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RESEARCH

Wear and Friction Behavior of Multi and Uniaxial Compressed AISI1010 Steel

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A B S T R A C T

Deformation processing is an important technique to produce improved and high strength steel products. Uniaxial compression (UAC) imparts high strength and hardness to processed material. On the other hand, multi axial compression (MAC), a type of severe plastic deformation (SPD) technique which is used to develop finer substructure/grains with increased strain. In the present work, two different techniques, warm MAC and warm UAC are used for processing of low plain carbon steel (AISI1010). Mechanical and tribological properties of processed and annealed steel are studied at room temperature and correlated with microstructural changes. Results reveal that hardness and tensile strength of processed steel using MAC and UAC techniques improved significantly as compared to annealed samples; however a reduction in wear resistance is observed which may be attributed to increased brittleness and lower pull-off work resulting in more wear loss due to third body abrasion wear. Fractured and worn surfaces were also studied under scanning electron microscope to understand the type of failure and wear mechanism involved.

1. INTRODUCTION

Steel have been used for its high strength, good corrosion resistance and sufficient wear resistance in past. Now days, a structural material requires high strength with sufficient toughness at low cost, and good formability, good weldability for variety of applications. These properties may be imparted into materials through grain refinement by severe plastic deformation (SPD) techniques [1,2]. Therefore, ultra-fine grained (UFG) steels with relatively simple chemical composition, strengthened primarily by grain refinement, have a great potential for replacing alloyed high strength steels [3]. Multiaxial compression (MAC) is one of the SPD techniques used for developing ultrafine grained steel [4]. The change in strain path associated with MAC and its higher deformation rates can significantly influence the microstructure development, especially in metals with composite microstructures such as mild steel with its ferrite plus lamellar pearlite structure. Another important metal forming process called uniaxial compression (UAC) imparts different material properties pertaining to hot as well as cold metal forging. Uniaxially compressed materials have commercial importance. Both deformation techniques viz MAC and UAC are expected to improvement in mechanical and tribological properties. But few extant studies [5,6] lead to a conclusion that there is no simple and direct correlation between hardness and wear resistance. Akio et al. [7] studied the warm deformation of low carbon steel in single pass. Belyakov et al. [8] in their study shows that substructures and internal stresses are developed under warm severe deformation on austenitic stainless steel. In another study by Miura et al. [9] it was observed that the second phase particles retard the evolution of UFG structure in multi axial forging (MAF) of austenitic stainless steel. Lim and Wahabi [10] performed MAC and torsion on Fe-C alloy and developed the sub grains in the range of 1-5 μm. Evolution mechanism of grain refinement has been studied in MAFed Fe–32 % Ni alloy cube of 14 mm side using forging temperature of 550 °C [11].

In view of the literature it is observed that among the different strengthening mechanisms, grain refinement is the only method to improve both strength and toughness simultaneously. The main benefits behind development of UFG materials through MAC/ MAF or any other severe plastic deformation techniques viz equal channel angular extrusion, high pressure torsion [12,13] are to avoid use of additional alloying elements and to skip complicated additional heat treatments like annealing, quenching and tempering. Moreover, most of studies are carried out on plain carbon steels having carbon percentage more than one. Very few studies are available on wear behavior of MAC and UAC of steel [14]. To the best of our knowledge no report is available on warm MAC and warm UAC on low carbon steel (AISI1010) having carbon percentage less than one.

Therefore in the present work an effort is made to improve the mechanical and tribological properties of low carbon steel (AISI1010) through MAC and warm UAC techniques to widen its application area. The properties are evaluated at room temperature and correlated with microstructural characteristics.

2. EXPERIMENTAL DETAILS

2.1 Specimen preparation

The chemical composition of low carbon steel (AISI1010) used in the present study has been shown in Table 1. Two different types of specimens have been machined for MAC and UAC of steel.

Table 1. Chemical composition of AISI1010 steel.

