

## Low stress abrasive wear response of boron steel under three body abrasion: Effect of heat treatment and peening intensities

Dushyant Singh<sup>a</sup>, D P Mondal<sup>b\*</sup>, O P Modi<sup>b</sup> & V K Sethi<sup>c</sup>

<sup>a</sup>Central Institute of Agricultural Engineering, Bhopal 462 038, India

<sup>b</sup>Advance Material and Processes Research Institute, CSIR, Bhopal 462 026, India

<sup>c</sup>UIT, Rajiv Gandhi Technical University, Bhopal

*Received 22 December 2009; accepted 11 May 2010*

The wear behaviour of medium carbon boron steel with various heat-treatment cycles (annealing, intercritical annealing, and quenching and tempering) has been examined after and prior to shot peening. Shot peening intensity varies in the range 0.17 - 0.47 mm ALMEN 'A'. The wear rate of intercritical annealed and quenched and tempered steels are considerably less than those of as-received and annealed steels, irrespective of the peening intensity. It is further noted that the wear rate reduced significantly irrespective of heat-treatment schedule at the critical peening intensity of 0.27 A, mm ALMEN.

**Keywords:** Heat treatment cycle, Shot peening, Shot peening intensity, Abrasive wear, Boron steel

Industrial components and soil engaging agricultural implements are facing serious problem of abrasive wear<sup>1,2</sup>. The wear rate depends extensively on chemical composition<sup>3</sup>, microstructure<sup>4</sup> and the surface properties<sup>5</sup> of the material and the ambient conditions and experimental parameters such as applied load, sliding distance and operational conditions<sup>6-8</sup>. Addition of boron, even in trace level, improves the hardenability as well as microstructures and properties of steels<sup>9-13</sup>. High toughness and cold formability are some special properties, which could be improved through boron addition. Sliding and abrasive wear of these medium carbon steels with boron addition are reported to be better than of the plain high carbon steels<sup>9-13</sup>. Heat-treatment cycles further change the micro-structure vis a vis mechanical properties of steels<sup>14,15</sup>. During heat-treatment of boron added steels relatively finer microstructure (fine micro-structure consisting of reduced martensitic lath width<sup>16</sup> and interlaminar spacing of pearlite) is observed<sup>14,15</sup>. This may lead to further improvement in mechanical properties and wear resistance. The wear resistance of a structurally heterogeneous material is equal to the sum of the products of the volumetric share of a separate constituent multiplied by its relative wear resistance<sup>17</sup>. A group of researchers<sup>17-20</sup> also found linear

relationship between hardness and wear resistance of metals. On the other hand, it is also reported by some investigators that dependency of wear resistance with hardness is not a thumb rule and they do not always follow the linear relationship. The hardness-wear resistance relationship strongly depends on other materials characteristics<sup>14,15</sup> such as microstructure, toughness and ductility and experimental conditions.

Systematic studies on the influence of different heat-treatment schedules on the low stress abrasive wear behaviour of these kinds of steels have not been carried out so far, to the best of our knowledge

Various surface treatment techniques such as diffusion coatings, thermal spraying, ceramic coating, hard-facing and shot peening are also found cost effective to tailor the surface properties such as microstructure, hardness and strength of the engineering components<sup>21-23</sup>. Shot peening is primarily used for introducing compressive residual stress on the surface of the material to improve its fatigue life<sup>24</sup>. The surface characteristics of shot peened specimens strongly depend on peening parameters, which can be adjusted to achieve the depth to which compressive stress presents and the magnitude of such residual stress required<sup>25</sup>. The beneficial effects of shot peening depend on uniformity of peening, level of maximum residual compressive stresses induced, depth of plastically deformed layer and type of metallurgical changes at

\*Corresponding author (E-mail: mondaldp@yahoo.com)

the sub-surface<sup>26</sup>. These could be controlled with precise control of shot peening parameters<sup>27</sup> such as shot type and size, shot speed, impact angle, exposure time, surface coverage<sup>26,28</sup>. In addition to these, material parameters<sup>27</sup> such as microstructure, hardness, surface condition and hardening characteristic of the material also influence the efficiency of peening process. Shot peening treatment refines the grain size at the sub-surface and increases the atomic level lattice strain. The grains size are even decreased to nano scale just at the subsurface level. The above factors, resulting from shot peening may lead to significant change in wear characterization of the material. In addition, the efficiency of all the aforesaid characteristics depends on the heat-treatment schedule vis a vis microstructure imposed on the material. However, to the best of our knowledge, no attempt has been made to examine the synergic effect of shot peening and heat-treatment schedule on low stress abrasive wear behaviour of plain carbon steel. The aim of the present study is to examine the synergetic effect of heat-treatment cycles and shot peening intensities on three body abrasive wear response of boron containing plain carbon steel and to examine the most suitable combination for improving the wear resistance of these steels with an aim towards its application for agricultural implements. The wear mechanisms of heat-treated and shot peened specimens were understood from wear surfaces and sub surfaces examinations.

## Experimental Procedure

### Materials and heat-treatment

Rolled sheets of 8 mm thickness were used in this study. The chemical composition of this steel is given in Table 1. The specimens were heat treated using three different heat-treatment schedules as shown in Table 2. The specimens were made from heat-treated and as-received materials. The hardness

Table 1– Chemical composition of the steel used for study

Name of element	C	Si	Mn	Cr	B
% Quantity	0.50	0.21	0.78	0.95	0.005

Table 2– Heat-treatment schedules for steels used for study

Name of treatment	Austenising temperature (°C)	Soaking time (min)	Quenching media	Tempering temperature (°C)	Tempering time (min)
Annealing	870	60		furnace cooling	
Intercritical annealing	870	60	water with	250	120
	775	30	8% NaCl		
Quenching and tempering	870	60	water with 8%NaCl	250	120

of as-received and heat-treated steel samples were tested on Vicker's hardness tester at a load of 30 kgf.

### Micro-structural examination

The microstructure of as-received and heat-treated specimens was examined on polished and etched specimen using scanning electron microscope (SEM). The specimens were metallographically polished and etched with 2% of nital. Prior to SEM examination, the etched specimens were sputtered with gold.

