rate at 5 bar pressure is higher than the sample peened at 4 bar pressure but lower than the sample peened at 3 bar pressure. This is because of over hardening of specimen surface and more subsurface crack formation, wider and fragmented lips formation at higher peening pressure. At lower pressure, dents become shallower, lips become shorter and rebounding action is relatively less. This makes the surfaces with soft shallower and finer lips. As a result, wear rate at 3 bar pressure is again higher than that at 4 bar peening pressure. If the wear rate of unpeened sample is compared with peened at 4 bar pressure, it is ~ 60% less in peened condition. The wear rate at peening pressure of 3 bar and 5 bar is 20% and 30% less than that of unpeened sample. The reduction in wear rate with sliding distances is due to work-hardening of surface, change in surface characteristics existence of affective residual stress. As the sliding distance increases the surface gradually become smother and smother. Finally, sharp lips are removal from the surface. The wear is primarily due to cutting and ploughing action.

2.6.2. Effect of shot size and peening pressure

The wear rate as a function of shot size for the materials tested at different shot pressures are shown in Figure 4(b).

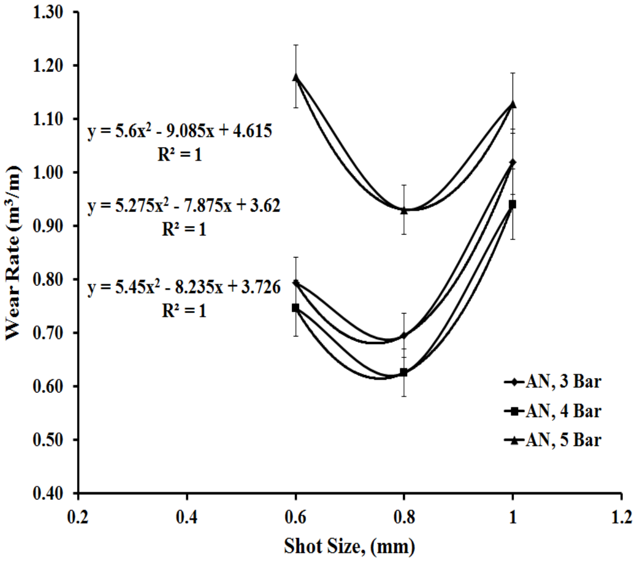

Fig. 4(b) Variation of wear rate with shot size for different peening pressures.

It is evident from this figure that the wear rate initially reduced with size significantly and reached to the minimum at 0.8 mm shot size and it increases again substantially with increase in the shot size from 0.8 mm to 1.0 mm, irrespective of peening pressure. It is further to be noted that the wear rate is the minimum when the samples are peened at 4 bar peening pressure.

Table2: Values of constants

$ax10^{-10}$	$bx10^{-10}$	$cx10^{-10}$	Pressure (Bar)
3.62	7.875	5.275	3
3.726	8.235	5.45	4
4.615	9.085	5.60	5

It is also observed that at fixed shot size, the minimum wear rate is encountered for the sample when peened at 4 bar and the maximum wear rate is accounted for the one when peened at 5 bar pressure. For example, the wear rate at 0.6 mm shot size for peening pressure of 3 bar, 4 bar and 5 bar are 7.9359E-11 m^3/m, 7.4781E-11 m^3/m and 1.1802E-10 m^3/m respectively. Similarly, at 0.8 mm shot size, the wear rate for peening pressure of 3 bar, 4 bar and 5 bar are 6.9694E-11 m^3/m, 6.2572E-11 m^3/m and 9.3095E-11 m^3/m respectively. At 1.0 mm shot size, the wear rate for peening pressure of 3 bar, 4 bar and 5 bar are 1.0276E-10 m^3/m, 9.4112E-11 m^3/m and 1.1395E-10 m^3/m respectively.The values of constants are given in table 2. It is interestingly noted that the wear rates at peening pressure of 3 bar and 5 bar are different. At low peening pressure and finer shot size, the surface deformation is expected to be less and the dents are finer. In addition, at finer shot size number of shots will also be more. This also causes more interaction with individual shots and chances of rebounding with other shots increases and this result in less effective peening. Furthermore, at the lips around the dents formed by finer shots are thinner and finer which easily removed during wear and thus material removal become faster. But the energy imposed by individual shot will be less causing less surface cracking. But overall work hardening is higher . In case of coarser shot size, there would be larger impact by each shot leading to surface over hardening and surface micro cracking. The lips around the dents formed by peening are also coarser and deeper. Cracks are also formed in these lips. This also causes more removal for materials. At higher peening pressure, this becomes more severe as the impact by peening become more. Even though, there is a greater chance of rebounding, but the pressure is so high that the overall impact is high and leading to more severe cracks, delamination of lips etc., as a result wear rate is also noted to be higher at higher peening pressure (i.e. at 5 bar). It is interesting to note that the difference in the wear rate between peening pressure of 3 bar and 4 bar is much less than between the pressure of 4 bar and 5 bar. This is because of lower hardness of annealed steel, which under less pressure exhibits reasonably good work hardening without surface cracking during peening. But, in case of high pressure and coarser shot size, the extent of deformation vis-à-vis work hardening become significantly severe leading to surface cracking, deeper and extended lips with fine microcracks. As a result, significantly higher materials removal takes place and leading to very high wear rate at 5 bar pressure.