Element	C	Si	Mn	Cr	S	P	Fe
wt.%	0.090	0.033	1.19	0.018	0.024	0.053	Remainder

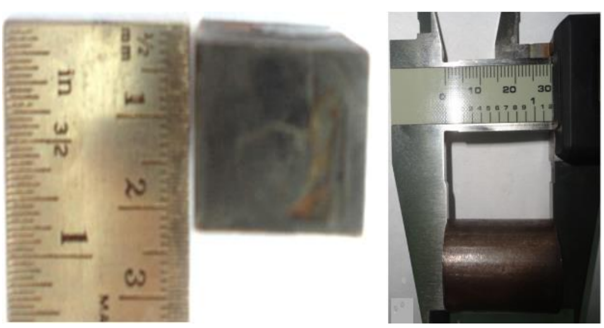
Table 2. Sample Designation.

Sample designation	**Processing**
Annealed or undeformed	Zero pass
MAC	Six pass
UAC	50 % reduction in thickness

The specimens were machined in size of 24x19.52x16 mm for MAC and while cylindrical shaped specimens were prepared for UAC with dimensions of 30 mm length and 20 mm diameter. Annealing of all the samples was carried out at 920 °C for 60 minutes to obtain the uniform initial microstructure. Table 2 shows the designation of different treated samples.

2.2 MAC

In multiaxial compression technique successive uniaxial compressions of ε = - 0.4 were applied to the longest side of the sample at each strain step. Samples were heated at 500 °C for a furnace holding time of 50 minutes before the samples were alternately compressed, with loading direction changed through 90°. Figure 1a shows the MAC processed sample.



(a) (b)

Fig. 1. (a) MAC sample (b) UAC sample.

Assuming volume conservation and material isotropy, this procedure enables the initial dimensional ratio to be maintained at the end of each compression pass [4,15]. Samples were quenched into water after each compression pass and graphite powder is used as lubricant to ensure the homogeneous deformation and to avoid the cracking by reducing the friction between surfaces of die and sample.

2.3 UAC

The specimen (aspect ratio, L/D=1.5) has been chosen less than 2, that is required for homogeneous compression and to prevent the buckling in shearing mode of deformation (Fig. 1b).Total compression strain about ε=-0.69 similar to previous work [16] is imparted in three stages. In every stage 5mm length is reduced and finally the specimen has been deformed up to the length of 15 mm from 30 mm length of original specimen. At every stage of compression specimen is heated up to 500 °C temperature with a holding time about 50 minutes. The specimen after compression has been quenched into the water. The graphite powder has been used as a lubricant similar to the MAC process.

2.4 Microstructure analysis

The Microstructural analysis was performed using optical microscope (Leica DMI 5000 M). Tensile fractured surface and worn surface are studied under scanning electron microscope (ZIESS EVO18) to understand the mechanism involved during tensile and sliding wear testing.

2.5 Mechanical Properties

Hardness tests were performed on Vickers hardness tester (FIEVM50 PC) using 10 kgf load with a dwell time of 10 seconds.

Fig. 2. Geometry of tensile sample.

Tensile tests were performed using H25 K-S Tinius Olsen on the small size samples with dimensions of 8 mm gauge length, and having width and thickness of 1.5 mm and 0.75 mm respectively (Fig. 2) [4].

2.6 Tribological properties

Dry sliding wear test were conducted using pin on disc machine (DUCOM, Bangalore, India). In this test study the disc of EN-32 hardened to 62-65HRc, was used. The tests were conducted at the constant speed of 1m/sec for different loads of 9.8 N, 19.6 N and 29.4 N. Every test was conducted for 30 minutes for three equal time intervals (MAC) and about 50 minutes (UAC) in three intervals of 10 min, 20 min, and 20 min for each specimen. Pin weight losses were measured at various time intervals, using an electronic balance having least count 0.1 mg. Wear surfaces were investigated using SEM.