### Shot peening

The specimens were ground up to 400 grade emery paper, prior to shot peening. Shot peening of steel samples was conducted on Mec Shot, Jodhpur, India make shot peening machine. The peening intensities were calibrated using standard ALMEN 'A' strip. The strips were shot peened keeping the parameters such as flow rate, stand off height (distance between nozzle and specimen surface), and peening pressure fixed and 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 3. The shot peening intensities 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 wear test apparatus is shown in Fig. 1. In these tests, a rubber wheel (177.8 mm

Table 3– Peening parameters

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

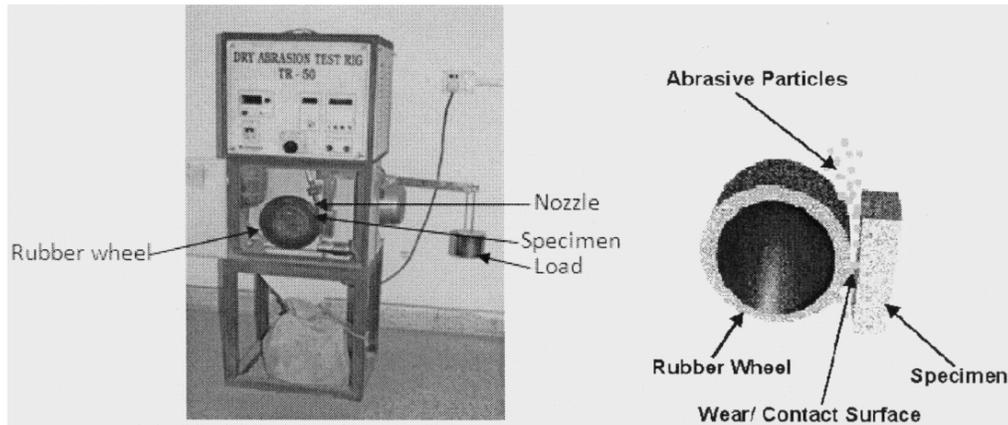


Fig. 1– Rubber wheel /dry sand abrasion test apparatus in conformity ASTM G65

Table 4 – The hardness and micro-structural characterization of steels

Treatment	Specimen code	Hardness (HV)	Vol. Fraction	Ferrite grain size( $\mu\text{m}$ )	Inter laminar spacing ( $\mu\text{m}$ )	Lath width ( $\mu\text{m}$ )
As received	AR	180	Near pearlitic structures 85%pearlite and 15 %ferrite	5.79	0.3165	
Annealed	AN	170	80%pearlite and 20 %ferrite	5.95	0.4265	
Intercritical annealed and tempered	ICA	446	20% ferrite and 80% martensite	4.14		0.425
Quenched and Tempered	QT	458	Tempered martensite (95%) and Retained austenite (4-5%)			0.511

diameter and 12.7 mm width) was rotated against the stationary flat (76.2 mm  $\times$  25.4 mm and 7 mm thick) rectangular specimens with test surface. Crushed silica sand particles of size (size 212-300  $\mu\text{m}$ ) were fed between wheel and specimen at the rate of 370 g/min. The applied load, sliding speed and test length were fixed at 200 N, 1.86 m/s and 2592 m (144 m  $\times$  18 nos.) respectively. The specimens were ground prior to the tests. The wear rate of the specimens was measured at an interval of 144 m of sliding distance. Tests were conducted until the specimens in each case attained steady state wear loss. Wear rate of the specimens were measured from weight loss measurement. The specimens were cleaned with acetone and dried with blown air prior and after tests.

#### Micro-hardness Measurement

From the surface towards the centre, micro-hardness measurements were taken on the cross-section of the polished and shot peened specimen at an interval of 25  $\mu\text{m}$  by using LICA make micro-hardness tester by using an applied load of 25 gf. In each case a large number of micro-hardness measurements were taken so that at each depth level at least 10 micro-hardness readings could be considered.

## Results and Discussion

### Material and microstructure

The microstructure of as-received (AR) and heat-treated (annealed (AN), intercritical annealed (ICA) and quenched & tempered (QT)) specimens are given in Fig. 2. In case of AR and AN specimen the microstructures are almost similar as shown in Fig. 2(a) and (b). It shows the pearlitic colonies (marked 'P') with ferrite net work (marked 'F'). But the interlaminar spacing is noted to be relatively coarser in case of AN specimen. In case of ICA and QT specimen, the microstructures were found to be mixture of tempered martensite (marked 'M') with ferrite (marked 'F'), and tempered martensitic (marked 'M') as shown in Fig. 2(c) and (d) respectively. The average hardness and volume fraction of the micro-constituents in the investigated steels are given in Table 4. The table shows that the percentage of ferrite is increased by about 5% when the steel under gone annealed process as compared to as-received steel. The ICA steel contains 80% tempered martensite and 20% ferrite. Whereas QT condition depicted 95% tempered martensites with 5% retained austenite (marked arrow in Fig. 2d). The martensitic structure is relatively harder in comparison to ferritic and pearlitic, so the hardness of

