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Effect of deformation and heat treatment on the dry sliding wear behavior of copper

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ABSTRACT

Since ages, copper and its alloys have found extensive applications in manufacture of bushes and bearings, heat transfer conductors, high conductivity electrical contactors and so on. However, currently, in all these applications, there is a significant enhancement in the service loads, wear resistance, conductivity and thus forcing the material researchers to develop a newer class of copper based advanced materials. In this direction, researchers have focused their attention on improving the strength and the tribological properties copper. The present investigation aims to evaluate the effect of deformation and heat treatment on the sliding wear and friction behavior of copper using a pin-on-disc wear testing machine, giving emphasis on the parameters such as wear rate and coefficient of friction as a function of sliding distance (0– 2000 m) at constant applied Pressure of 0.2 MPa and at a fixed sliding speed of 3.35 m/s, characterizing the deformed and heat treated copper samples in terms of microstructure, micro hardness and wear surface analysis through scanning electron microscope. The results revealed that the highly deformed copper exhibited superior wear resistance properties than the as received copper, while the coefficient of friction followed an opposite trend. Moreover, the wear rate of the copper, heat treated at above recrystallisation temperature is noted to be invariant to the sliding distance and decreased with increasing degree of deformation. Microstructure of as received copper shows fairly uniaxial grains in the matrix where as highly deformed copper shows elongated grains in the structure. The wear mechanism of the investigated materials was studied through worn surfaces examination of the developed wear tracks.

Introduction

Pure copper has always attracted considerable interests because of its high electrical and thermal conductivities. But it has some distinct shortcomings such as low hardness and strength, restricting its applications. The strengthening of engineering metals and alloys through grain refinement has long been only a strategy for microstructure design [1,2]. Bu the material's wear resistance is of primary concern in many industrial applications. The tribological behavior of copper and its alloys has received much attention in the past decade as these materials can be used for rubbing machine parts. Many experimental studies have reported a significant enhancement of the wear resistance due to grain refinement only [3–5]. While to the best of our knowledge, no information is available in the literature concerning the tribological behavior of copper subjected to different uni axial compressive deformations and heat treatments.

In the light of the above an attempt has been made to deform the copper and subject it to different heat treatments (below Rx, Rx and above Rx). It was proved that highly deformed copper has higher hardness, better wear resistance and low coefficient of friction when compared with pure copper.

Theory of Wear

Wear occurs as a natural consequence when two surfaces with a relative motion interact with each other. Wear may be defined as the progressive loss of material from contacting surfaces in relative motion. Scientists have developed various wear theories in which the Physico-Mechanical characteristics of the material and the Physical conditions (e.g. the resistance of the rubbing body and the stress state at the contact area) are taken into consideration. In 1940 Holm [5] starting from the atomic mechanism of wear, calculated the volume of substance worn over unit sliding path.

Barwell and Strang [6] in 1952: Archard [7] in 1953 and Archard and Hirst [8] in 1956 developed the adhesion theory of wear and proposed a theoretical equation identical in structure with Holm's equation. In 1957, Kragelski developed the fatigue theory of wear. Because of the Asperities in real bodies their interactions on sliding is discrete and contact occurs at individual locations, when taken together, form the real contact area. Under normal force the asperities penetrate into each other or are flattened out and in the region of real contact points corresponding stress and strain rise. In sliding, a fixed volume of material is subjected many times to repeated action, which weakens the material and leads finally to rupture.

Though all the theories are based on different mechanisms of wear, the basic consideration is the frictional work. Hence friction is the prime consideration.

Archard's Equation

Wear of a material is influenced by many factors, including properties of the material, the geometry of the wearing bodies, environmental and the operating conditions. Many mechanical properties of a material, such as hardness, elasticity, yielding strength, tensile strength, strain hardening and fracture strain,

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influence its wear behavior [9 – 14].

Many quantitative models for wear have been developed over the years. But one of the prominent and simplest is the Archard equation (1953), in which the wear loss is related only to hardness and such estimated wear loss is often consistent with experimental observations.

It states that the wear loss is linearly proportional to the sliding distance and the normal load, but inversely proportional to the hardness of the material. In Archard's equation, the wear loss is related only to hardness and such estimated wear loss is often consistent with experimental observations.

The given form is Q = KW/H

Where Q is the volume removed from the surface by wear per unit sliding distance, W is the normal load applied between the surfaces, and H is the indentation hardness of the softer surface. The constant K, usually termed the Archard wear coefficient, is dimension less and always less than unity. The value of K is of fundamental importance and provides a valuable means of comparing the severity of different wear processes. For some purposes, the quality K/H, given the symbol k and sometimes termed "specific wear rate" is useful. The units of k are usually mm^3m^{-1} N^{-1}, representing the volume lost (mm^3) per unit sliding distance (m) per unit normal load on the contact (N). These units are commonly used in quoting experimentally measured rates of wear. In some instances of sliding wear, sharp transitions are found between ranges of conditions over which Equation (1) is obeyed, and ranges where it also obeyed, but for which K has a value some 100 times greater. For the sliding wear of metals, these transitions are usually between regimes of "mild" or "oxidational" wear, and those of "severe", "metallic," or "plasticity-dominated" wear. Typical values of K for the mild wear of metals are 10^{-4} to 10^{-6}, while K may be ca. 10^{-3} to 10^{-2} for severe wear. But these transitions between mild and severe wear can be induced by changes in load, sliding, Speed, temperature or atmospheric composition.