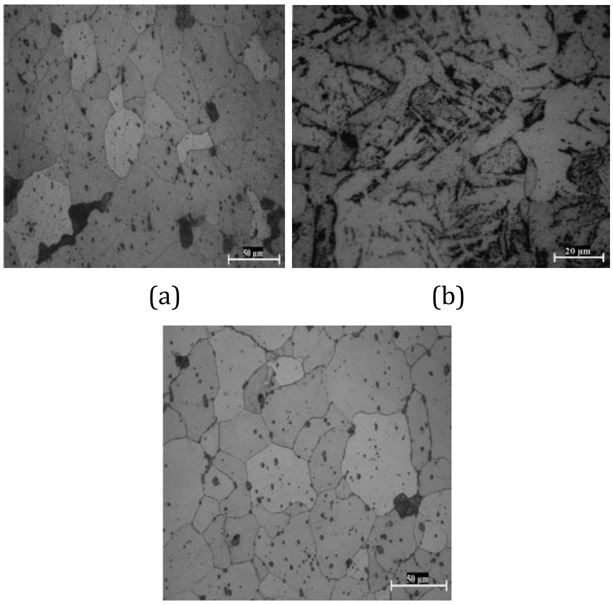
3. RESULTS AND DISCUSSION

3.1 Microstructural Characterization

Optical micrographs of annealed samples are shown in Fig. 3a. The figure clearly shows large equiaxed grains of ferrite phase. Average grain size of the ferritic steel is about 47 μm. Linear intercept method is used for determining the grain size. Figure 3b shows the microstructure after six MAC Passes. Dense substructures are observed after the 6 MAC passes. These substructures in six MAC Pass samples are due to the heavy strain induced into the samples. This may also be attributed to complex stress reversal during MAC where strain path is changed after each pass [4]. Formation of these substructures is assumed to be the primary stage of the development of ultrafine grains. Figure 3c represents the optical micrographs of deformation induced ferrite specimens after uniaxial compression at 500 °C temperature after 50 % reduction in thickness sample about. No change has been observed in these micrographs.

3.2 Mechanical Properties

Hardness of the specimens has been tabulated in Table 3 and shown in Fig. 4a. The hardness increased by about 1.7 times in six MAC pass as compared to annealed samples which may be attributed to strain hardening and substructure development [17]. These results are in agreement with the earlier work [18]. Similarly hardness is increased about two times during uniaxial compression after a reduction of 50 % of initial length of the sample.



(a) (b) (c)

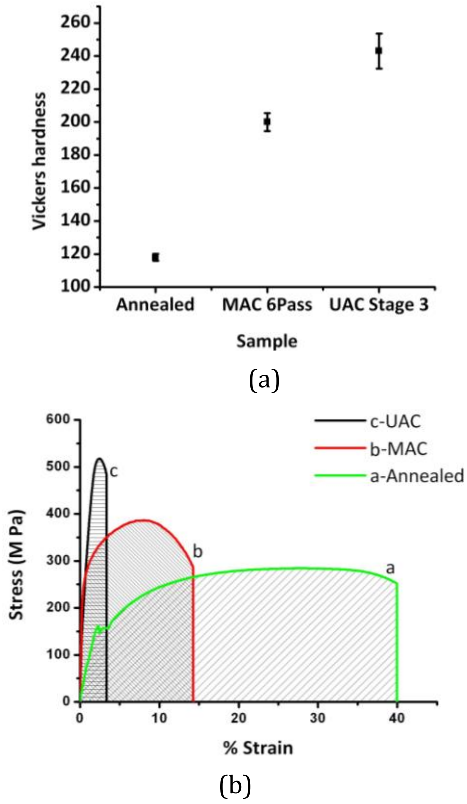
Fig. 3. Optical micrograph of (a) annealed (b) six MAC pass and (C) UAC steel sample after 50 % reduction.

Table 3. Mechanical properties in different conditions.