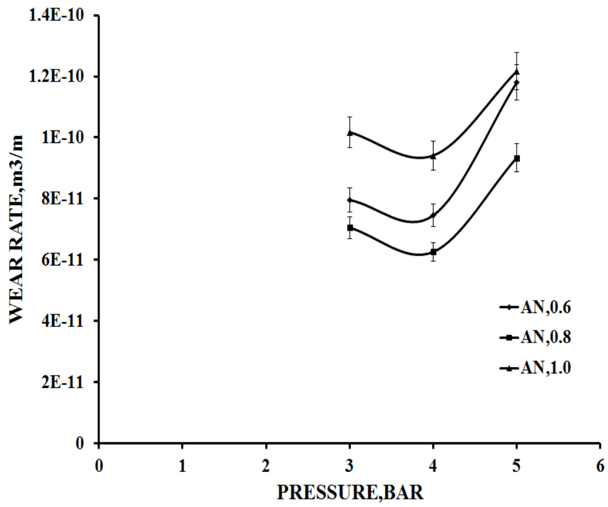

Fig. 4(c). Variation of wear rate with peening pressure at different shot sizes.

The wear rate as a function of peening pressure for the samples peened using different shot sizes are shown in Figure 4(c) for better understanding. Through this figure, it is noted that initially, the wear rate decreases with peening pressure and reaches to the minimum at peening pressure of 4 bar and increases sharply when peening pressure increases from 4 bar to 5 bar. Also, it is noted that the wear rate at shot size of 0.6

mm and 1.0 mm are almost same especially when the peening pressure is 3 bar or 5 bar. This has been explained in earlier paragraph. Because of the synergic effect of pressure and shot size, surface deformation, microcracking tendency, shot to shot interaction, rebounding, nature of lips etc. change, and cause such kind of variation in wear rate pressure or shot size. At intermediate shot size (0.8 mm) and peening pressure (4 bar), the sample surface is work hardened and the surface is not subjected to any severe microcracking. The lips are more stable. The rebounding action may be higher than that at lower peening pressure but the overall extent of impact due to peening is higher. As the shot sizes are coarser, the rebounding possibility is less. Thus more effective impact is expected which led to greater surface deformation and cause and more surface subsurface crackly. This also cause higher wear rate over work hardening. The subsurface is free from cracks and get refined also. All these factors led to the minimum wear rate at intermediate shot size (0.8 mm) and peening pressure (4 bar). At higher peening pressure and coarser shot size over work hardening, greater surface, and subsurface cracking. Whereas at lower peening pressure relatively less work hardening, lower degree of residual stress and less micro-structural refinement which are, causing less surface hardness; vis.-a-vis. higher wear rate.

3.2.4 Correlating wear rate with shot size and peening pressure

The wear rate data are best filled with shot size and for each peening pressure and following for relations are achieved:-

$WR = 10^{-10}(5.275s^2 – 7.875s + 3.62)$… for 3 bar (3)

$WR = 10^{-10}(5.45s^2 – 8.235s + 3.726)$…for 4 bar (4)

$WR = 10^{-10}(5.6s^2 – 9.085s + 4.615)$ ……………………………………………for 5 bar (5)

Thus the above relations in general can be written as follows:

$WR = a – bs + cs^2$……..……………………….(6)

Where s is the shot size and WR is the wear rate (m^3/m). The coefficients associated with each of the factors in the equations are functions of peening pressure.