Method of Testing

50 mm dia. pure copper samples with aspect ratio 1.5 were subjected to 20%, 40%, 50% and 60% deformations using a computer controlled servo hydraulic 300T (FIE-UTE Model) universal compression testing machine operated at a constant crosshead speed of 0.25 mm/sec. Care was taken in lubricating the end faces and also to keep the samples at the centre of the compression test.

All the as received as well as deformed copper samples were cut into four quarters manually with a hacksaw. The first quarter was kept as it is. The other three quarters were subjected to heat treatments at 200^0 C (below Rx), 270^0 C (Rx) and 350^0 C(above Rx)for about 2 hours.

Experimental Procedure For Sliding Wear Studies

Samples were machined from the central normal plane and central rolling plane areas of the quarter portions of the as received and heat treated copper specimens as well as those subjected for different deformations and heat treatments. Sliding wear tests were conducted on a pin-on-disc wear testing apparatus (model: TR20-LE, Ducom Make, Bangalore, India). The cylindrical copper pin samples (12 mm in diameter and 30 mm in length) were held against a heat treated EN 31 steel disc (confirming to AISI 52100) of hardness 62 HRc with surface roughness 1.6 Ra. During sliding, the load is applied on the specimen through cantilever mechanism and the specimens are brought in intimate contact with the rotating disc at a track radius of 100 mm (Fig.1). All the pins were subjected to running-in-wear under a constant applied load of 10 N (applied pressure 195 MPa) up to a sliding distance of 2000 m against the EN 31 steel disc at a fixed sliding speed of 3.35 m/s. In order to ensure effective contact of fresh surface with the steel disc, the fresh samples were subjected to sliding on emery paper of 240 grit size fixed on the steel disc. The samples were cleaned with acetone, dried and weighed (up to an accuracy of 0.001 gm using a DONA microbalance) prior to and after each test. The wear rate was calculated from the weight loss measurement and expressed in terms of volume loss per unit sliding distance. The frictional force was recorded from the digital display interfaced with the PC based data login system of the wear testing machine. Coefficient of friction was computed from the recorded frictional force and the applied load (i.e. the ratio of frictional force to the applied load). A set of three samples was tested in every experimental condition, and the average along with standard deviation for each set of three tests is measured.

Hardness has some influence on the wear behavior on any material. Micro hardness of the worn surfaces of the deformed as well as heat treated copper samples was measured using (model: Leica VMHT 30A) micro hardness tester. The indentation was produced using 136^0 square based Vickers diamond pyramid at the impact load of 5 kgf. In each sample, four indentations were taken and the average hardness value along with standard deviations was reported. During hardness measurement precaution was taken to get the indentation at a distance of at least twice the diagonal length of the previous indentation.

The wear damage on the specimens was evaluated via wear rate (micro meters) calculated. A complete wear micro structural characterization was carried out via scanning electron microscopy (JEOL JSM 5600). The wear tracks on the disc were also investigated with optical microscopy.

Results and Discussion

Wear rate as a function of deformation.

The wear rates of the as received as well as deformed (20%, 40%, 50% and 60%) and heat treated [below recrystalization, recrystalization and above recrystalization] copper samples from the central normal plane and the central rolling plane are plotted as a function of percentage of deformation at a fixed sliding velocity of 3.35 m/s, for a fixed applied pressure of 0.2 MPa, up to a sliding distance of 2000 metres. Fig. 2(a) and 2(b) represents the variation of wear rate with percentage of deformation.

Wear rate - central normal plane:

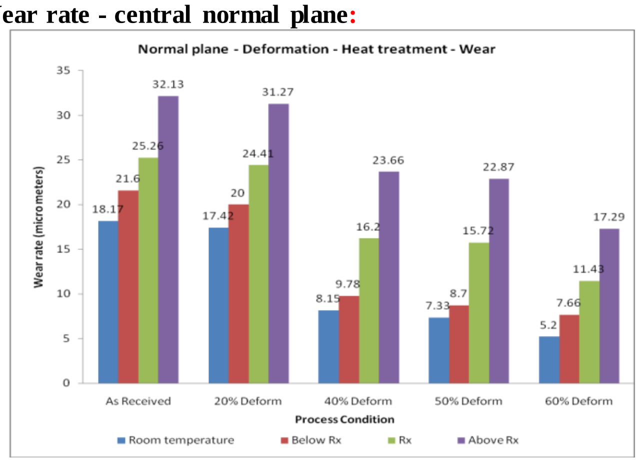


Fig. 2(a) variation of wear rate of copper from central normal plane with deformation

