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RESEARCH PAPER

Dry Sliding Friction and Wear Resistance of SnPb-Solder Affected Copper against Stainless Steel Counter Surface

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Abstract: *This paper reports the wear behavior of Cu, high Cu-Sn alloy, high Cu-Pb alloy and high Cu-Sn-Pb alloy under dry sliding at ambient conditions. These four materials were chosen for the wear resistance characterization of SnPb-solder affected old/scraped copper (high Cu-Sn-Pb alloy) to explore its reusing potentials. Wear tests were conducted using a pin-on-disk tribometer with the applied load of 20 N for the sliding distance up to 2772 m at the sliding speed of 0.513 ms^{-1}. The applied load was also changed to observe its effect. The investigation reveals that the presence of a small amount of Sn increased the hardness and improved the wear resistance of Cu, while a similar amount of Pb in Cu reduced the hardness but improved the wear resistance. The general perception of 'the harder the wear resistant' was found to match partially with the results of Cu, Cu-Sn alloy and Cu-Sn-Pb alloy. Coefficient of friction (COF) values revealed non-linear gradual increasing trends at the initial stage and after a certain sliding distance COF values of all four sample materials became almost steady. SnPb-solder affected Cu demonstrated its COF to be in between that of Cu-Pb alloy and Cu-Sn alloy with the maximum COF value of 0.533.*

Keywords: *Scraped Cu, SnPb-solder inclusion, Micro-hardness, Sliding wear, Coefficient of friction.*

1. INTRODUCTION

Copper (Cu) is extensively used in many applications due to several factors including electrical and thermal conductivities, corrosion resistance, wear resistance, fatigue resistance and ease of fabrication along with good mechanical strength [1]. Mariners do prefer the use of copper for propeller shaft bearings, thrust bearings, rudder stock bearings, sleeves, sliding bearings and so on for such worthy properties. With the rapid scientific and technological advancement as well as economic development, the use of Cu has got more rising requirements continuously [2]. To meet such extensive demand, it is important to get copper from old products/scraped items considering the depletion level of copper ores in the nature [3]. However, after a long span of operational life of copper items including the waste electrical and electronic equipment (WEEE), there are two options, i.e., either recycling of copper through a rigorous extraction process or reusing the scraped materials at their leftover state for suitable engineering applications. Recycling is a very difficult and costly affair but preferred for regaining the properties as close to the original state. On the other hand, reusing is very cheap but properties are yet to be anticipated. If the reusing option is chosen, characterization of different properties of old/scraped Cu is essential to explore its potential rehabilitation [4, 5]. It is because old Cu items might have come across solder materials during their operational life or during repair and maintenance purposes. As a result, old copper wires and machine parts coming out from industries and ship breakings usually contain a little amount of solder materials comprising of lead (Pb), tin (Sn), etc. The inclusion of such soldering elements in Cu might be of very little amount, but its effect on the associated properties is not negligible [6-8]. Moreover, the wettability and bond strength of SnPb-solder affected Cu might have been changed in shear behavior of the solder/copper couples, which might result in alteration of the functional ability of scraped copper materials [9, 10]. Wear behavior is not an exception to the adaptation in properties of aged Cu items while there is a presence of solder elements in it.

In this context, scraped Cu requires the characterization of attainable properties with extra attention to the surface behavior i.e., wear and friction properties; because major failures of a component occur from surface wear, which induce the surface deformation and lowering of the strength. There are several studies dealing with wear resistance and friction considering the applications of Cu materials for plain bearings. Few of such researches have addressed the friction and wear behavior of pure Cu and its commercial alloys [11-14], few works looked into the effect of Pb in Cu on tribological possessions [15-17] and few works have observed the contribution of Sn on enhancing lubrication properties of Cu based materials [18-20]. However, the effect of Sn and Pb together in Cu is yet to be characterized to obtain the most suitable rehabilitations of SnPb-solder affected scraped copper in producing the high-value engineering products including bearings. Moreover, Cu based bearings and associated fittings are being preferred for stainless steel shafts in shipbuilding industries, and for that reason, there is a need to have reliable information in relation to the friction and wear while Cu-Sn-Pb bearings are applied against stainless steel shafts.

But the literature review has not provided any such work that has considered stainless steel as the counter surface for dry sliding wear tests against Cu based materials. Therefore, the present work is an imperative attempt to look for the friction and wear behavior of SnPb-solder affected old/scraped Cu against stainless steel counter surface at dry sliding conditions for applications in marine shafting, fin-stabilizer and steering systems.

2. MATERIALS AND METHODS

2.1. Materials

About 80 kg extensively old/used Cu was collected from different sources such as old buildings, scraped ships, renovated industries, etc., and melted together in the furnace. The chemical composition tests appreciated that the old Cu contains a little percentage of Pb [1.0~1.5%] and Sn [1.0~1.5%]. To ascertain the influence of tin and lead in the old copper materials, three more combinations of sample materials such as pure copper [Cu 99.99%], high copper-tin alloy [about Cu 98.5% + Sn 1.2%], and high copper-lead alloy [about Cu 98.5% + Pb 1.2%] were selected as supporting materials. Melting was carried out using a clay-graphite crucible in a gas-fired pit furnace under suitable flux cover while the final temperature of the melt was maintained at 1300±15°C. Preheated steel moulds (200°C) of size 20 mm × 100 mm × 150 mm were prepared and coated inside with a water-clay film to carry out the casting. The melts were then allowed to be homogenized under stirring at about 1200°C and poured in the preheated moulds to have all four sample materials at the same treatment level. The cast materials were machined to remove the oxide layer from the skins. Thereafter, their chemical compositions were examined using XRF machine (model: Olympus DPO-2000-CC) and the results attained are presented in Table 1.