The coefficients were than plotted against peening pressure and for each coefficient one gets the following relation:

$a= 0.391p^2 – 2.634p + 8$ …………………..…(7)

$b= 0.245p^2 – 1.355p + 9.735$ ……………….…(8)

$c= -0.012p^2 + 0.262p + 4.6$ ….……………...(9)

Replacing a, b & c in equation (6), one get the following relation:

$WR = 10^{-10}[(0.391p^2 – 2.634p + 8) – (0.245p^2 – 1.355p + 9.735)s + (-0.012p2 + 0.262p + 4.6)s^2$……………………………………..….(10)

The experiments on randomly selected shot sizes (s) and peening pressure (p) are carried out and then compared with the predicted results and reported in Table 3.

Table 3: Wear rate differences For annealed steel

Sr.No.	Peening Pressure (p), Bar	Shot Size (s), mm	$WRX10^{-10}(m^3/m)$ (Experimental) [E]	$WR X10^{-10}(m^3/m)$ (Predicted from equations)[P]	Difference, (m^3/m) [P-E]	% Difference
1.	2.5	0.5	1.127553	1.214375	0.086822	7.14
2.	3.5	0.7	0.645036	0.606425	(-)0.038611	(-)6.36
3.	4.5	0.9	0.865145	0.810035	0.05511	6.80
4.	5.5	1.1	1.647005	1.548005	(-)0.099	(-)6.39

The comparison between experimental and predicted results demonstrates that the experimental values are within ±6-8% of the predicted value. This confirms that the experimental values are in good agreement with the predicted ones. Thus, the equation (A) can be used for determining low stress wear rate within the present experimental domain.

3.3.1. Wear Coefficient

The wear coefficient under each experimental parameter at three different sliding distances were measured using the equation as follows:

Wear Coefficient, K= WR X H/L………………………………………………………….(11)

Where WR is the wear rate, H is hardness and L is the load applied.

The wear coefficient, as a function of sliding distance, peening pressure and shot size are calculated as given in table 4. It is observed that it varies between 10^{-03} to 10^{-04}order. It is minimum at 0.8 mm shot size and 4 bar peening pressure. The order of coefficient signifies that at the initial period, mainly abrasive wear is predominating. During this process, the wear particles entrapped in the dents may cause higher abrasion causing continuous grooves. At the higher sliding distance, the surface become smoother, heat is generated and thus there is a possibility of rolling of abrasive particles to some extent and also adhesion slipping action in few locations. It also causes generation of mechanically mixed layer. These have been reflected through lower wear coefficient.

Table 4. Wear Coefficient for annealed Steel

Shot Size [mm]	Peening Pressure [Bar]	Sliding Distance[m]	Wear Rate $[m^3/m]x10^{-10}$	Hardness $(N/m^2)*10^7$	Applied Load[N]	Wear Coefficient $[K]x10^{-3}$
0.6	3	100	1.74	138	50	4.81
		1000	1.11	138	50	3.06
		2000	1.03	138	50	2.85
	4	100	1.74	138	50	4.81
		1000	1.03	138	50	2.85
		2000	0.847	138	50	2.34
	5	100	1.62	138	50	4.47
		1000	0.996	138	50	2.75
		2000	0.922	138	50	2.54
0.8	3	100	1.12	138	50	3.09
		1000	0.760	138	50	2.10
		2000	0.704	138	50	1.94
	4	100	1.12	138	50	3.09
		1000	0.722	138	50	1.99
		2000	0.654	138	50	1.80
	5	100	1.74	138	50	4.8
		1000	1.15	138	50	3.16
		2000	0.990	138	50	2.73
1	3	100	1.62	138	50	4.47
		1000	1.05	138	50	2.89
		2000	1.05	138	50	2.90
	4	100	1.99	138	50	5.50
		1000	1.15	138	50	3.16
		2000	9.84	138	50	2.72
	5	100	1.87	138	50	5.16
		1000	1.20	138	50	3.30
		2000	1.15	138	50	3.16