Sample Condition	Vickers Hardness HV	Tensile Strength (MPa)	% strain to failure	Pull-off-work (MJ/m^3)
Annealed or undeformed	118	285	40.00	0.9996
MAC (6 pass)	200	387	14.25	0.4939
UAC (50 % reduction in thickness)	243	517	3.40	0.1343

Stress-strain curve of annealed, six MAC pass, and UAC sample after 50 % reduction is shown in Fig. 4b. While the tensile strength and percent strain to failure has been shown in Table 3. The value of maximum tensile strength in six pass steel is about 387 MPa while 285 MPa in annealed sample. It is observed that maximum tensile strength of the six pass increases about 1.4 times as compared to the annealed samples. It can also be observed that strain to failure decreased after six MAC pass to 14 % as compared to 40 % in annealed samples. The area under these curves show the pull-off work and it is clearly observed from the Fig. 4b that pull-off work is low in steel after six MAC pass. The pull-off work has been quantified for different conditions and shown in Table 3. It can also be observed that strain to failure decreased in six MAC pass specimen as compared to annealed sample but it exhibits sufficient elongation to result in ductile failure which has been further verified in Fig. 5. It can also be observed that in UAC sample, the maximum tensile strength increased to about 517 MPa but the strain to failure is reduced to 3.4 % after a reduction of 50 %.

It can be concluded that change in strain path during MAC retains sufficient ductility in the material even after a larger number of strain passes as compared to uniaxial compression where compression at each stage is in only one direction. The mode of failure of six MAC pass fractured surface tensile specimen has been analyzed by using SEM. Fractographs of sixth MAC pass has been shown in Fig. 5 that dimples are formed which represent that ductile failure of the material even after a reduction in percent strain from 40 % in the annealed samples to 14 %.



(b)

Fig. 4. (a) Vickers hardness and (b) engineering stress-strain curve for annealed, six MAC pass, and UAC sample after 50 % reduction.

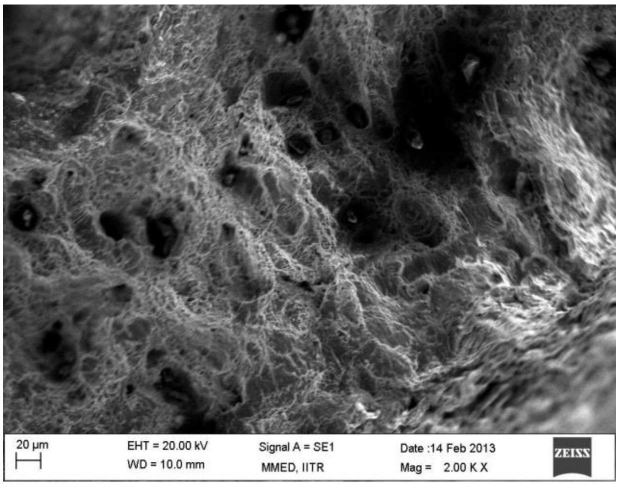


Fig. 5. SEM Factrograph of fractural tensile specimen for six MAC pass.

3.3 Wear and Friction Behavior

Dry sliding wear tests were performed at room temperature on two different samples which are addressed as zero pass (annealed) and six MAC pass samples. The volume loss with respect to sliding distance for zero pass samples and six MAC pass sample at different loads 9.8 N, 19.6 N and 29.4 N is shown in Fig. 6a and 6b respectively. The volume loss increases with sliding distance and with increase in load. This is because with an increase in the force, the friction increases which causes the enhanced volume loss. The volume loss is greatly influenced by increase in applied load. The volume loss is highest for the load of 29.4 N and it is lowest for the load of 9.8 N for zero pass as well as six MAC pass specimens. It has been observed from Figs. 6a and 6b that the wear volume and wear rate both are marginally higher in case of six MAC pass samples as compared to zero pass samples. The wear rate shown in Fig. 6c is calculated from the slope of linear fit in Figs. 6a and 6b. The wear rate increases with the increase of normal load. It is also observed from Fig. 6c that the wear rate increases with increase in load. This is because increased normal load increases frictional force that results in heat at the contact surface and hence strength of materials decreases. Wear rate for both the linear segments are observed to increase almost linearly with load for zero pass sample and six MAC pass specimen. The observed linear variation of volume loss with respect to sliding distance and wear rate with load is indicative of Archard`s wear law [19].