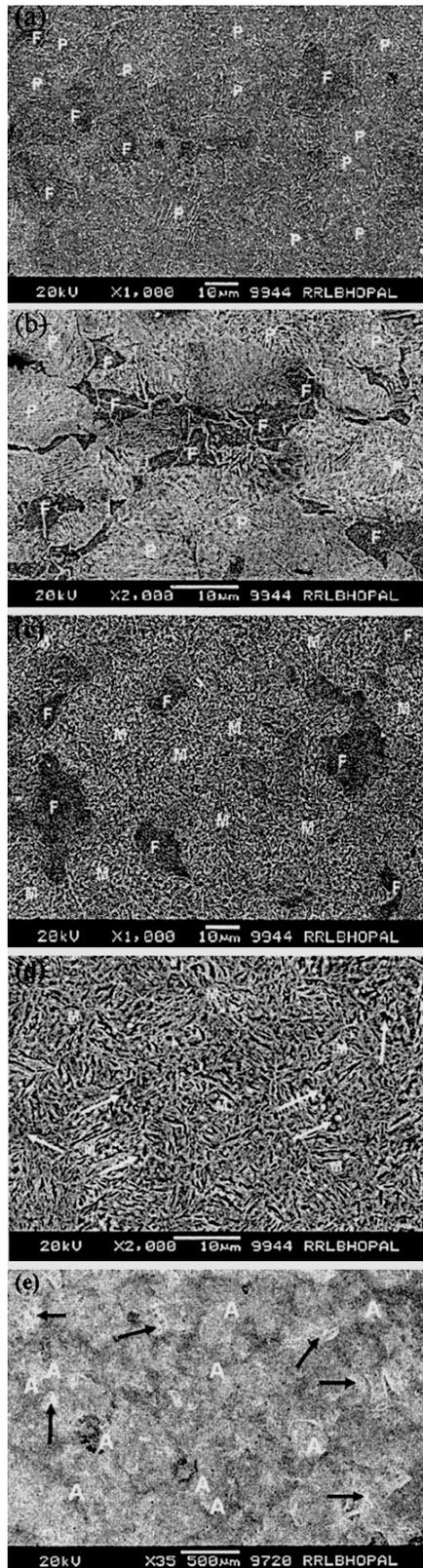


Fig. 2– Microstructure of 50B50 steel (a) As-received, (b) Annealed, (c) Intercritical annealed, (d) Quenched & tempered and (e) Peened at 0.47 A

the heat-treated specimen increases with increase the martensite content. The hardness of the ICA and QT specimens were found to be more than twice the hardness of AR and AN steels. Microstructure and hardness variation of the steel before and after various heat-treatment processes are also given in Table 4. A typical microstructure of peened (0.47 A) AN specimen is shown in Fig. 2e. The dents (marked by ‘A’) and leaps (marked by ‘arrow’) are visible from microstructure. The dents formed by the impact of shots on the surface of the specimen were observed identical in size irrespective of peening intensities which may be attributed to same parameters (shot size, pressure, stand off height) were used during peening operation, only the time of exposure was varied.

#### Abrasive wear

##### *Effect of sliding distance and heat treatment*

The surface work-hardening of the specimen could be noted from the sub-surface relative micro-hardness measurement as a function of peening intensity and depth of micro-hardness in AN steels (Fig. 3a). Relative micro-hardness is defined as the ratio of the micro-hardness at a depth to the micro-hardness of bulk material (un-deformed material). Relative micro-hardness is considered to avoid experimental and manual errors for measurement and for more rationalization of its behaviour. It is clearly seen from this figure that the relative micro-hardness of the specimen increases with peening intensity. The value of micro-hardness was found to be increased by 1.32, 1.44, 1.52 and 1.69 times when peened at 0.17, 0.27, 0.37 and 0.47 A peening intensities. The figure also revealed that the micro-hardness of the specimen decreased gradually with the depth and after 0.4 mm, it became almost equal to un-peened condition (bulk material). Other steels also showed similar trend of variation. But, the depth of peening is noted to be higher in case of AR and AN steels as compared to that in ICA and QT steels as the former ones are more easily and plastically deformed as compared to the latter ones which could be revealed from Figs 3b-3d.

The wear rate of heat-treated un-peened specimens as a function of sliding distance was examined in Fig. 4. This figure states that the work hardening due to continuous plastic deformation reduces the wear rate monotonically with sliding distance. Figure 4 also shows that in un-peened condition the wear rate of AR and AN specimens are almost equal in

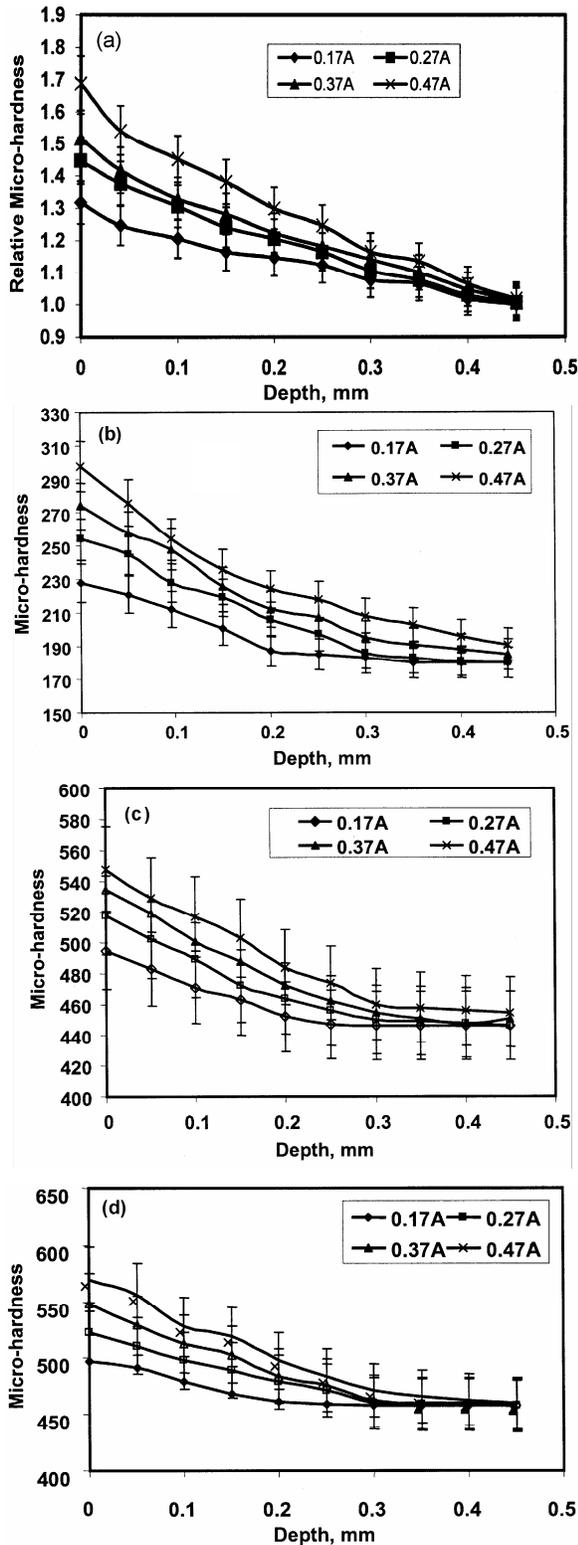


Fig. 3– Relative micro hardness and absolute micro-hardness distribution after shot peening at the surface of steel at varying peening intensities (a) Relative micro hardness of AN, (b) Absolute micro-hardness distribution of AR, (c) Absolute micro-hardness distribution of ICA and (d) Absolute micro-hardness distribution of QT specimens