2.2. Methods

Two groups of samples were prepared to carry out the investigations: one group samples were for hardness tests and another group for wear tests. In the first group, there were 96 samples having the size of 20 mm × 20 mm × 15 mm for the examination of micro-hardness with different thermal ageing conditions. Half of the first group samples, i.e., 48 pieces were processed through isochronal ageing at the temperatures of 25°C, 100°C, 150°C, 200°C, 250°C and 300°C for one hour and the remaining samples (48 pieces) were kept for isothermal ageing. Then they were mechanically ground with 160, 300, 600, 900, 1200 and 1500 grits of SiC emery paper successively.

Table 1. Chemical composition of the materials under study (mass fraction %)

Material	Pure Cu	Cu-Sn Alloy	Cu-Pb Alloy	Cu-Sn-Pb Alloy
Cu	99.9862	98.4555	98.4334	97.1132
Sn	-	1.1335	-	1.2572
Pb	-	-	1.1973	1.1949
Si	0.0026	0.1415	0.1129	0.1726
P	0.0112	0.2695	0.2564	0.2621

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On completion of dry grinding, all the samples were wet polished using alumina paste and dried up through air blow at room temperature. On preparation, the micro-hardness readings of the samples after isochronal ageing at the temperatures of 25°C, 100°C, 150°C, 200°C, 250°C and 300°C were taken using Vickers Hardness Tester of model TM HV-1000DTE following ASTM E92-82 standard with 1.0 kgf load applied for 10 seconds. Twenty readings were taken with indentations at different locations of each sample against each ageing temperature to have data authenticity of the experiments. Following the experimental results of micro-hardness obtained for the isochronally aged samples, the remaining samples of this group kept for isothermal ageing were then heat treated at 150°C corresponding to the stable higher micro-hardness values with the variation of time from 15 minutes to 240 minutes. Thereafter, the experiments were carried out to investigate the effect of ageing period variation on micro-hardness of the sample materials.

The second group samples were machined with the size of 12 mm length and 5 mm diameter for wear study using pin-on-disk (POD) tribometer following ASTM Standard G99-05. These samples were also aged at 150°C for one hour to attend the homogeneity and stable hardness for all four materials. The end surface (5 mm diameter) of the pin samples were polished using emery papers in sequence with the course to fine grits and finally of 1500 grits. Thereafter, the samples were cleaned in running water and dried up after the immersion in acetone. Since the stainless steel is normally used for the shafts in marine applications, disks of SS 309s material containing 60% Fe, 23% Cr, 14% Ni, 2% Mn, 0.84% Si, 0.08% C, 0.05% P and 0.03% S were used as the counter-body. The hardness of the stainless steel disk was found on average as 168 HV. The surface of the disk was ground by a surface grinding machine and cleaned with acetone as well as dry cotton. Surface roughness of both disk and pin at the time of experimental setup was on average, i.e., center line average (R_a) 40μin (~1 μm). During sliding wear tests, the end surface of the pin sample was pressed against a horizontal rotating stainless steel disk with the applied load of 20 N which yielded nominal contact pressures of 1.02 MPa. The effect of loading was observed with the change of load as 5 N, 10 N, 30 N, 40 N and 50 N. The track diameter of the rotating disk was 49 mm. The tests were conducted at the sliding speed of 0.513 ms^{-1} with sliding distances varied up to 2772 m without providing any lubricant at the contact surface.

The sample pins and the wear track of disks were cleaned with acetone every after the designated period of test run, i.e., 2 minutes, 10 minutes, 30 minutes, 60 minutes, 90 minutes, etc., and the pin was weighed using the weighing machine (model: Sartorius Entris 224-1S) having pan diameter of 90 mm with the maximum weighing capacity of 220 g and of 0.01 mg precision. Moreover, the length of the pin was measured using an ultrasonic thickness gauge (model: CG100 ABDL) having measurement resolution of 0.01 mm to examine the loss of length, in turn, volume loss for every wear test run. Thereafter, the volume loss values and densities of the sample materials were used to calculate the wear loss values in μg unit. These wear loss values were rechecked with the weight loss values directly measured using the weighing machine to ensure the data reliability. The frictional forces and applied load for individual test run were measured by using the experimental setup arrangements. The test for each case was repeated at least three times to examine the weight and height (length) of sample pins, applied load, frictional force and coefficient of friction.

Specific wear rates were then calculated from the average of weight-loss values, the applied load and the sliding distance using equation (1) as follows, which is a modified expression based on the Archard equation [21, 22].

$$\mathrm{WR} = \frac{\Delta \mathrm{W}}{(\mathrm{SD} \times \mathrm{L})} \quad (1)$$

where,

WR = Specific wear Rate (μg N^{-1} m^{-1})

ΔW = Wear Loss (μg)

SD = Sliding Distance (m)

L = Normal Load (N)

The coefficient of friction (COF) values were obtained directly from the experimental setup. However, following very fundamental equation was also used to calculate the COF to ascertain the reliability of machine readings.

$$\mu = \frac{\mathrm{FF}}{\mathrm{L}} \quad (2)$$

where,

FF = Frictional Force (N)

L= Normal Load (N)

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μ = Coefficient of Friction

The metallographic images were examined before and after wear test using computer interfaced Optical Electronic Microscope (OEM) (model: Nikon BW-S500 having 4.19 Mpixel camera) at different magnifications to find out the microstructural changes in the surfaces during dry sliding experiments. Moreover, micrographs were also taken using field emission scanning electron microscope (FE-SEM) of model JEOL JSM-7600F to observe surface microstructures after wear.