3.4. Wear surface and Subsurface

3.4.1. Wear surface

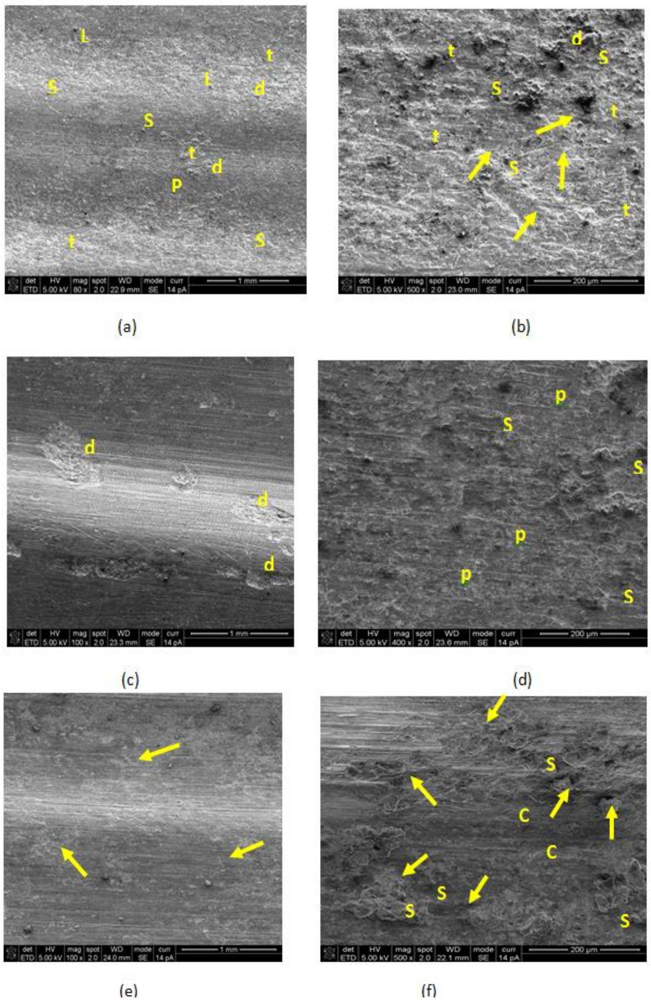

Fig. 5 Micrograph of wear surface of annealed steel after wear test (a) peening pressure is 4 bar and shot size is 0.6mm (b) higher magnifications (c) peening pressure is 4 bar and shot size is 0.6mm(d) higher magnification (e) shot size 1.0mm at peening pressure of 4 bar (f)higher magnifications

At most similar kind of wear surface is noted when the peening pressure is 4 bar and shot size is 0.6mm (Fig. 5(c)). This figure indicated hips and valley on surface with micro-wear grooves in each of the lips and valleys. Small dents (marked 'd') are also noted. At higher magnification, micro-pits (marked 'P') entrapment of sand particles (marked's') and wear grooves are observed (Fig. 5(d)). No surface cracks noted. But when the shot size increases to 1.0mm at peening pressure of 4 bar, the wear surface is associated with surface micro-cracks (marked 'arrow') (Fig. 5(e)) in addition to other feature found in Figure 5(a). at higher magnification the surface micro-cracks (marked 'arrow') are clearly visible (Fig. 5(f)). In addition the surface gets severely damaged and the wear tracked changed sharply (marked 'c'). Fine sand particles (marked 's') are also entrapped in deep grooves or dense. This again indicated that the wear surface damaged to a greater extent when peening pressure increases above 4 bar and shot increases above 0.8mm.