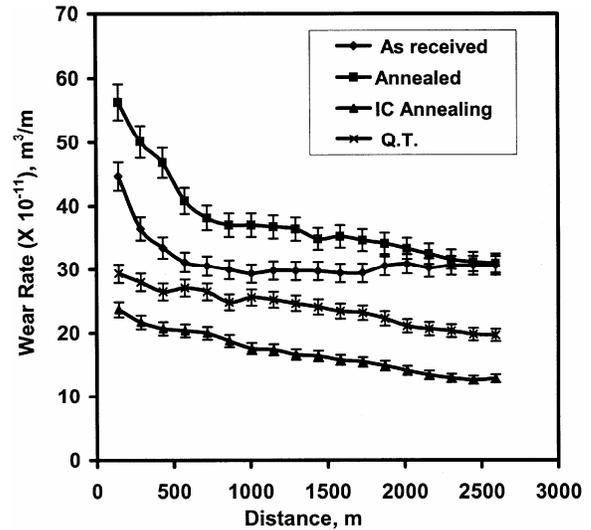


Fig. 4- Variation of wear rate with sliding distance for 50B50 steel under different heat-treatment condition

steady-state condition, although the initial wear rate of AR specimen was lower than the annealed specimen. Whereas, in case of ICA and QT the wear rate are considerably less than that of AN and AR specimens. It is 36% and 61% lower in QT and ICA, respectively (Fig. 4) as compared to AR/AN one. Again, ICA specimen shows relatively lower wear rate (39% approx.) in comparison to QT specimen. The significant reduction in wear rate in ICA and QT treatment could be due to formation of dual phase ferrite-martensitic structure or tempered martensitic structures which provide good combination of strength and toughness, primarily required to resist the abrasive wear. In case of mild peening (0.27 A), the wear rate in steady-state condition is 38% lower in AN specimen as compared to AR specimen as shown in Fig.5. This may be attributed to greater work hardening effect, improved toughness, more homogeneous structure, absence of pre-processed residual stresses or flaws, higher ductility in AN steel as compared to AR one which make the former one more active towards shot peening. Lower hardness and greater ductility of AN again facilitates entrapment of fine abrasives and holdings of wear debris for longer duration. The wear rate is again noted to be decreased considerably in case of ICA and QT specimens, i.e., 43.5% and 50.76%, respectively as compared to AR specimen.

*Effect of peening intensity and heat treatment*

The effect of shot peening may be realized more clearly when the wear rate at different intervals of sliding distance in the peened specimen surface is

examined separately. For better understanding the wear behaviour of AR (peened at 0.27 A) shot peened steel specimens, the wear rate at each interval for the investigated samples when tested at 200 N load were compared in Fig. 6. It is clear from the figure that wear rate of shot peened samples is significantly less in all intervals but the magnitude of variation varies in each interval. It may be noted that the wear rate of peened and un-peened samples are comparable at interval equivalent to 2016 m of distance and above. Same trend of variation is observed in AN, ICA and QT specimens. It demonstrates that the significance of peening is more during initial stages. For the present steel, the effect of shot peening is limited to a certain distance, i.e., up to 2016 m. The study suggests that for getting better and continuous wear resistance (less wear rate), the specimens irrespective of heat-treatment should be shot peened after the

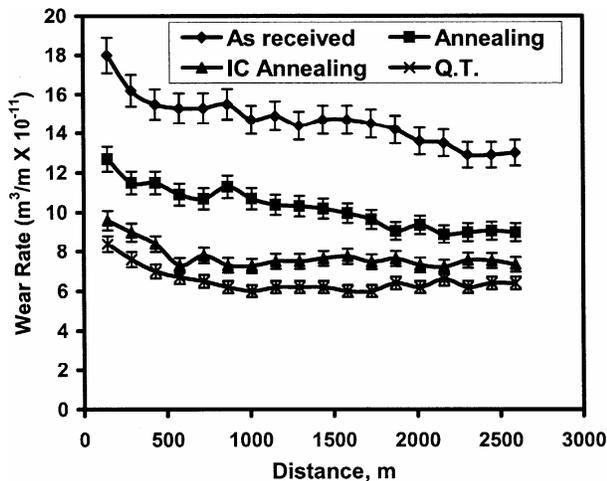


Fig. 5— Variation of wear rate with sliding distance for 50B50 steel under different heat-treatment condition after peening at 0.27A intensity

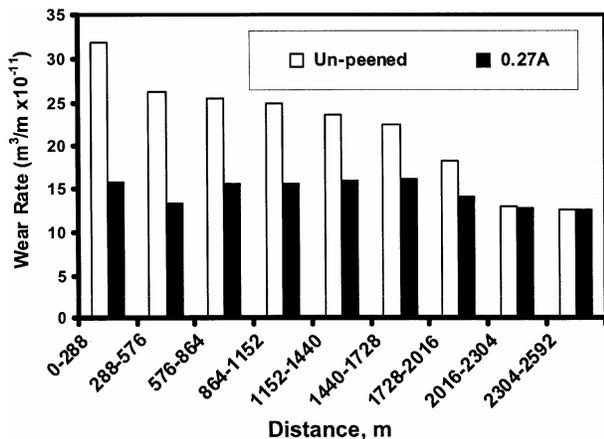


Fig. 6— Wear rate of peened (0.27A) and un-peened as-received samples at different intermediate intervals

certain interval of sliding distance. The wear volume loss as a function of sliding distance in peened and un-peened condition is depicted in Fig. 7. It shows that in case of both un-peened and peened samples, there are three distinct regimes (each regime considered to be linear) having different slopes. In case of un-peened samples, the slope in these three regime decreases gradually (from I to III). But, in case of peened samples, the slope in regime I and II are less as compared to that in regime III. The slope in regime I and regime II in peened specimens are considerably less than those in un-peened samples. These effects are due to shot peening. The slope in regime III, in both the peened and un-peened samples are noted to be almost same indicating same wear rate and this regime starts at a distance of ~2000 m. This could be visualized from the depth of wear at this distance. Simple calculation from the volume loss, width (10.8 mm) and length (46.5 mm) of wear track, showed that depth of wear at this distance for ICA peened sample is ~0.35 mm. This value is in good agreement with peening depth measured through micro-hardness measurement (Fig. 3c)