3. RESULTS AND DISCUSSION

3.1. Micro-hardness Measurement

The micro-hardness values of pure Cu, high Cu-Sn alloy, high Cu-Pb alloy and SnPb-solder affected Cu on average at room temperature along with the standard deviations for twenty readings are shown in Table 2.

The results depict that the addition of about 1.15% Sn with copper has increased the hardness by 12.69%, whereas the addition of about 1.17% Pb has decreased the hardness by 15.91%, and the addition of about 1.26% Sn and 1.19% Pb together has increased the hardness of copper by 10.14%. It may be mentioned here that the micro-hardness values of Sn and Pb have been found as 8.5 HV and 6.4 HV respectively. So, the Cu-Sn and Cu-Pb alloys should have less micro-hardness than that of pure Cu, and the obtained result for Cu-Pb alloy is matching. But the problem has occurred with sample materials where a little amount of tin is present, which have shown higher hardness than pure copper. The reason behind the increase in micro-hardness with the addition of Sn is mainly due to the formation of Cu_xSn_y intermetallic compounds. On the contrary, the decrease of micro-hardness with the addition of Pb is considered to be the effect of no propensity of forming any intermetallic compounds while alloyed with copper [6].

Fig. 1 shows the changes in micro-hardness values of sample materials after isochronal ageing for 60 minutes at different temperatures. Once the isochronal ageing is done at 25°C, 100°C or 150°C, the changes in micro-hardness values are very negligible. Therefore, all four sample materials can be considered sustainable comfortably with respect to hardness up to the operating temperature of 150°C. But, while the ageing is done at elevated temperatures like 200°C or above, the micro-hardness values of sample materials have been found to be significantly reduced. The reason behind such reduction in micro-hardness for the thermal ageing at a higher temperature is the recrystallization effect. The dislocations of the crystalline structures of copper based materials have got affected during thermal ageing above the recrystallization temperatures. As a result, the micro-hardness values of sample materials for the ageing temperature of 300°C are reduced to 41.55 HV, 61.16 HV, 44.89 HV and 57.72 HV, i.e., reduced by 31.5%, 10.6%, 12.1% and 13.7% from their as-cast values, respectively. After ageing at 300°C temperature, Cu-Sn alloy depicts to be the hardest, which is followed by Cu-Sn-Pb alloy and thereafter CuPb alloy.

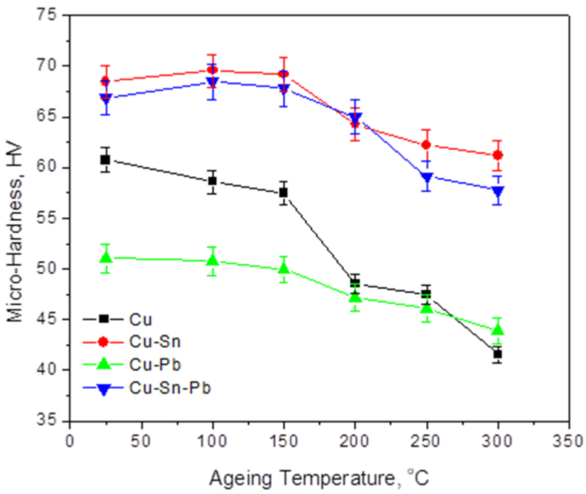

Fig. 1. Micro-hardness of sample materials against isochronal ageing temperature while aged for 1 hour.

Table 2. Microhardness at room temperature

Particular	Pure Cu	Cu-Sn Alloy	Cu-Pb Alloy	Cu-Sn-Pb Alloy
Micro-hardness (HV) on average	60.71	68.42	51.05	66.87
Standard Deviation (HV)	1.21	1.64	1.53	1.67

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At this condition, the lowest hardness is observed for pure Cu with a significant loss of its compressive strength. Fig. 1 also indicates that alloys are less affected than pure copper on hardness by ageing at elevated temperatures. It exhibits high softening resistance due to the solid-solution strengthening of the alloys. The change of micro-hardness with respect to ageing temperature for both pure Cu and high Cu alloys can be considered as an effect of atomic diffusion in the recovery phase and variation of dislocation density during the ageing at elevated temperature for copper based materials [6, 23, 24].

Since the stability of micro-hardness values are found up to ageing temperature of 150°C while aged for one hour and the softening rate is increased for elevated temperature, the ageing period for 150°C temperature has been varied from 15 minutes to 240 minutes to look for the effect of ageing period on hardness. Fig. 2 shows that the micro-hardness values of pure Cu have started to decrease at the very beginning of rising the ageing period.

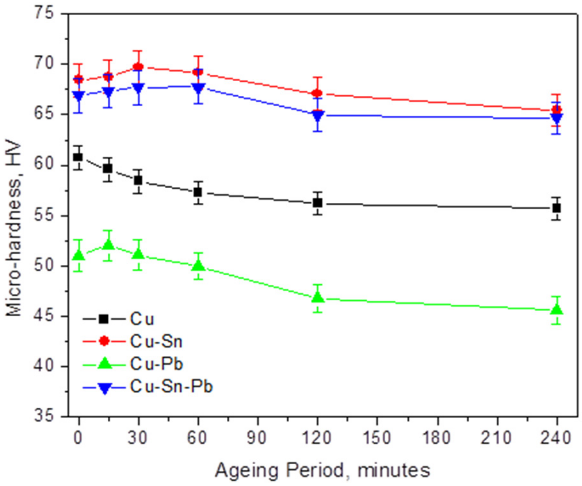

Fig. 2. Micro-hardness of four sample materials against ageing period, while aged at 150°C.