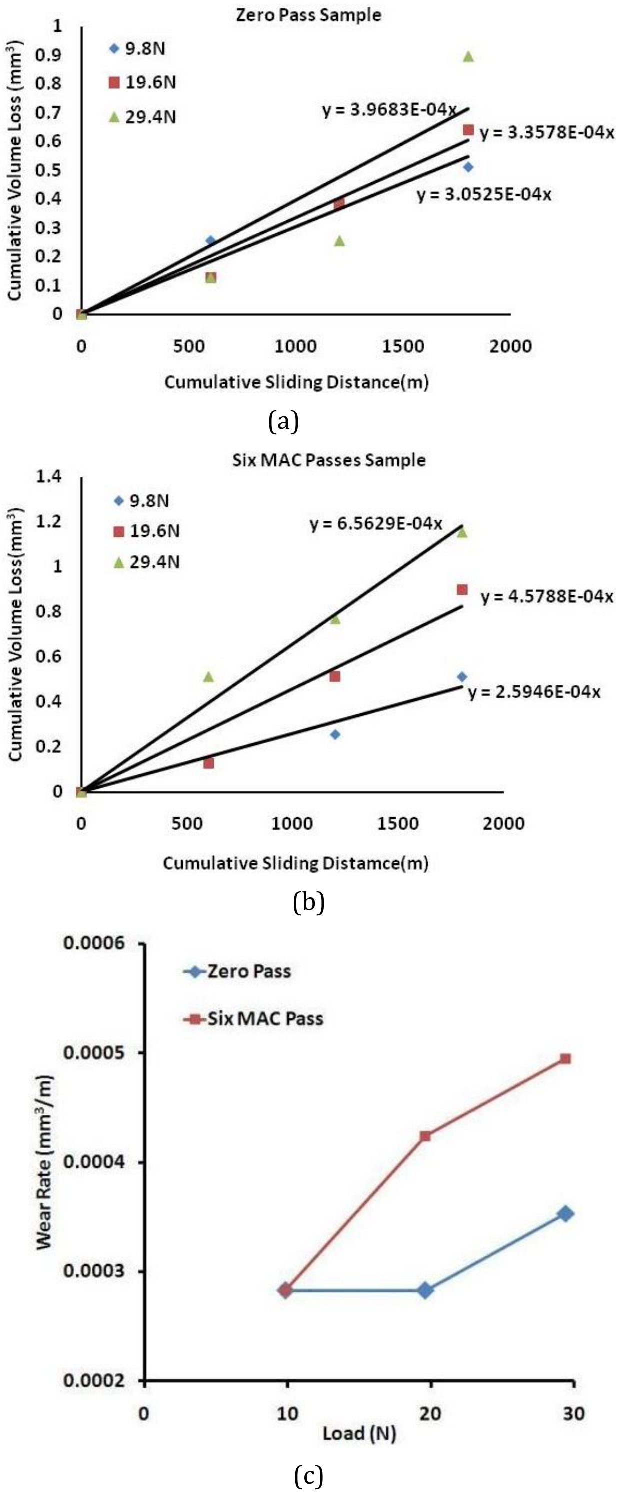
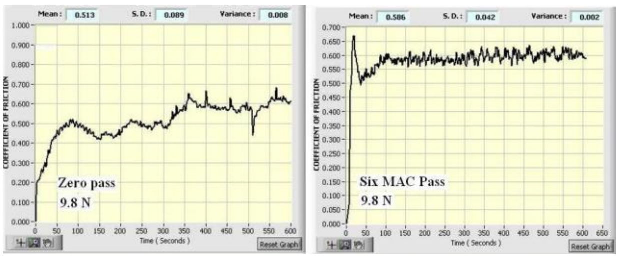


Fig. 6. Cumulative volume loss Vs cumulative sliding distance at 9.8 N, 19.6 N and 29.4 N for (a) zero pass, and (b) six MAC passes (c) variation of wear rate versus normal load.