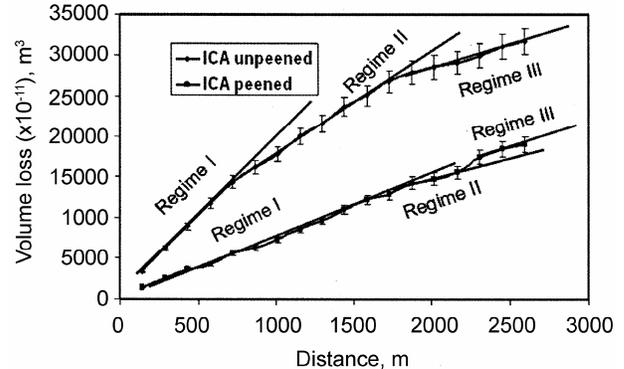


Fig. 7— Volume loss as a function of sliding distance for unpeened and peened (0.27A) ICA specimen

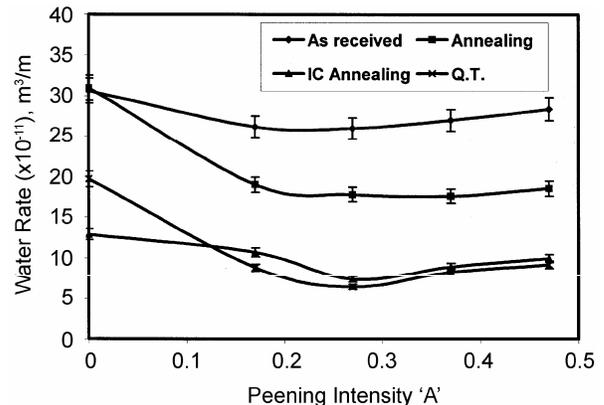


Fig.8— The variation of wear rate with peening intensity for differently heat-treated steels at an applied load of 200 N

The effect of peening intensity on the wear rate for differently heat-treated specimens when tested at 200 N loads is shown in Fig. 8. This figure, in general, exhibits that for all the heat-treated conditions the wear rate decreases with peening intensities, up to 0.27 A. But when the peening intensity increases beyond this limit the wear rate again increases. Thus, the peening intensity should be restricted up to 0.27 A value for achieving the minimum wear rate. At very high peening intensities, the wear rate is considerable high for all the heat treated specimens except AN steel, and some times exceed the value of wear rate of un-peened samples (AR samples). This figure, more clearly shows that the wear rate in case of QT and ICA are comparable and significantly lower than AR and AN specimens. The wear resistance of shot peened specimen is found in increasing order, viz., QT > ICA > AN > AR.

The study revealed that the wear rate reduced by 0.848, 0.574, 0.568 and 0.325 times respectively in AR, AN, ICA and QT conditions due to shot peening. It is also noted that reduction in wear rate is significantly more in case of AN, ICA and QT specimen. The explanation for this has been given earlier. QT specimen contains tempered martensite consisting of nano size carbide phase distributed in ferrite phases are more susceptible to shot peening. The tempered ICA already exhibits improved wear resistance compared to other specimens because of good combination of hardness and ductility. Shot peening is a cheaper surface modification technique for reduction in wear rate hence one can prefer it to that of heat treatment. But it is effective only up to a limited depth. Hence for improvement in bulk wear resistant one could prefer heat treatment. But, the present study (Fig. 8) shows that the combination of shot peening and heat treatment would give synergic improvement in wear resistance (considerable decrease in wear rate). The AR specimen due to annealing followed by shot peening (0.27 A) reduces the wear rate significantly (~42%). The same specimen when subjected to ICA or QT treatment only, the wear rate is reduced 57.8% and 35.7% respectively. While these samples are subjected to peening (0.27 A) the wear rate reduced further by ~43-67%. Severe peening (peening at higher intensity) damaged the dimples and leaps. The interaction of the cracks developed during severe peening leads to delaminating type wear in addition to abrasive wear.

#### **Wear surface and sub-surface studies**

The wear surfaces of AN unpeened and peened (at 0.27 A intensity) specimen, when tested at an applied load on 200 N for a sliding distance of 2592 m, are shown in Fig.9 (a) and (b) respectively. It could be noted that both the wear surfaces are almost same irrespective to the nature of wear grooves, grooves width and other characteristics. The groove width of both the peened and unpeened samples is noted to be almost same (~20  $\mu\text{m}$ ). The grooves are also noted to be almost continuous. This indicates that the abrasive type wear is predominating where cutting and ploughing action are dominating wear mechanism. The wear surface of ICA specimen after a sliding distance of 500 m is shown in Fig. 9c. It shows the presence of large number of micro dents (marked by 'D') indicating that the shot peened layer associated with micro-dents is not removed in the initial stage. This figure also depicts a large wear debris gets entrapped (marked 'A') and micro cracks (marked 'arrow'). The above figures in general suggests that in case of shot peened specimens, the dents are removed continuously and after a certain sliding distance, the shot peened layer gets removed completely. The cutting and ploughing actions are dominating in AR and AN specimens, whereas considerable extent of abrasive rolling took place in case of QT and ICA specimens, irrespective of peening condition. But, in case of peened condition (Fig. 9d) a large number of pits are noted, which is attributed to the dents produced during peening prior to wear. A similar type of wear surface is noted in as-received peened and unpeened samples. The wear surface of the QT peened (0.17 A peening intensity) specimen is shown in Fig. 9d. It shows finer discontinuous wear grooves (4  $\mu\text{m}$ ) and large number of micro pits (marked 'D') and entrapped wear particles (marked 'A') on the wear surface. The pits are formed due to entrapment of abrasive particles for a short duration in localized regions which subsequently rolls over the specimen surface or due to filling up of the dents with wear debris or particles. This is especially observed in case of QT and ICA specimens because of considerably higher hardness under such heat treated conditions. Figure 9e represents the wear surface of AN specimen at higher magnification. It also reveals entrapment of fine abrasive particles (marked 'A'), flakes