The wear rates of as received copper from central normal plane subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures for a sliding distance of 2000 m are noted to be 21.26,25.26 and 32.13 micro meters respectively. The wear rate of 20% deformed copper from central normal plane subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures at a sliding distance of 2000 m are noted to be 20,24.41and 31.27 micro meters respectively. The wear rate of 40% deformed copper subjected to heat treatments at below recrystallization , recrystallization and above recrystallization temperatures at a sliding distance of 2000m are noted to be 9.78,16.2 and 23.66 micro meters respectively. The wear rate of 50% deformed copper subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures at a sliding distance of 2000m are noted to be 8.7,15.72 and 22.87 micro meters respectively. The wear rate of 60% deformed copper subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures at a sliding distance of 2000m are noted to be 7.66, 11.43 and 17.29 micro meters respectively The wear rates of copper in the as received condition and the same that was subjected to 20%, 40%, 50% and 60% deformations at room temperature is found to be 17.42,8.15,7.33, 5.2 micro meters respectively.

The plots drawn between wear rate and deformation show the similar trends in all the cases. Comparison of all the figures, it clearly indicates that wear rate is increased with increase in heat treatment temperature i.e from below recrystallization temperature to above recrystallization temperature but decreased with increasing degree of deformation. For example the wear rate of copper at below recrystallization, recrystallization and above recrystallization temperatures for 20% deformation are 20, 24.41 and 31.17 micro meters respectively which shows a increase in wear tendency with increase in heat treatment temperature. Similarly, the wear rates of copper subjected to 20%, 40%, 50% and 60% deformations at room temperature are noted to be 18.17, 17.42, 8.15, 7.33, 5.2 micro meters respectively which shows a decrease in wear tendency with increase in degree of deformation. Similar trends were also noted in all the as received, deformed and heat-treated copper samples.

Wear rate - central rolling plane

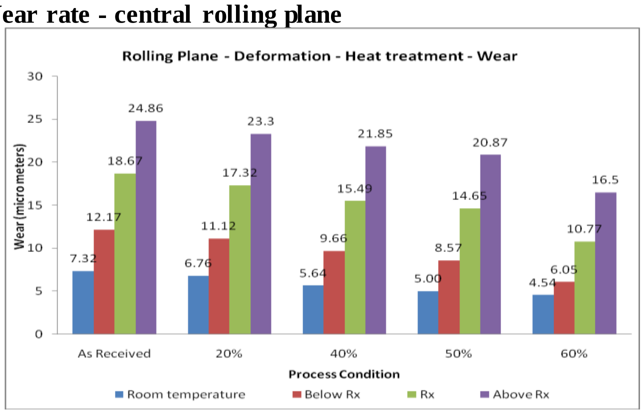


Fig. 2(b) variation of wear rate of copper from central rolling plane with deformation

. Similarly, the wear rates of as received copper from central rolling plane subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures for a sliding distance of 2000 m are noted to be 12.17,18.67 and 24.86 micro meters respectively The wear rate of 20% deformed copper subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures for a sliding distance of 2000 m are noted to be 11.12,17.32 and 23.3 micro meters respectively. The wear rate of 40% deformed copper subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures for a sliding distance of 2000m are noted to be 9.66,15.49 and 21.85 micro meters respectively. The wear rate of 50% deformed copper subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures for a sliding distance of 2000m are noted to be 8.57,14.65 and 20.87 micro meters respectively. The wear rate of 60% deformed copper subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures for a sliding distance of 2000m are noted to be 6.05,10.77 and 16.5 micro meters respectively The wear rates of the copper subjected to 20%, 40%, 50% and 60% deformations at room temperature is found to be 6.76,5.64,5.00,4.54 micro meters respectively.

The plots drawn between sliding distance and wear rate show the similar trends in all the cases. Comparison of all the figures: it clearly indicates that wear rate is increased with increase in heat treatment temperature i.e from below recrystallization temperature to above recrystallization temperature but decreased with increasing degree of deformation. For example the wear rate of 20% deformed copper at below recrystallization, recrystallization and above recrystallization temperatures are 11.12,17.32 and 23.3 micro meters respectively which shows a increase in wear tendency with increase in heat treatment temperature. Similarly, the wear rates of copper in the as received condition and the same that was subjected to 20%, 40%, 50% and 60% deformations at room temperature for a sliding distance of 2000m are noted to be7.32, 6.76, 5.64, 5.00, 4.54 micro meters respectively, which shows a decrease in wear tendency with increase in degree of deformation. Similar trends were also noted in all the as received, deformed and heat-treated copper samples.