On the contrary, alloy samples have not been affected by ageing period up to 60 minutes. However, the micro-hardness values of alloy samples fluctuate like a transient variation at the initial period of isothermal ageing, i.e., 15 minutes and 30 minutes. Thereafter, while ageing period is increased, the results are of steady state nature showing almost horizontal graphs with very little reductions for all four materials. It illustrates that the sample materials have got softened with the reduction of their micro-hardness values by 4.88%, 4.86%, 13.96% and 3.99%, respectively, against the increase of ageing period due to elongated soaking phase with the increase of ageing period from 15 minutes to 240 minutes. The standard deviations of the micro-hardness values over the ageing period of 240 minutes for all four sample materials have been found to be 1.285, 1.640, 2.904 and 1.539, respectively. In overall consideration, the hardness values of alloy materials are sustainable at higher ageing temperature as well as ageing period than that of pure copper.

3.2. Wear Loss Examination

The wear loss values of sample materials, i.e., Cu, high Cu-Sn alloy, high Cu-Pb alloy and SnPb-solder affected Cu have been observed to be dependent on applied load, sliding distance and hardness. Fig. 3 illustrates the wear losses obtained at the sliding speed of 0.513 ms^{-1} with the normal load of 20 N in dry sliding conditions and the wear loss values have been found to be increased gradually with the increase of sliding distance for all four sample materials.

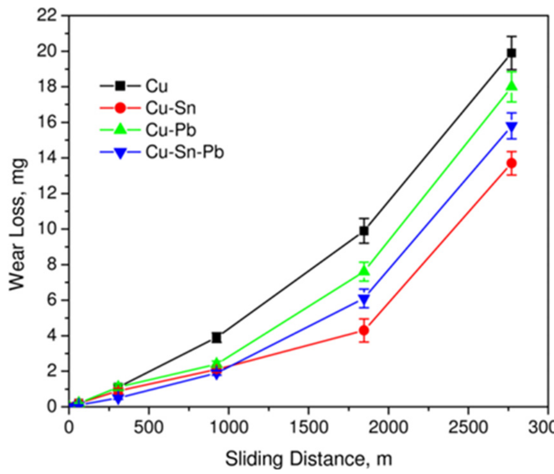

Fig. 3. Wear loss against the sliding distance at the sliding speed of 0.513 ms^{-1} with the normal load of 20 N (with the pressure of 1.02 MPa) in dry sliding condition.

Basically, during relative motion, materials on the contacting surfaces have been deformed and displaced, but little or no material is lost at first. After covering a certain sliding distance, the material has started removing from the surface and wear occurs almost continuously. As such, the cumulative wear loss has been found to be increased with the increase of sliding period. The

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graphs illustrated by Molian et al [16] depict the wear loss both in linear and non-linear patterns, but the present wear loss results do not have such linearity against sliding distance. Furthermore, the occurrence of wear from one or both of two solid surfaces during sliding is caused by plowing or/and asperity removal, which is not fully a material property; rather it is a system response where the material property is only a part of that system [25]. Besides, the system-induced wear mechanisms include the progressive extrusion of material from the asperity junctions into debris and/or the fracture of a thin surface layer leading to flake-like debris [26]. The present results indicate that the addition of Sn or/and Pb in Cu has reduced the wear loss in dry sliding conditions, which agrees with Pathak & Tiwari [17] and Kumar et al [19]. As per Fig. 3, the alloying effect on wear loss is clearly visible with the increase of sliding distance, and after the sliding distance of 2772 m, the wear losses of four sample materials have been found to be 19.9 mg, 13.7 mg, 18 mg and 15.8 mg with the corresponding standard deviation of 0.94, 0.67, 0.85 and 0.73, respectively. It shows that the lowest wear loss trend is observed for Cu-Sn alloy which is followed by Cu-Sn-Pb alloy and then Cu-Pb alloy; the highest wear loss is observed for pure Cu. Therefore, tiny alloying elements such as 1.15% Sn, 1.17% Pb and 1.26% Sn + 1.19% Pb with Cu have reduced the wear losses of Cu in the dry sliding friction by 31.2%, 9.6% and 20.6%, respectively. Here, Sn is found as dominant to alter the wear behavior of Cu. The easy separation of Sn particles which are weakly bonded to each other is considered to be the prime reason for its tribological effect. The Sn particles slid apart with minimal force due to inherent lubricity of tin. At the same time, the inclusion of Pb in Cu has also an effect on the lubricity to some degree. Basically, Pb does not affect the structure and properties of Cu because it is practically insoluble in solid copper and Pb globules at the grain boundaries or in the inter-dendritic regions during the solidification process of copper-lead alloy. As a result, the wear-resistances of Cu-Sn-Pb alloy and Cu-Pb alloy have been observed to be more than that of pure copper.