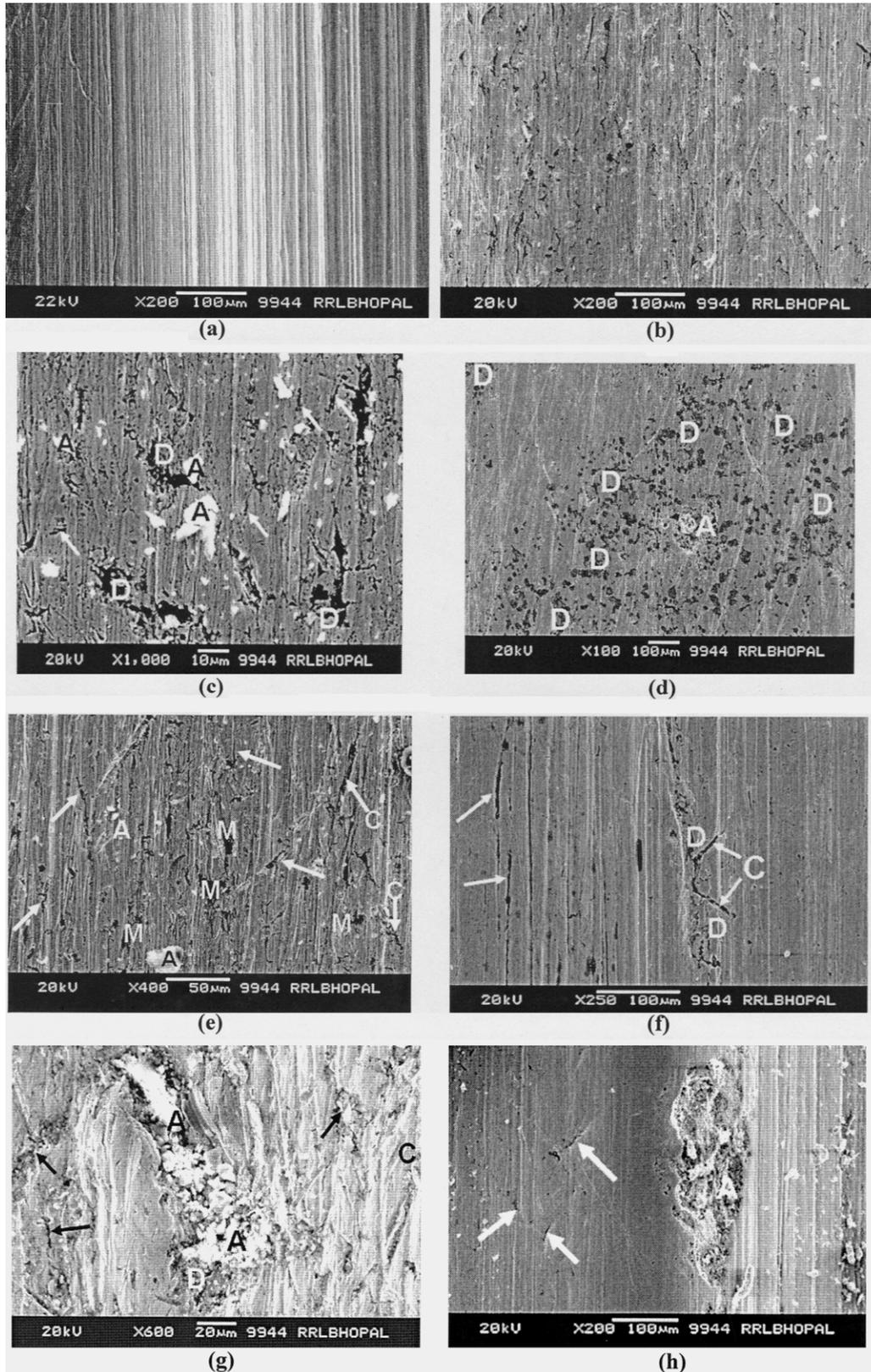


Fig.9– Worn surfaces of the investigated steels (a) AN un-peened, (b) AN peened at 0.27A, (c) ICA peened at 0.17A after 500m sliding distance, (d) QT peened at 0.17A, (e) AN un-peened specimen at higher magnification, (f) AN peened at 0.17A showing change of track, micro cracks and cavities, (g) QT peened at 0.47A, (h) ICA peened at 0.47A

around the wear grooves (marked 'arrow'), micro-pits (marked 'M') and micro cracks (marked 'C'). This signifies that the rolling actions is also prevailing in the AN and AR specimens to a significant extent. Severe damage due to entrapment of abrasive particles and its subsequent scratching action on the wear surface of AN steel is more clear in Fig. 9f. This figure also depicts large surface cracks (marked 'arrow'), cavities (marked 'D') and change in wear track (marked 'C') on the wear surface. The cavities are attributed to the interaction of micro-cracks and the wear grooves due to abrasive action which leads to delaminating type of wear in micro scale. The changing of wear track (marked 'C'), large number of cavities (marked by 'D'), severe surface cracks (marked 'arrow') and severely damaged region (marked 'A'). Fine crushed sand particles and wear debris are found to be accumulated in it are clearly noted on the QT severely peened specimen (Fig. 9g). Figure 9h demonstrates severely damaged regions (Marked 'A'), and large number of micro-cracks (arrow marked) on the wear surface of ICA severely peened specimen. Figure 9g also exhibits smearing of wear surface indicating significant localized heating during wear process. The temperature of the wear surface was measured by inserting a thermocouple into the specimen surface 1.5 mm away from the wear track. The measured temperature is recorded to be 40 to 50°C higher than the ambient temperature. The localized temperature is expected to be considerably higher during testing. This indicates that the specimen is subjected to severe micro-cracking due to considerably high peening intensity. This micro-cracking tendency at higher peening intensity causes the steel to suffer from higher wear rate.