3.4.2. Wear subsurface

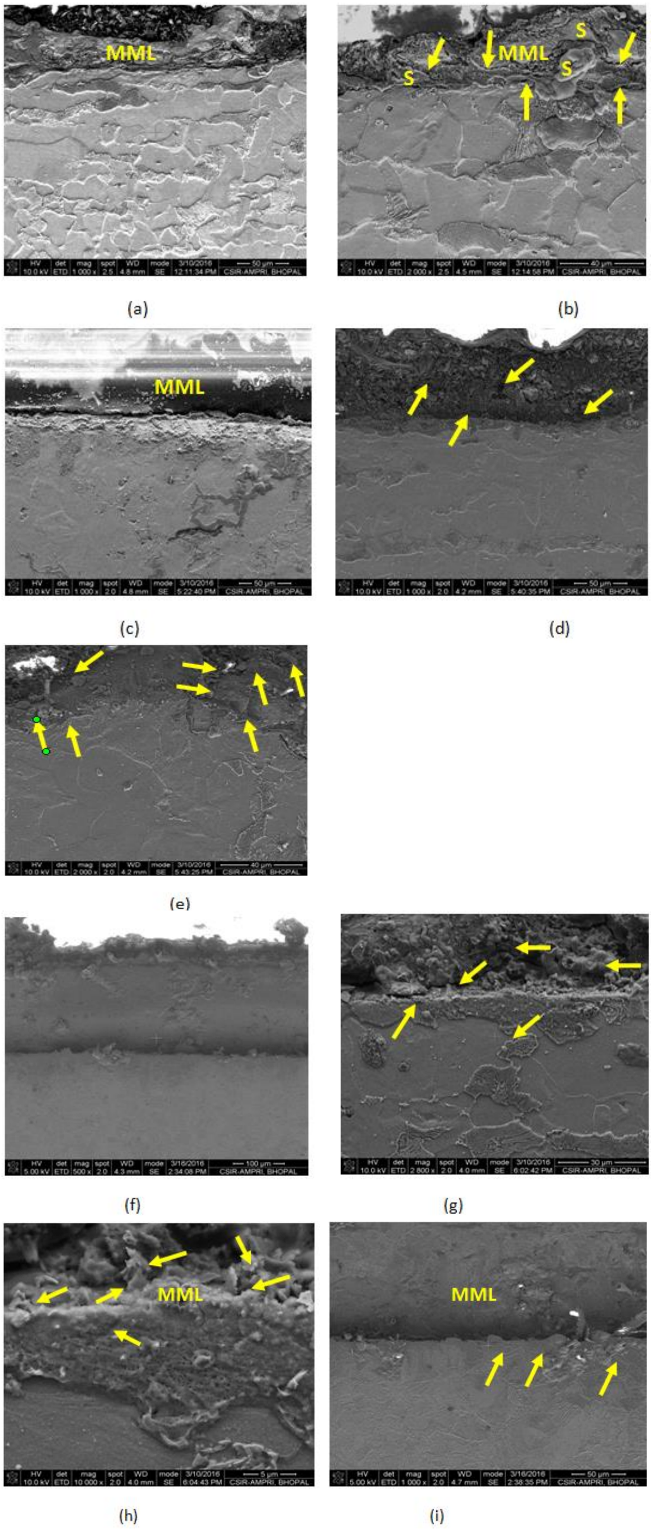

Fig. 6 The subsurface of peened sample after wear test (a) peened with 0.6mm shots at 3 bar pressure (b) higher magnification (c) peening pressure 4 bar with 0.6mm shots (d) peening pressure 3 bar and shot size 1.0 mm (e) higher magnification (f) MML is full of cracks (g) peening pressure 4 bar at 1.0 mm shot size (h) peening pressure is 4 bar (i) 5 bar pressure at 1.0 mm shot size

The wear subsurface of AN steel under different peening conditions are examined under SEM. Figure 6(a) represents the wear subsurface of AN peened with 0.6mm shots at 3 bar pressure. It is evident from this figure that a very thin MML (Marked with MML) with lateral and transverse cracks are formed on the wear surface. Just below the MML there is a highly deformed region, in which also transverse cracks are formed and the materials try to flow along sliding direction. At higher magnification, Figure 6(b), the lateral and transverse cracks [marked arrow] on the subsurface are more clear. The pearlite lamellae are aligned along the sliding direction. Further it reveals entrapment of fine sand particles (marked 's') at the MML. When the peening pressure increased to 4 bar, the MML was there but relatively more stable, Figure 6(c). Generally, surface and subsurface cracking tendency is less. Here also, the material below MML is subjected to get aligned towards sliding direction. If the peening pressure is kept at lower limit (3 bar) and shot size increased to 1.0 mm, the severity of wear increases because of very unstable MML which is due to formation of large number of lateral and transverse cracks (marked arrow) in this region, Figure 6(d). The extent of severity of damage could be understood more clearly through higher magnification micrograph, (Figure 6(e)). It reveals that the MML is full of cracks and the subsurface below MML is also subjected to severe cracking (marked 'arrow') and the pearlite lamellae aligned towards sliding direction in less degree, Figure 6(f).Again, when the peening pressure increased to 4 bar, even at 1.0 mm shot size, the subsurface is subjected to higher deformation. The pearlite lamellae are highly aligned towards sliding direction, and relatively less cracks are generated (Fig. 6(g)). These alignments of pearlite lamellae will improve wear resistance. But the MML is found to be quite unstable even though the peening pressure is 4 bar, (Figure 6(h)). This is because of higher shot size, Figure 6 (h) also reveals a large number of lateral and transverse cracking (marked 'arrow') at MML. Significantly damaged subsurface is observed when the peening is carried out at 5 bar pressure using 1.0 mm shot size (Figure 6(i)). It demonstrates that the subsurface especially the MML is full of lateral and transverse cracks and the lamellae are about to removed. But the subsurface of AN steels when peened at 4 bar pressure using 0.8 mm shots, reveals relatively stable and thicker MML and the pearlite lamellae (marked 'arrow') are aligned well along the sliding direction. These subsurfaces thus states that the stability of MML and the deformed region is better when the samples are peened using 0.8 mm shots and at peening pressure of 4 bar. The optimum stability of subsurface is observed under the peening condition of 0.8 mm shots and 4 bar peening pressure.