From the observations, it may be noted that the wear rates of all the copper specimens from the central normal plane as well as central rolling plane increase with increasing sliding distance as a general tendency under dry sliding conditions. At the same sliding speed of 3.35 m/sand for the same sliding distance of 2000 m , the wear rates of all the copper samples decreases with increasing degree of deformation (as received to 60%). It is further observed that the wear rates of the copper samples subjected to different heat treatments (below Rx, Rx, above Rx) from the as received condition as well as those from different deformations also decreases substantially with increasing degree of deformation .It can be concluded from the below observations that the wear resistance of copper subjected to heat treatment above recrystallization temperature enhanced simply and poor wear resistance can be cited in case of copper subjected to heat treatment above recrystallization temperature and the same trend can be observed with reference to the increasing degree of deformation i.e from as received to 60% . Further the wear rates of copper samples from the central normal plane are observed to be higher when compared to those of from central rolling plane in all the cases. It is now concluded from the above that central rolling plane of the as received as well as deformed copper has better wear resistance than central normal plane.

Coefficient of friction as a function of sliding time

The coefficient of friction is measured from the recorded frictional force and the applied pressure on the specimen surface. The coefficient of friction of the as received , deformed (20%, 40%, 50% and 60%) and heat treated [below recrystallization, recrystallization and above recrystallization] copper samples from central normal plane areas and central rolling plane areas are plotted as a function of sliding time at a fixed sliding velocity of 3.35 m/s, for a fixed applied pressure of

0.2 MPa(applied load of 10 newtons), up to a sliding distance of 2000 metres. Fig. 3(a) to 3(f) represents the variation of the coefficient of friction with sliding time.

Coefficient of friction - Central normal plane:

It is noted that the coefficient of friction of the as received , deformed (20%, 40%, 50% and 60%) and heat treated copper varies up and down, within a band, with sliding distance. The range of coefficient of friction of the as received copper subjected to heat treatments below recrystallization, recrystallization and above recrystallization is primarily between 0.1 and 0.4, and finally reaches a steady state between 0.2 and 0.5. For 20% deformed copper subjected to below recrystallization, recrystallization and above recrystallization heat treatments, the coefficient of friction varies between 0.25 to 0.6. In case of 40% deformation of copper subjected to below recrystallization, recrystallization and above recrystallization heat treatments, the range of coefficient of friction lies between 0.3 and 0.7 and later decreased to the range of 0.5 and 0.6. For 50% deformed copper subjected to below recrystallization, recrystallization and above recrystallization heat treatments, the coefficient of friction again varies between 0.4 and 0.6 steadily through out the 2000 m sliding distance. For 60% deformed copper subjected to below recrystallization, recrystallization and above recrystallization heat treatments, the coefficient of friction again varies between 0.2 and 0.7.

The trend of variation of coefficient of friction is noted to be similar in all the cases. The overall variation of coefficient of friction for the as received , deformed (20%, 40%, 50% and 60%) and heat treated copper ranges between 0.1 and 0.7. Maximum coefficient of friction is noted in case of 60% deformed copper (0.7) and minimum is noted for as received copper (0.1). Both these figures states that amongst the as received, deformed and heat-treated copper samples, coefficient of friction increases simply by the increasing degree of deformation. Further, the coefficient of friction varies in a zig-zag fashion with sliding distance, irrespective of the as received condition, deformation and heat treatment

As regard to the coefficient of friction, it initially increases with sliding distance and after very initial period, it remains almost invariant with sliding distance. The average friction coefficient however, remains unchanged with sliding distance. The coefficient of friction is higher for 60% deformed copper but the wear rate is significantly less than that of the as received copper. This can be attributed to be the high hardness of the highly deformed copper.

Coefficient of friction - Central rolling plane:

The coefficient of friction of the as received , deformed (20%, 40%, 50% and 60%) and heat treated copper samples from the central rolling plane areas varies up and down, within a band, with sliding distance in similar to the samples that are extracted from the central normal plane areas. The range of coefficient of friction of the as received copper subjected to heat treatments at below recrystallization, recrystallization and above recrystallization temperatures is primarily between 0.15 and 0.4. For 20% deformed copper subjected to heat treatment at below recrystallization, recrystallization and above recrystallization temperatures, the coefficient of friction varies between 0.15 to 0.4 In case of 40% deformation of copper subjected to below recrystallization, recrystallization and above recrystallization heat treatments, the range of coefficient of friction lies between 0.25 and 0.45. For 50% deformed copper subjected to below recrystallization, recrystallization and above recrystallization heat treatments, the coefficient of friction again varies between 0.25 and 0.5 steadily through out the 2000 m sliding distance. For 60% deformed copper subjected to below recrystallization, recrystallization and above recrystallization heat treatments, the coefficient of friction again varies between 0.3 and 0.50.

The trend of variation of coefficient of friction is noted to be similar in all the cases. The overall variation of coefficient of friction for as received, deformed (20%, 40%, 50% and 60%) and heat treated copper ranges between 0.15 and 0.35. Maximum coefficient of friction is noted in case of 60% deformed copper (0.50) and minimum is noted for un deformed copper (0.15). Both these figures states that amongst the as received, deformed and heat-treated copper samples, coefficient of friction increases simply by the increasing degree of deformation. Irrespective of the as received condition, deformation and heat treatment, the coefficient of friction varies in a zig-zag fashion with sliding distance.