The subsurface after wear testing of AN un-peened specimen is shown in Fig.10a. It shows alignment of fractioned pearlitic lamellae (marked 'A') along the sliding direction of the wheel. It further demonstrates that the lamellae just below the wear surface get fragmented and refined considerably (marked 'B'). Highly deformed region is also denoted by 'HD', where microstructure gets refined significantly. These particles get mixed into the surface due to combined action of load, speed and temperature rise and leading to formation of mechanically mixed layer (MML). This clearly demonstrates sub-surface

deformation and micro-structural changes during wear process. The worn surface of 0.27 A shot peened AR specimens is shown in Fig.10b which also indicates alignment of pearlitic lamellae (marked 'A') and refinement of microstructure (Marked 'B'). It also depicts distinct mechanical mixed layer (MML) separated with longitudinal sub-surface cracks (arrow marked). All these facts demonstrate that the sub-surface is subjected to considerable extent of sub-surface plastic deformation and refinement of microstructure during abrasion. Highly deformed region (HD), mild deformed region (MD) and mechanically mixed layer (MML) are also clearly shown in this figure. The sub-surface below the worn surface of QT specimen shot peened to 0.17 A is shown in Fig.10c which does not show any significant alignment of the martensitic needle along the sliding direction. This is because of the higher strength and strain hardening capability of QT steel as compared to the AN and AR steels. But the entrapment of crushed abrasive particles and wear debris on the surface (marked 'P') is clearly visible from this figure. The microstructure of the subsurface below the worn surface of the QT steel shot peened at 0.27 A (Fig.10d), almost similar to that in case of QT steel shot peened at 0.17 A (Fig.10c), but the former one is associated with mechanically mixed layer (MML) entrapped wear debris (marked 'D') and fine crushed abrasive particles and the wear surface material (marked 'P'). This figure also indicated large sub-surface cracks ('arrow marked') between the MML and specimen surface. The wear surface and sub-surface examination demonstrates that abrasive type (cutting and ploughing action) wear is prevailing wear mechanism. Irrespective of specimen peening intensity and heat-treatment, pitting action due to free movement of abrasive particles are also prevailing. In case of peened specimens, the dents are gradually removed and the peened layer removed subsequently. Severe peening causes greater extent of surface and sub-surface cracks. The sub-surface also gets mechanically deformed during wear process. The extent of deformation is less in case of QT and ICA specimen. The microstructure in sub-surface region gets refined significantly specially in case of AN and AR specimen. Formation of MML is also evident from the sub-surface. The cracks associated with MML makes it unstable. But still it plays a vital role in controlling the wear behaviour.

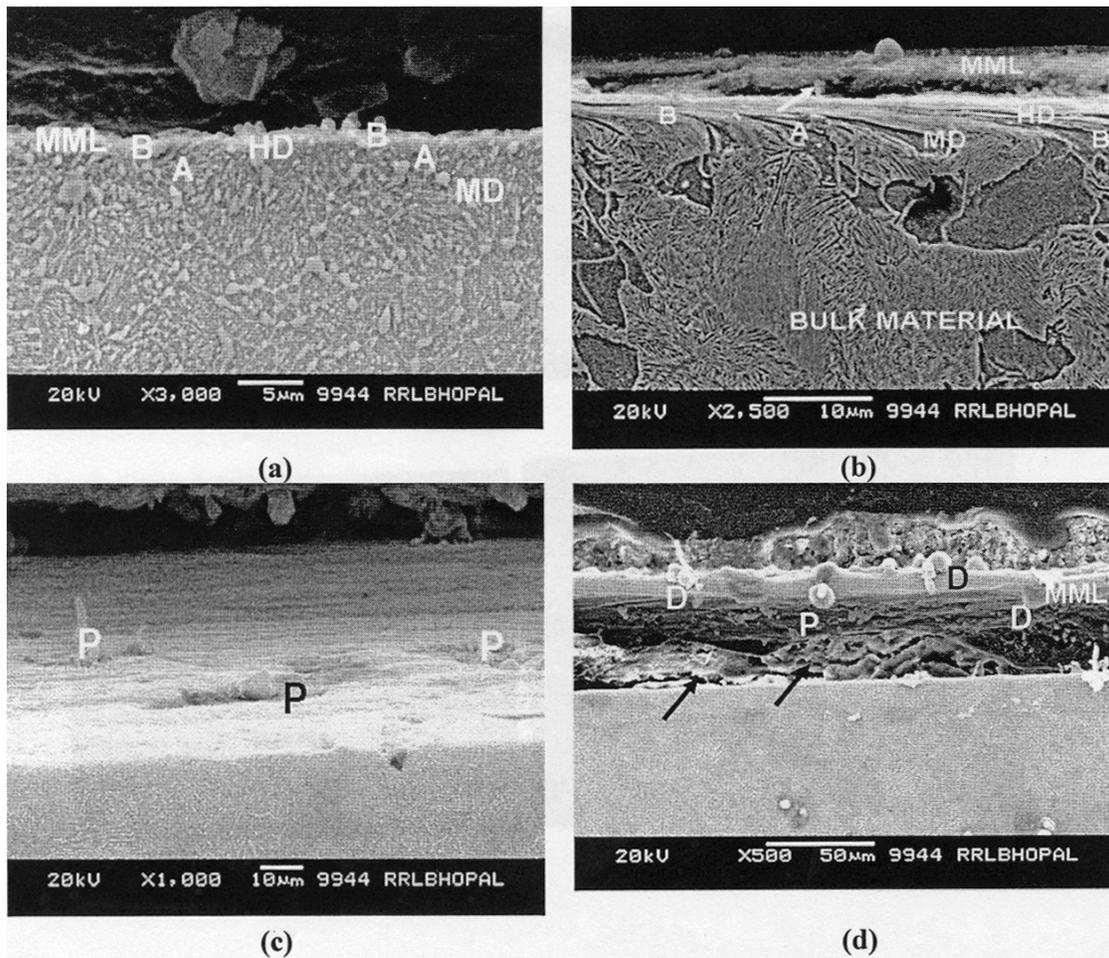


Fig. 10 –Sub-surfaces below the worn surface: (a) Sub-surface of annealed un-peened specimen, (b) Sub-surface of as-received and peened at (0.27A) specimen, (c) and (d) Sub-surface of quenched and tempered and peened at (0.17A and 0.27A) specimen