For the thermal ageing condition from room temperature to 150°C, the sequence of sample materials from high to low hardness is as Cu-Sn alloy > Cu-Sn-Pb alloy > pure Cu > Cu-Pb alloy. But the wear loss sequence after sliding distance of 200m or more is as Cu-Sn alloy < Cu-Sn-Pb alloy < Cu-Pb alloy < pure Cu. Considering the behavior of pure Cu and Cu-Pb alloy, the correlation between wear loss and micro-hardness has not been noticed significantly at this thermal ageing condition. However, frictional wear losses are found to be inversely correlated with the coefficient of -0.97 to the micro-hardness values of four sample materials at an elevated temperature like 300°C as seen in Fig. 1, i.e., the hardest material (Cu-Sn alloy) has shown the lowest wear loss (highest wear resistance), which is followed by Cu-Sn-Pb alloy as the second hardest, then Cu-Pb alloy; and pure Cu is observed to be the least wear-resistant with the highest wear loss in dry sliding friction.

3.3. Specific Wear Rates

Specific wear rate magnitudes of all four sample materials have been calculated using wear loss data in Eq. (1) for the corresponding sliding distance. The results are found to be dependent on the surface roughness and relative hardness of the two contacting surfaces, on the size, shape and hardness of wear debris, and reaction products trapped between them [26]. Fig. 4 depicts that pure Cu has the poorest wear resistance performance with the highest wear rate amongst four sample materials under dry sliding condition, which is followed by high Cu-Pb alloy and then high Cu-Sn-Pb alloy, where high Cu-Sn alloy has shown the best wear performance.

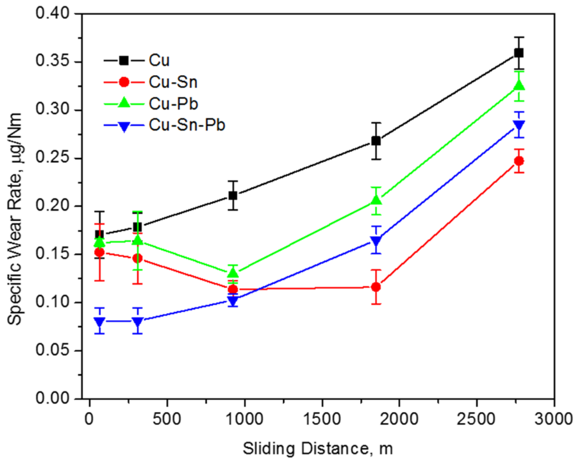

Fig. 4. Wear rate against the sliding distance at the sliding speed of 0.513 ms^{-1} with the normal load of 20 N (with the pressure of 1.02 MPa) in dry sliding condition.

The specific wear rates of Cu, high Cu-Sn alloy,

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high Cu-Pb alloy and SnPb-solder affected Cu for the operation period of 90 minutes have been found to be 235.85 × 10^{-3} μg$N^{-1}m^{-1}$, 157.17 × 10^{-3} μg$N^{-1}m^{-1}$, 200.3 × 10^{-3} μg$N^{-1}m^{-1}$ and 143.09 × 10^{-3} μg$N^{-1}m^{-1}$, respectively. As such, Cu-Sn alloy, Cu-Pb alloy and SnPb-solder affected Cu have shown 33.35%, 15.07% and 39.32% less specific wear rates than that of pure Cu. It means the addition of a small amount of alloying elements like Sn or/and Pb in Cu plays an important role to reduce the wear rate, which confirms the findings of Buchanan et al [15], Pathak & Tiwari [17], Kumar et al [19] and Taga et al [27].

The hardness results (shown in Fig. 1 and 2) and the wear results (Fig. 3 and 4) agree with a common understanding on 'the harder has the lesser wear' partly for alloys. Because the specific wear rates of both harder alloys (Cu-Sn alloy and SnPb-solder affected Cu) and softer alloy (Cu-Pb alloy) have been found to be lesser than that of pure Cu, and it disproves the universal acceptance of reverse proportionality of wear rate against hardness. However, solder affected copper has shown a moderate position amongst the four materials and it may be considered suitable to use for machine parts having sliding motions. Furthermore, Fig. 4 demonstrates a certain level of wear rate sensitivity over the sliding distance covered during the experiment, and the wear rates are found to be increased against the sliding distance. It might be the reason of adhesion occurring at the asperity contacts in the interface resulting in the detachment of a fragment from one surface and might get away or attached to the other surface. As the sliding process continues further, the fragments that have transferred to the other surface might also be finally removed as loose wear particles.

3.4. Coefficient of Friction

Coefficient of friction (COF) values have been obtained directly from the pin-on-disk apparatus and also calculated using Eq. (2). The results obtained for all four sample materials have been plotted against sliding distance in Fig. 5. COF values for all four sample materials at the initial sliding period are found to be significantly less under dry sliding condition. For instance, COF is only about 0.14 for the sliding period of 2 minutes covering the sliding distance of 15.4 m for all samples. Basically, COF depends on plowing mechanism, height of agglomerated particles, number of particles and the tribological condition of the sliding system which includes lubrication level and normal load [28]. At the beginning of sliding, plastic deformation is significant when adhesion is weak, and thus, COF values for all samples are low. Once the sliding time or distance is increased, adhesion actions of the plastically deformed materials are increased and the COF values are rising gradually but non-linearly. The graphs in Fig. 5 have shown a non-linear gradual increasing trend of COF up to a sliding distance of about 1500 m and finally reached to some steady-state level for all four sample materials. With the increase of sliding distance, there is a transition from grooving abrasion to rolling abrasion, which has resulted in steady values of COF. However, Cu-Pb alloy has shown the highest COF amongst four sample materials over the entire range of sliding distance in the experiment with the maximum value of 0.591, which is followed by Cu-Sn-Pb alloy (max value 0.533) and then pure Cu (max value 0.478). The lowest COF has been observed for Cu-Sn alloy throughout the sliding distance with the maximum value of only 0.251 under dry sliding condition.