As regard to the coefficient of friction, it initially increases with sliding distance, after very initial period, it remains almost invariant with sliding distance. The average coefficient of friction however, remains unchanged with sliding distance. The coefficient of friction is higher for 60% deformed copper but the wear rate is significantly less than that of the as received copper. This can be attributed to be the high hardness of the highly deformed copper.

From the above, the coefficient of friction of copper samples of the central normal plane are observed to be higher when compared to those of from central rolling plane in all the cases which is also confirming with that of wear rate phenomena as was observed earlier. It is also now concluded from this that the central rolling plane of the as received as well as deformed copper has better wear resistance than central normal plane.

Wear surface examination

Initially, both the surfaces of the copper pin material and counter face EN-31 steel disc are associated with a large number of sharp asperities, and contact between the two surfaces takes place primarily at these points. Under the influence of applied load and speed, when the asperities on each surface come in contact with relative motion, they are either plastically deformed or remain in elastic contact.

When the copper specimen is rubbed against En-31 steel disk, the hard asperities on the steel counterpart penetrated and cut deeply into the surface of copper, which resulted in a large amount of material removal from the copper pin. Continuous grooves and a considerably extent micro cutting on the worn surface of the copper were observed. The presence of grooves of varying sizes was observed frequently on the worn surfaces. The local plastic deformation on the worn surfaces was greatly reduced, because of the high hardness and wear resistance of the highly deformed copper (60%) samples as well as those samples that was subjected for heat treatments at below recrystallization temperature. Additionally, no cracking can be seen in the worn surface.

Heavy noise and vibration were observed during the testing process. Transfer of significant amount of the copper pin material to the disc was also observed. The wearing surface is characterized by this significant transfer of copper material between the sliding surfaces. At a slow sliding velocity (3.35 ms^{-1}), the wearing surface was covered with a little amount of transferred material layer.

The worn surface produced by adhesive wear, is defined as the transfer of material from one surface to another during relative motion by a process of solid-phase welding or because of localized bonding between contacting surfaces.

As the wear test is carried is carried at a low load of 10N , a normal wear regime was reported, and there by the wearing surfaces were described as relatively smooth and wear debris were small and brittle. Oxidation of copper was considered an important part of this wear mechanism even though no quantitative data regarding oxidation was given.

The worn surfaces of the all the deformed as well as heat treated copper samples from both the central normal and central rolling planes rubbing against En-31 steel disk at an applied load of 10N under a sliding speed of 3.35 ms^{-1}. were examined with scanning electron microscopy (SEM).

A higher magnification micrograph of wear surface of the as received, deformed (20%, 40%, 50% and 60%) and heat treated copper from normal and rolling planes clearly shows damaged regions and the formation of equi axed debris. It also shows the formation of cracks along the longitudinal direction. A higher magnification micrograph of highly deformed 60% copper clearly depicts equi axed debris on the wear surface of 1-2 µm in size.

It is interesting to note that the highly deformed copper (60%) not only shows the cracking along the transverse and longitudinal direction but also formation of equiaxed debris and formation of mixed wear debris. Because of combined action of load, sliding speed and sliding distance, subsurface micro cracks are generated which finally leads to removal of wear debris. As a result, it is expected that the wear rate will increase with increase in sliding distance. However, as the sliding distance increases the subsurface deformation also increases which leads to alignment of stronger precipitates along the sliding direction. With further increase in sliding distance, the temperature rise increases to a critical value at which specimen surface gets oxidized in to copper oxide. This copper oxidized surface either gets fragmented or become stable to some extent. The fragmented copper oxide particles sometimes acts as lubricating agent and thus these copper oxide layers reduce the effective wear rate. Furthermore the fragmentation and compaction of wear debris, counter surface material and thin copper oxide layers leads to formation of mechanically mixed layer which protects the specimen surface from wear.

Conclusions

Following conclusions can be drawn from the present investigation:

1. Wear rate is decreased with increase in degree of deformation, where as wear rate has increased with increase in heat treatment from below recrystalization to above recrystalization temperature irrespective of deformation, sliding distance and also irrespective of the location of the specimen i.e central normal plane or central rolling plane.

2. The wear rates of central normal plane are slightly higher than that of central rolling plane which can be attributed that the central rolling plane has more wear resistance.

3. Coefficient of friction of the as received, deformed as well as heat treated copper varies up and down within a narrow band with sliding distance and increases with increase in degree of deformation, an opposite trend contrary to the wear rate that was observed.

4. The coefficient of friction values of the central normal plane are also slightly higher than that of the central rolling plane which can be again attributed that the central rolling plane has better wear resistance.

5. The surface hardness values of the as received, deformed as well as heat treated copper samples from the central normal plane are lower than that of central rolling plane, attributing that the central rolling plane has high wear resistance.

6. From the SEM observations, it is inferred that at lower deformation (20%), the wear surface is characterized by the formation of deep continuous grooves, cracking along the transverse and longitudinal direction and also formation of equiaxed debris and mixed wear debris. It is also observed that at higher deformation (60%), formation of continuous grooves and some damaged regions were observed on worn surfaces.