### Conclusions

The following conclusions have been drawn from the present study:

- (i) The wear rate decreases with sliding distance and obtains a steady state condition irrespective of heat-treatment cycle and peening intensity after a sliding distance of 1500 m.
- (ii) The heat treatment of steel causes microstructural changes which leads to change in mechanical properties of the steel. The wear rate is considerably lower in case of ICA and QT steel in comparison to AR and AN steels.
- (iii) Shot peening increases the surface hardness and micro-hardness considerably. When its intensity is restricted to a certain critical value, i.e., 0.27 mm ALMEN ‘A’ it reduces the wear rate considerably irrespective of heat-treatment cycle because of combined effect of work hardening, reduction in micro-crack development and its propagation tendency at the specimen surface during the abrasive wear.
- (iv) If the peening intensity increases more than the critical value, i.e., 0.27 mm ALMEN ‘A’, the steel becomes more brittle which leads to cracking at surface and sub-surface level during peening itself and causes reduction in wear resistance during abrasive wear.
- (v) After a sliding distance of 2.3 km, the shot peened layer gets removed and thus the peened and un-peened specimen exhibits almost same wear rate after this sliding distance. Hence to achieve improved wear resistance, the steel should be shot peened intermediately during operation if possible.

- (vi) For optimum wear resistance, material would be heat-treated for ICA and QT condition and then peened to 0.27ALMEN 'A'. Shot peening is more effective in AN and QT. But, if only heat-treatment is considered, the ICA is the most effective. If shot peening and heat-treatment is considered separately, AR specimen due to shot peening provides equivalent wear resistance to that of un-peened ICA specimen. A techno-economic optimization in this aspect is required.

### References

- 1 Holmberg K & Mathews A, *Properties, techniques and applications in surface engineering*, vol. 28 (Elsevier, London), 1994.
- 2 Eyre T S, *Tribol Int*, 9 (5) (1976) 203-212.
- 3 Ueda M, Uchino K & Kobayashi A, *Wear*, 253 (7) (2002)107-113.
- 4 Goto H & Amamoto Y, *Wear*, 254 (12) (2003) 1256-1266.
- 5 Iordanova I, Surtchev M & Forcey K S, *Surf Coat Technol*, 139 (2001) 118-126.
- 6 Severnev M M, (American Publishing Co., New Delh), 1984.
- 7 Burwell J T & Strang C D, *J Appl Phys*, 23 (1) (1952) 18-28.
- 8 Archard J F, *J Appl Phys*, 24 (8) (1953) 981-988.
- 9 Bhakat A K, Mishra A K, Mishra N S & Jha S, *Wear*, 257 (3-4) (2004) 338-346.
- 10 Rautaruukki's Raex® B boron steels for St. *Rautaruukki Steel*, 1-7, (2005).
- 11 Boron steel, Corus, *Brinsworth Hot Strip Mill*, [http://www.corusautomotive.com/file\\_source/StaticFiles/Business%20Units/Narrow%20strip/Brinsworth%20Hot%20Mill.pdf](http://www.corusautomotive.com/file_source/StaticFiles/Business%20Units/Narrow%20strip/Brinsworth%20Hot%20Mill.pdf), Status 6<sup>th</sup> July 2007.
- 12 Oh Me Oh My, <http://www.pitt.edu/~rjw9/engineerengevent.html>, Status 6<sup>th</sup> July 2008.
- 13 Boron: *Ferroalloys & Alloying Additives: Online Handbook*, <http://www.shieldalloy.com/boronpage.html>, Status 26<sup>th</sup> May 2005.
- 14 Modi O P, *Tribol Int*, 40 (3) (2007) 490-497.
- 15 Modi O P, Pandit P, Mondal D P, Prasad B K, Yegneswaran A H & Chrysanthou A, *Mater Sci Eng A*, 458 (2007) 303-311.
- 16 Wang X M & He X L, *ISIJ Int*, 42 (2002) S38-S46.
- 17 Khrushchov M M, *Wear*, 28 (1974) 69-88.
- 18 Larsen-Badse J & Mathew K G, *Wear*, 14 (1969) 199-205.
- 19 Richardson R C D, *Wear*, 10 (1967) 291-309.
- 20 Khrushchov M M & Babichev M A, *Frict Wear Machinery*, 12 (1958) 5-23.
- 21 Homer S E & Vanluchene R D, *J Mater Shap Technol*, 9 (2) (1991) 89-101.
- 22 Sharma M C & Mubee A, *J Mech Working Technol*, 8(2&3) (1983) 155.
- 23 Sharma M C & Mubee A, *J Mech Working Technol*, 8(4) (1983) 399.
- 24 Meo M & Vignjevic R, *Ware*, 34 (2003) 569-575.
- 25 John C, *The Shot Peener*, 15 (3) (2001) 7-8.
- 26 Pandey R K & Deshmukh M N, *Int Conf Shot Peening and Blast Cleaning*, MACT, Bhopal, India, 2001, 1-20.
- 27 Prevey P S, *Shot peening theory and application*, Series edited A, Niku-Lari, IITT- Int, Gournay- Sur-Marne, France, 81-93, (1990).
- 28 Fridrici V, Fouvry S & Kapsa P, *Wear*, 250 (2001) 642-649.