Figure 7a shows the variation of coefficient of friction and friction force for a complete test of ten minutes at a load of 9.8 N for zero pass and six MAC pass samples. Distribution of frictional force is also given in the graph. It can be observed that the fluctuation is more during the initial stage of the test which shows the steady behavior at the later stage for both the steels. The average value for the coefficient of friction for zero pass samples is 0.51±0.089 whereas for the six pass sample it is about 0.58 ± 0.042. Figure 7b shows that coefficient of friction varies very little with respect to load in both the materials. The increased wear volume and wear rate in MAC sample may be attributed to the microstructural changes occurred due to multiaxial compression and mechanical properties. The wear rate for annealed sample is found to be low at higher loads as compared to MAC samples which may be attributed to the lower pull-off-work of six MAC pass samples. With reference to mechanical properties, the inferior adhesive wear resistance of MAC steels can be explained on the basis of pull-off work. The pull-off work involved in generating the wear particles is a function of area under the stress-strain curve of the material [7]. It is clear from Fig. 4b that even though the strength of MAC sample has been increased but the area under the curve has been decreased. Hence, due to lower pull-off-work wear resistance has been decreased.



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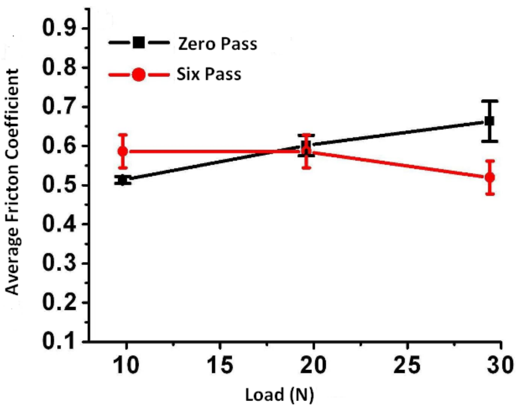
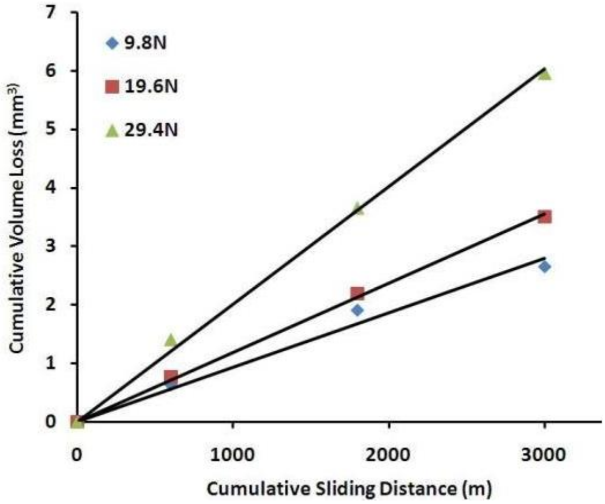


(b)

Fig. 7. (a) Average coefficient of friction and friction force for a test of 10 minute at a load of 9.8 N for zero and six MAC passes, (b) variation of average friction coefficient with load.



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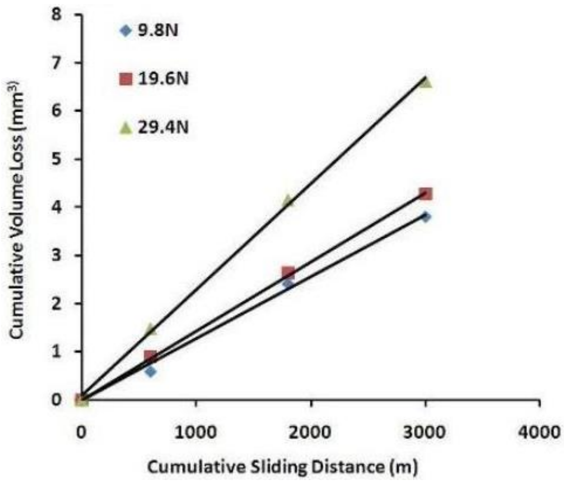