Fig.3(a) to 3(f) represents the variation of the coefficient of friction with sliding time

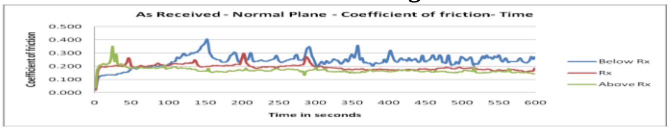


Fig. 3(a) Variation of coefficient of friction of as recieved copper with sliding time

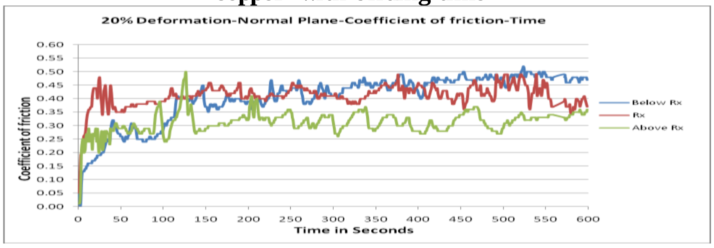


Fig. 3(b) Variation of coefficient of friction of 20% deformation with sliding time.

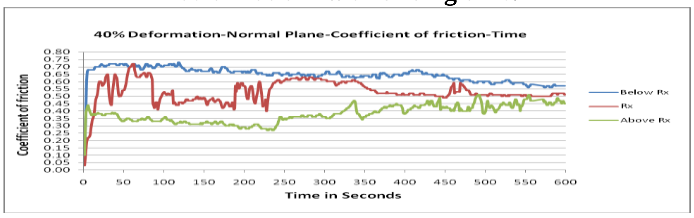


Fig. 3(c) Variation of coefficient of friction of 40% deformation with sliding time.

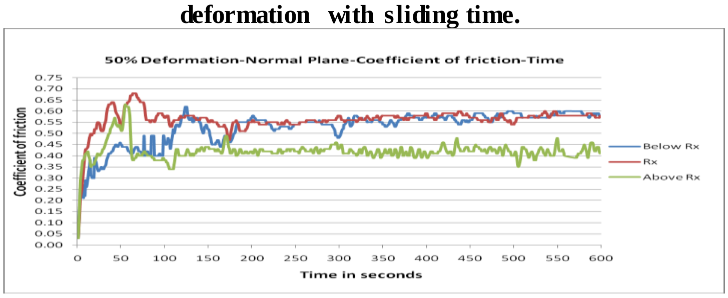


Fig. 3(d) Variation of coefficient of friction of 50% deformation with sliding time.

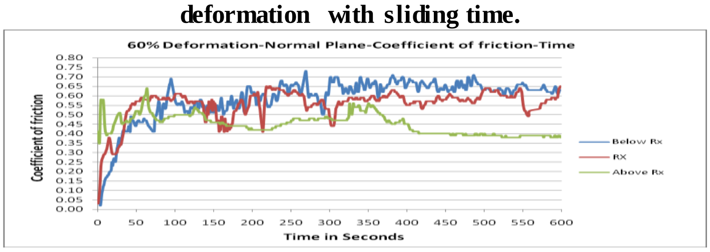


Fig. 3(e) Variation of coefficient of friction of 60% deformation with sliding time

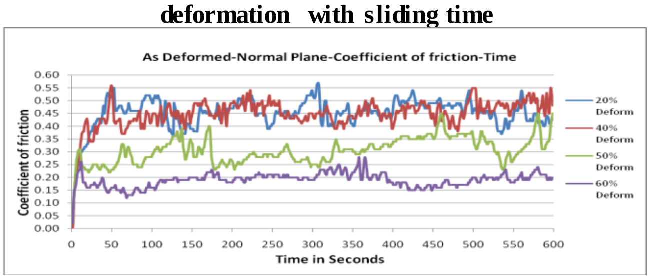


Fig. 3(f) Variation of coefficient of friction of different deformations with sliding time

Fig.4(a) to 4(f) represents the variation of the coefficient of friction with sliding time

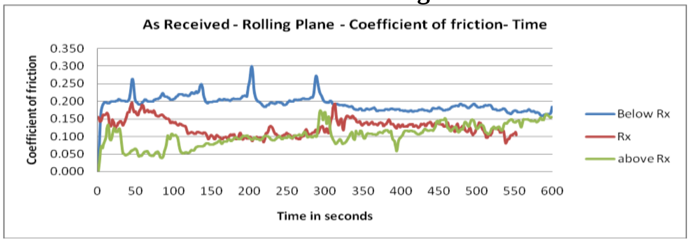


Fig. 4(a) Variation of coefficient of friction of as received copper with sliding time