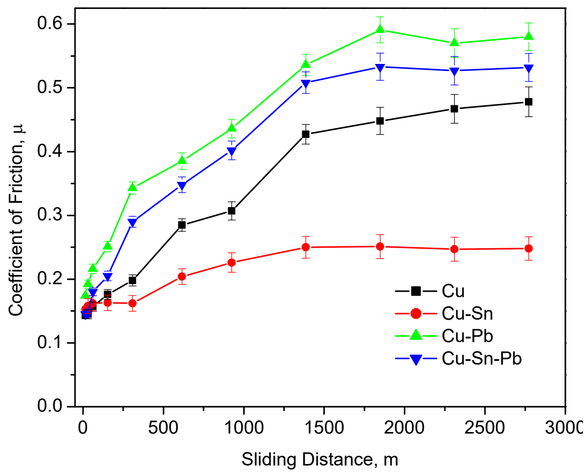

Fig. 5. COF against sliding distance at sliding speed of 0.513 ms^{-1} with normal load of 20 N (with the pressure of 1.02 MPa) in dry sliding condition.

From the present results, the hardest material (Cu-Sn alloy with micro-hardness value of 68.42 HV) shows the lowest values of COF and the softest material (Cu-Pb alloy with micro-hardness value of 51.05 HV) displays the highest COF values. It may be considered that the lower value of COF occurs for the higher hardness. But, Cu-Sn-Pb alloy being harder (66.87 HV) than pure Cu

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(60.71 HV) is displaying higher COF than that of Cu unexpectedly, and thus, they are showing reverse behavior in this regard. Therefore, there is no strong relation to having lesser COF for harder materials, especially for alloys. Again lesser COF of Cu-Sn alloy than Cu and higher COF of Cu-Pb than Cu indicates that the alloying element may have sometimes a discriminating effect (rising or again falling) in friction, which also agrees with the findings of Buckley [29].

The effects of applied load on COF values of sample materials have been observed with the applied load of 5 N, 10 N, 20 N, 30 N, 40 N and 50 N for the sliding distance of 2772 m and the results are presented in Fig. 6. COF values of all four samples are almost of a similar pattern against load. It is seen in Fig. 6 that COF values are not maintaining constant characteristics as normally considered.

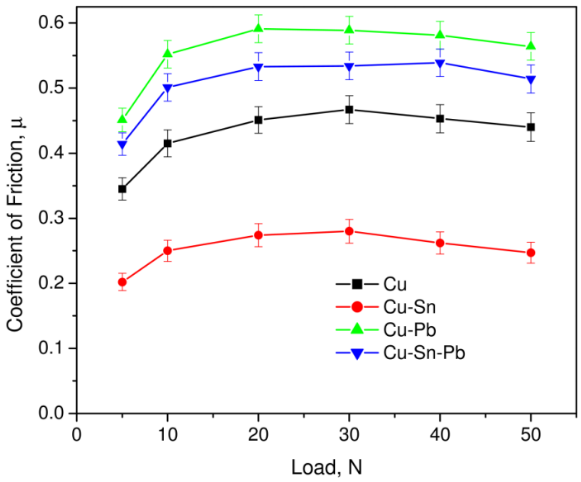

Fig. 6. COF against applied load at the sliding speed of 0.513 ms^{-1} for sliding distance of 2772 m.

All curves are showing increasing trends at the initial rise of loads, and thereafter, they have become steady with little reductions in COF values for the loads of 40 N and 50 N. The standard deviations of COF for pure Cu, Cu-Sn alloy, Cu-Pb alloy and Cu-Sn-Pb alloy for changing load from 5 N to 50 N are 0.044, 0.028, 0.053 and 0.047, respectively. COF is usually considered to be a constant value for a particular tribological environment irrespective of normal loading conditions. But, the present study has revealed that COF values can vary with the rise of normal loads for all four copper based materials, which also agrees with the behavior of Molybdenum Disulfide as seen by Karpe 1965 [30]. It confirms that the COF values are influenced by the normal load; however, the influence level for comparatively higher load is negligible.

3.5. Microstructure Evolution

The surface micrographs of all four sample materials taken without etching before and after wear tests under dry sliding conditions are presented in Fig. 7. Etching was avoided in taking the microstructures to reveal the real condition of the surface without dropping any loosely held particle after frictional wear. Microstructures of pure Cu, high Cu-Sn alloy, high Cu-Pb alloy and SnPb-solder affected Cu taken before the wear test are shown in the first column. These micrographs indicate moderately smooth surfaces with regular asperities and exhibit no symptom of any plastic deformation or drawing. They show only some scratches which might have remained after polishing with the SiC paper during the sample preparation stage to carry out the wear tests.

Micrographs of the second column taken immediately after the wear test signpost many irregular asperities of the worn-out surfaces after sliding at dry condition. Different categories of large wear particles, oxide debris and particles, and the deep grooves parallel to the sliding direction are observed in these micrographs for all four sample materials. Moreover, plastic deformation and many large cracks can be detected here. The wear scars and fragments demonstrate the wear mechanisms of adhesive integration with abrasive behavior as well as delamination and oxidation wear.