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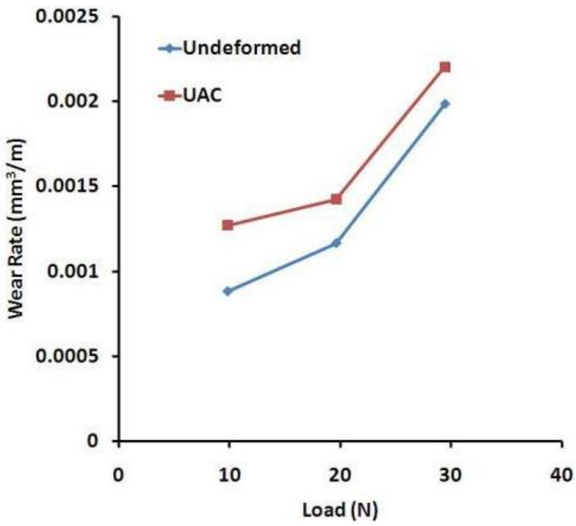
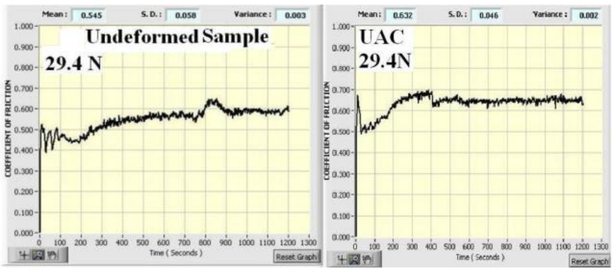


(c)

Fig. 8. Cumulative volume loss Vs cumulative sliding distance at 9.8 N, 19.6 N and 29.4 N for (a) annealed sample (b) UAC sample after 50 % reduction (c) Variation of wear rate versus load for UAC and undeformed sample.

The variation of the cumulative volume loss with cumulative sliding distance at three different normal loads for annealed specimen and specimen deformed after UAC at 500 °C are shown in Figs. 8a and 8b. It is observed that the volume loss increases with increasing sliding distance as well as normal load. The variation of wear rate with normal load for annealed and UAC specimen at 500 °C temperature is shown in Fig. 8c. It is observed that wear rate for deformed specimen is higher than the annealed at room temperature. In uniaxial compressed specimen the hardness and strength is increased due to strain hardening but ductility decreased as compared to annealed and six MAC pass samples. This decreased ductility may be the reason for poor increased wear rate of UAC specimen as during sliding wear debris particles may be entrapped between the interfaces resulting in third body abrasive wear [20-23]. However, it is reported [6] that there is no simple relationship between hardness, ductility and wear resistance.



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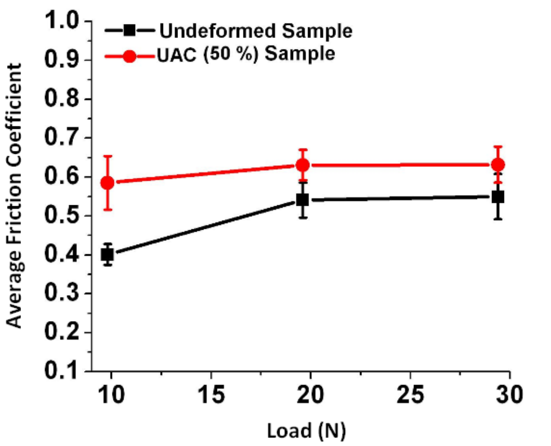
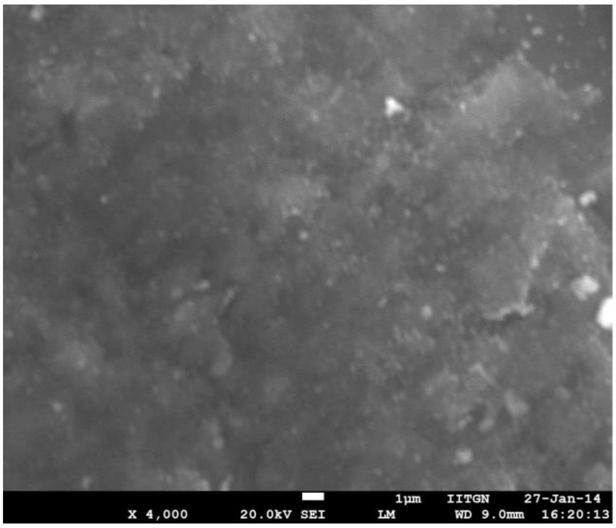