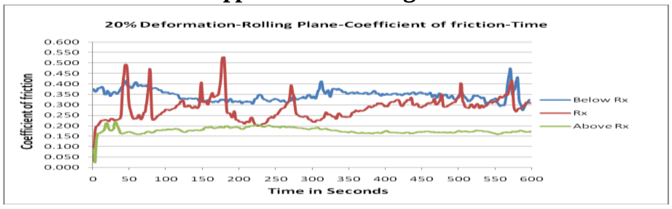


Fig. 4(b) Variation of coefficient of friction of 20% deformation with sliding time

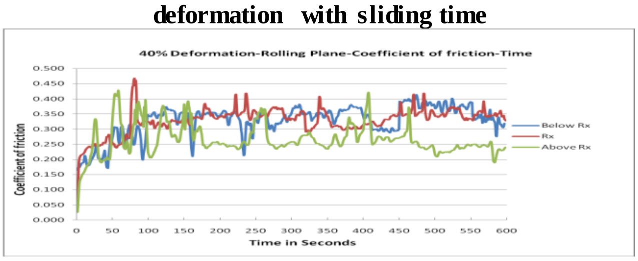


Fig. 4(c) Variation of coefficient of friction of 40% deformation with sliding time

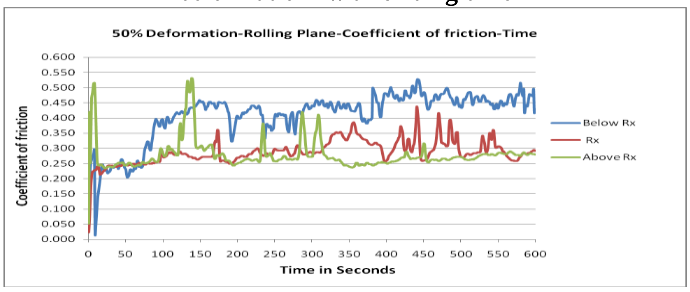


Fig. 4(d) Variation of coefficient of friction of 50% deformation with sliding time

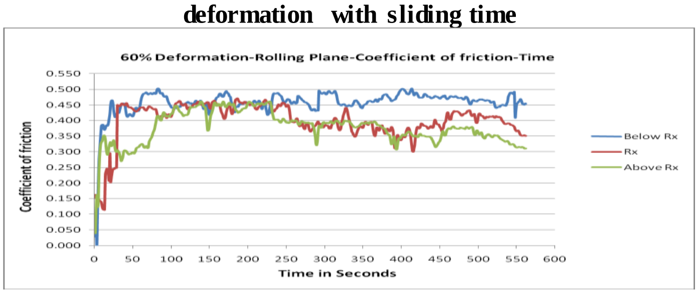


Fig. 4(e) Variation of coefficient of friction of 60% deformation with sliding time

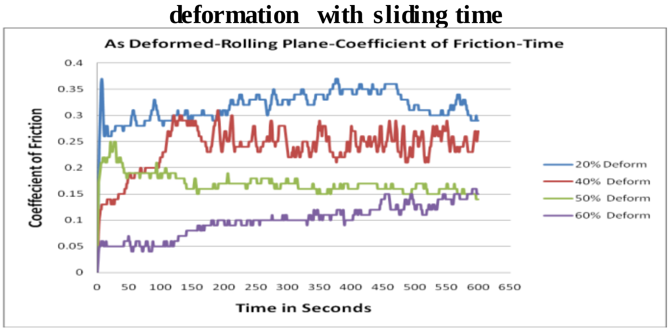
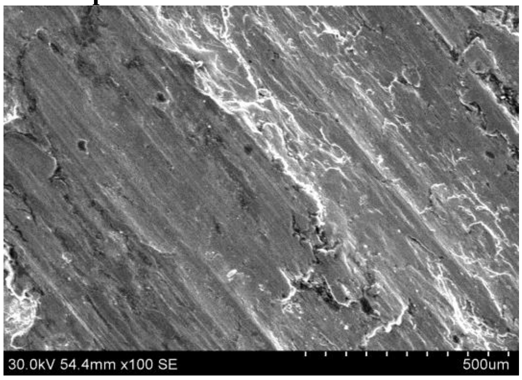
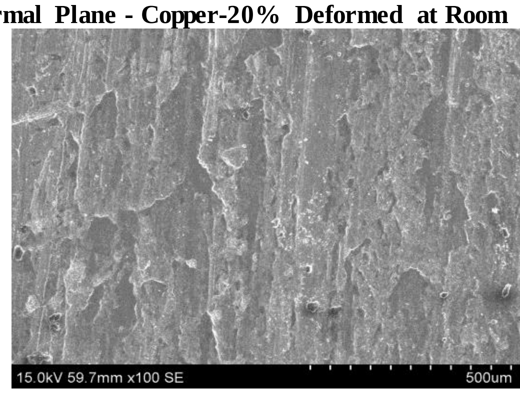


Fig. 4(f) Variation of coefficient of friction of different deformations with sliding time