The micrographs of debris produced from pure Cu, high Cu-Sn alloy, high Cu-Pb alloy and SnPb-solder affected Cu after dry sliding are shown in Fig. 8. As seen in Fig. 8 (a), debris of Cu is of fine grains with small size distribution but not homogeneous. Figure 9 (b) indicates that Cu-Sn debris is small but irregular in size and shape. Figures 9(c) and 9(d) show comparatively larger flake like debris of high Cu-Pb alloy and SnPb-solder affected Cu. However, some fine particles are also evident amongst the coarse debris which might be indicating the slip and twining effects during dry sliding. As a whole, no firm relation has been observed between the size of debris and the wear rate or COF of the four sample materials FE-SEM images of the worn-out surfaces of pure

Cu, high Cu-Sn alloy, high Cu-Pb alloy and SnPb-solder affected Cu after the sliding period of 90 minutes covering the sliding distance of 2772 m at the applied pressure of 1.02 MPa (Load = 20 N) and sliding speed of 0.513 ms^{-1} are presented in Fig. 9. In the case of pure Cu as shown in Fig. 9(a), the severity of roughness along with the grooves, scars and adhesions are noticed in the sliding direction, which indicate that the sliding of hard counter surface of stainless steel over the softer surface of the copper matrix has caused the micro-cutting through rubbing but in an irregular manner. Figure 9 (b) depicts the less severity of wear for high Cu-Sn alloy than that of pure Cu. However, adhesion of displaced ribbed particles is noticed. Figure 9 (c) indicates the removal of flakes from high Cu-Pb alloy at larger scales which have left the surface comparatively smoother than that of pure Cu or high Cu-Sn alloy. In FE-SEM image of SnPb-solder affected Cu shown in Fig. 9 (d), the combined effect of Sn and Pb inclusion in Cu gets elucidated on wear behavior through the presence of intermetallic large flakes which result in its moderate wear rate as well as COF in dry sliding condition.

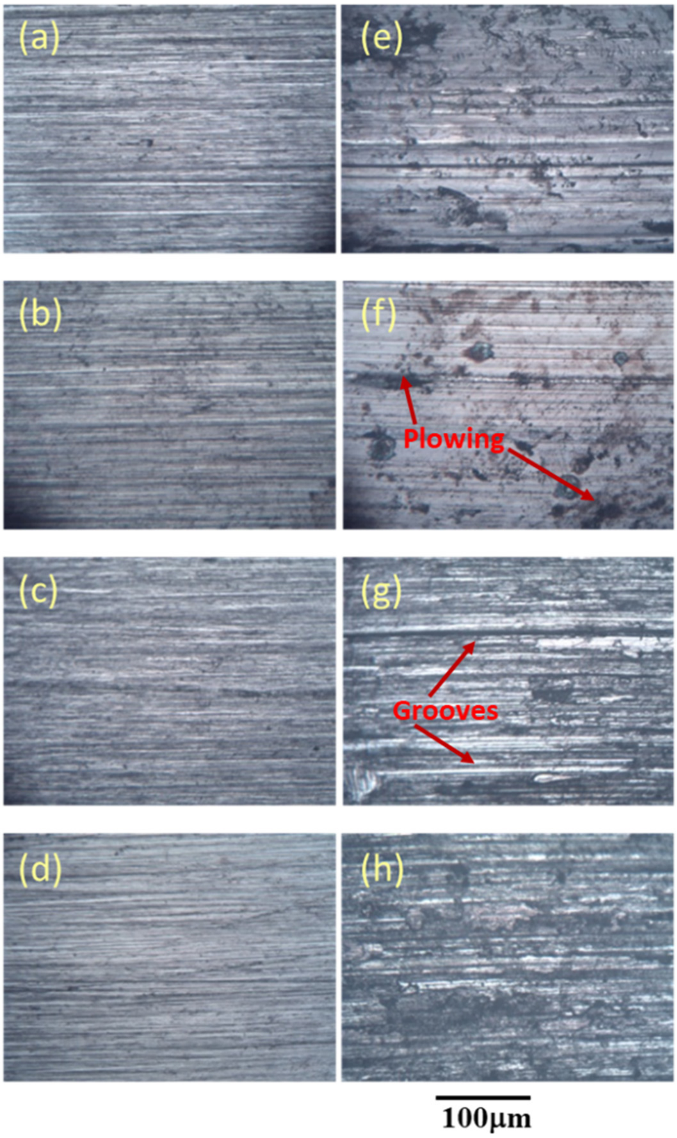

Fig. 7. Optical micrographs before wear and after the sliding distance of 2772 m at applied pressure of 1.02 MPa and sliding speed of 0.513 ms^{-1}: (a) Cu before wear, (b) Cu-Sn alloy before wear, (c) Cu-Pb alloy before wear, (d) Cu-Sn-Pb alloy before wear (e) Cu after sliding wear, (f) Cu-Sn alloy after sliding wear, (g) Cu-Pb alloy after sliding wear, (h) Cu-Sn-Pb alloy after sliding wear.