(b)

Fig. 9. (a) Average coefficient of friction for a test of 20 minutes at a load of 29.4 N for undeformed and six MAC pass specimen, (b) variation of average friction coefficient with load for undeformed and UAC specimens at three different loads

The coefficient of friction for a test of 1200 m for undeformed or annealed and UAC sample is shown in Fig. 9a. The variation between the average friction coefficient and load is shown in Fig. 9b. The coefficient of friction increases with increasing load in both samples. The coefficient of friction is higher in deformed sample than annealed specimen. Therefore, the wear resistance is lesser in deformed sample than annealed because the plastically deformed metals are usually much harder than their annealed counterpart but their wear resistance is not necessarily increased after the plastic deformation and sometimes it is even reduced [24].



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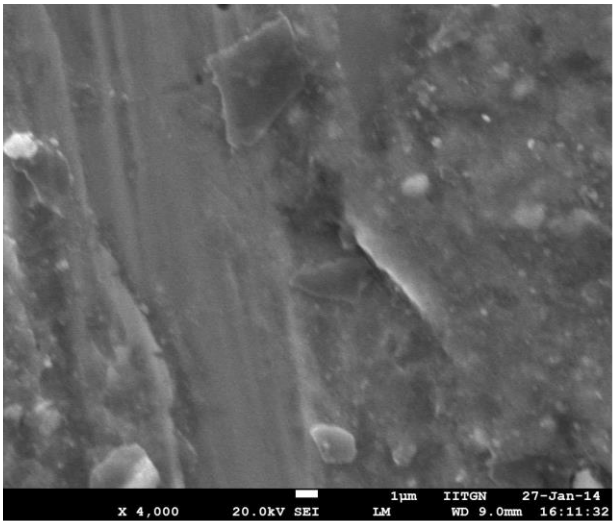

(b)

Fig. 10. Worn surfaces of (a) annealed steel (b) UAC steel (50 % reduction) specimen subjected to load 19.6 N.

The worn surfaces of wear pin have been observed by scanning electron microscopy. The worn surfaces of pin subjected to load of 19.6 n of annealed and UAC steel (50 % reduction) specimens are shown in Figs. 10a and 10b, respectively. It is observed that worn surface of UAC steel pin is large flaky with dipper and larger groove with compare to annealed pin surface. Hence, it shows that there is enhanced wear in deformed specimen as compared to the annealed specimen.

4. CONCLUSION

Following conclusion can be inferred from the present study:

I. Substructural development was observed in steel after six MAC passes while no such microstructural change is detected after UAC.

II. Hardness increased from 118 VHN in annealed sample to 200 VHN after six MAC passes and up to 243 VHN in UAC specimen after reduction of 50 %.

III. Tensile strength increased from 285 MPa in annealed sample to 387 MPa with percent strain to failure reduced 40 % to 14 % after six MAC passes while maximum tensile strength is to be about 517 MPa in UAC steel sample after 50 % reduction and shows less ductile failure with 3.4 % strain failure. Change in strain path during MAC retains the sufficient ductility into material even after a larger number of strain passes as compared to uniaxial compression where compression at each stage in only one direction.

IV. Wear rate increased in both the samples processed using MAC and UAC. Wear rate is more in UAC specimen as compared to MAC specimens. Lower pull- off work and decreased ductility is found to be responsible for the increased wear rate in MAC and UAC samples as compared to annealed samples.

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