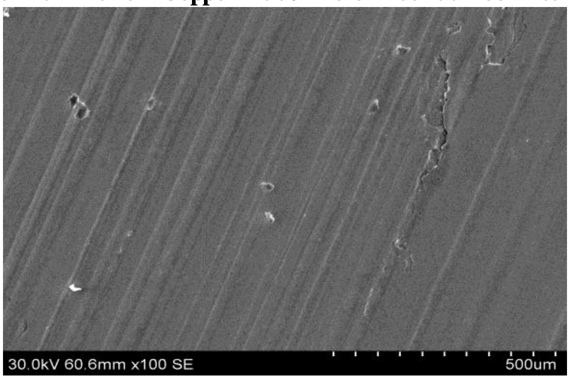
Worn surface SEM photos graphs of copper pins from central normal plane



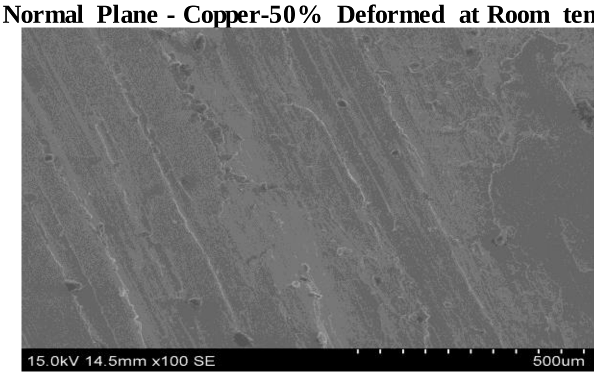
Normal Plane - Copper-20% Deformed at Room temp



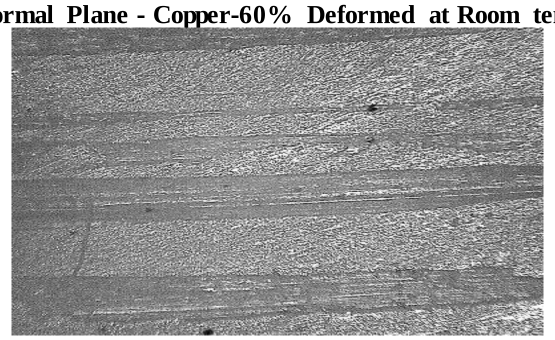
Normal Plane - Copper-40% Deformed at Room temp



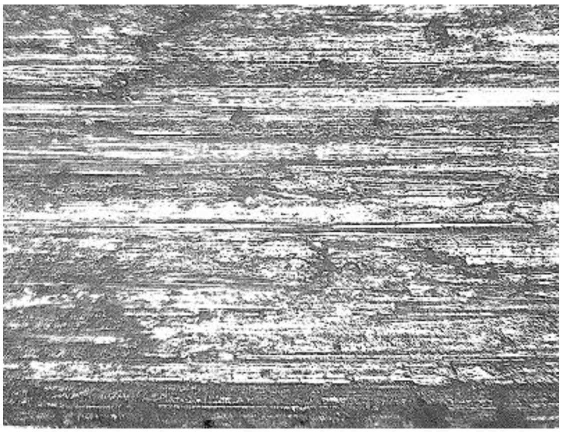
Normal Plane - Copper-50% Deformed at Room temp



Normal Plane - Copper-60% Deformed at Room temp

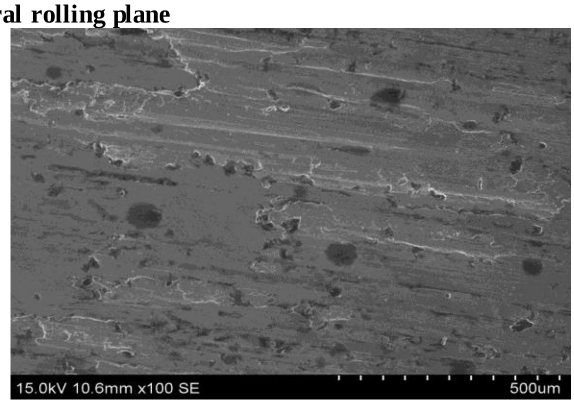


Wear track of En 31 steel disc

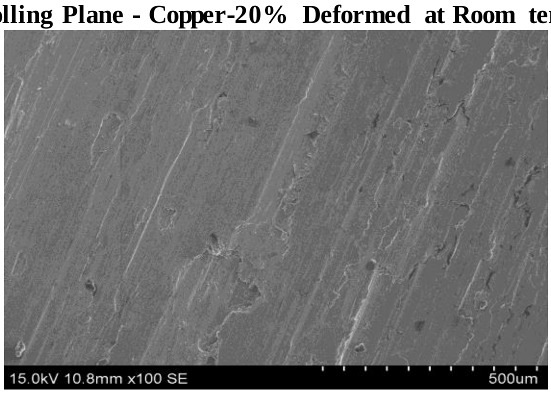


Wear track of En 31 steel disc

Worn surface SEM photos graphs of copper pins from central rolling plane



Rolling Plane - Copper-20% Deformed at Room temp



Rolling Plane - Copper-40% Deformed at Room temp

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