The subsurface microhardness values were also examined after wear tests. The average of microhardness values upto a depth of 100μ below the MML were measured using Vicker's microhardness testing equipment. The average values are reported along with standard deviation in the Table 5.

Table 5: Micro hardness values of annealed steel at the subsurface

Shot Size (mm)	Peening Pressure (Bar)	Depth below wear surface					
		25µm	50µm	75µm	100µm	125µm	150µm
0.6	3	178±8.90	158±7.90	145±7.25	140±7.00	136±6.80	138±6.90
	4	189±9.45	172±8.60	168±7.90	145±7.25	140±7.00	138±6.90
	5	181±9.05	157±7.85	147±7.35	139±7.45	138±6.90	138±6.90
0.8	3	183±9.15	165±8.25	148±7.40	144±7.20	139±6.95	136±6.80
	4	190±9.50	178±8.90	169±8.45	149±7.45	144±7.20	138±6.90
	5	179±8.95	162±8.10	147±7.35	138±6.90	139±6.95	136±6.80
1.0	3	170±8.50	161±8.05	145±7.25	138±6.90	138±6.90	138±6.90
	4	178±8.90	158±7.90	149±7.45	140±7.00	140±7.00	138±6.90
	5	165±8.25	155±7.75	142±7.10	138±6.90	138±6.90	136±6.80

It is noted that the AN steels when peened with 0.8 mm shots at a peening pressure of 4 bar exhibits the maximum microhardness values in the subsurface region. This is because of less cracking tendency prior to wear during peening and also optimum subsurface deformation during peening. Because of less cracks, compressive residual stresses in these samples are expected to be more, which also harden the surface. The surface and subsurface demonstrate that the subsurface microstructure, alignment of pearlite lamellae, surface subsurface cracking changes with peening pressure and shot size. All these factors due to their synergic effect cause the stability of MML and the specimen surface against abrasive. The optimum surface and subsurface stability observed at 0.8 mm shots and 4 bar peening pressure, causing the minimum wear rate.

IV. CONCLUSIONS

1. The wear rate of AN steel decreases with increase in sliding distance. This is due to reduction in lips, increasing surface smoothness and work hardening with sliding distance.
2. The wear rate is a strong function of peening pressure and shot size. The minimum wear rate is not at 0.8 mm shot size and 4 bar peening pressure, irrespective of shot size and peening pressure.
3. This is due to changes in surface and subsurface characteristics. At higher peening pressure and coarser shot size, there is a tendency of micro crack formation and creation of longer lips.
4. The subsurface micro hardness also changes during wear. The maximum work hardening during wear is noted under shot size of 0.8 mm and peening pressure of 4 bar.
5. The surface work hardening is measured through micro hardness values.
6. The wear surface and subsurface also showed surface micro cracks, relatively unstable MML and severe wear under coarser shots and higher peening pressure.
7. Higher wear coefficient irrespective of peening pressure and shot size indicates that abrasive wear primarily cutting and ploughing actions are the dominating wear mechanism.
8. The wear rate has been correlated with peening pressure and shot size through second order polynomial equation.

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