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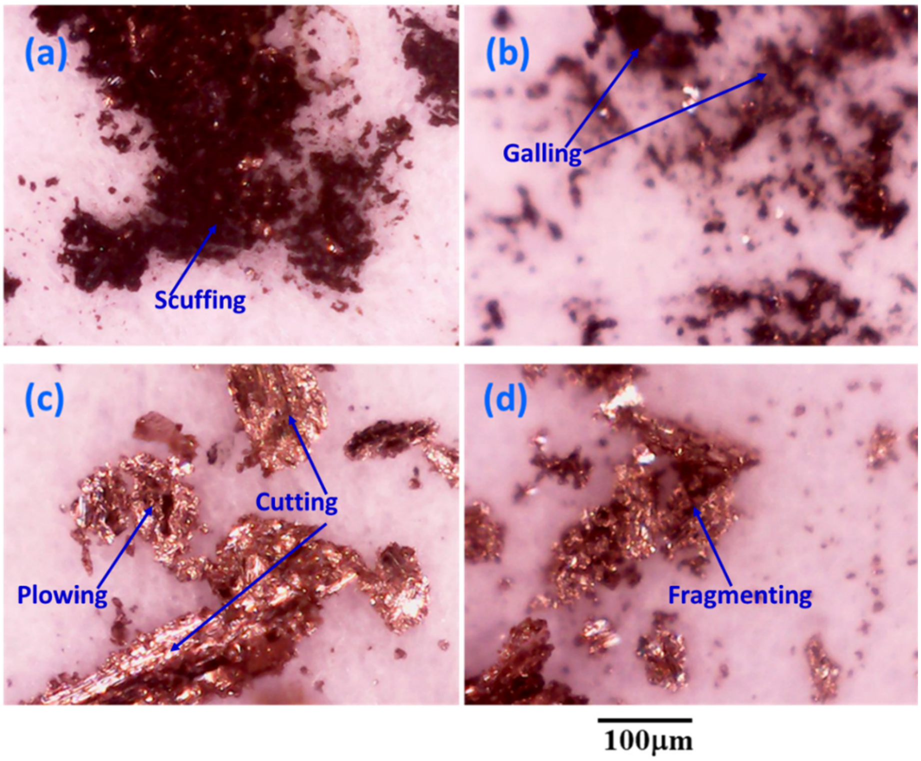

Fig. 8. Optical micrograph of the debris of experimental alloys generated during wear experiment with applied pressure of 1.02 MPa (Load = 20 N) and sliding speed of 0.513 ms^{-1} at dry sliding condition: (a) Cu, (b) Cu-Sn alloy, (c) Cu-Pb alloy and (d) Cu-Sn-Pb alloy.

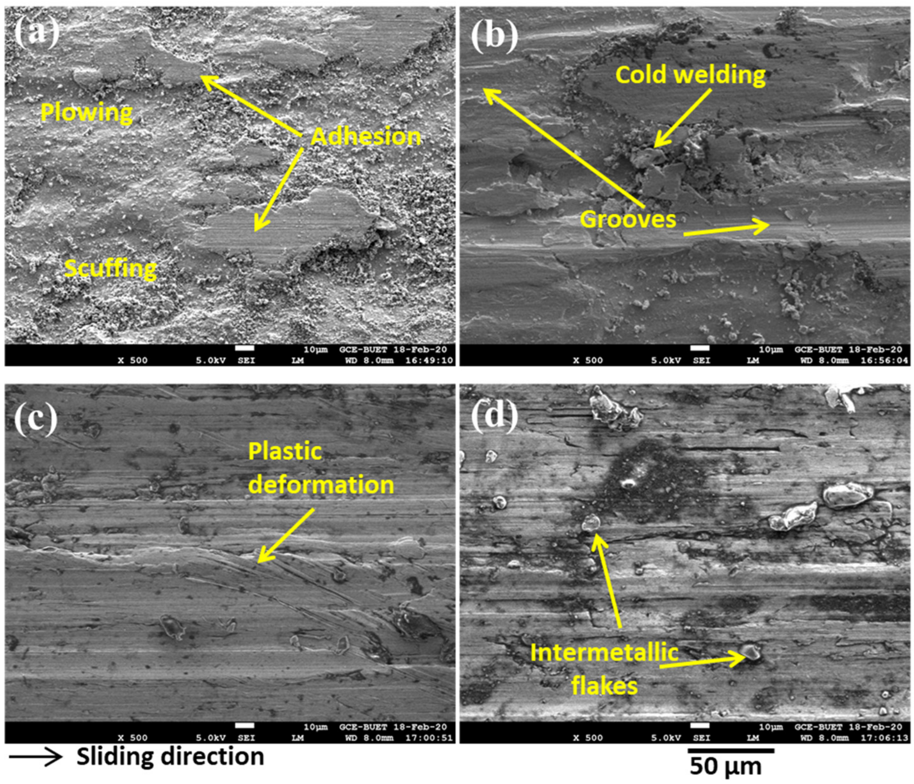

Fig. 9. SEM images of worn surfaces after the sliding distance of 2772 m at the applied pressure of 1.02 MPa (Load = 20 N) and sliding speed of 0.513 ms^{-1} at dry sliding condition while the arrow placed at the bottom of the figure indicates the sliding direction: (a) Cu, (b) Cu-Sn, (c) Cu-Pb and (d) Cu-Sn-Pb alloys.

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4. CONCLUSIONS

Wear behavior studied for pure Cu, high Cu-Sn alloy, high Cu-Pb alloy and SnPb-solder affected Cu in dry sliding condition provides the following concluding remarks:

a) Presence of small amount of Sn increased the hardness and improved the wear resistance of Cu based material to a significant level, while a similar amount of Pb in Cu reduced the hardness but increased the wear resistance. Thermal ageing at elevated temperature reduced the hardness for all four samples.
b) 'The bigger the hardness value the better the wear resistance' matched partly with the results of pure Cu, high Cu-Sn alloy and high Cu-Sn-Pb alloy. But Cu-Pb alloy exhibited considerable high wear resistance even with lower hardness values than of pure Cu.
c) COF values of all samples showed non-linear gradual increasing trends at the initial stage and after a certain sliding distance reached to some steady-state level. The highest COF was found for high Cu-Pb alloy amongst four sample materials over the entire sliding distance, whereas the lowest COF was found for high Cu-Sn alloy. The SnPb-solder affected Cu remained in between them with the maximum COF value of 0.533.
d) Micrographs using OEM and SEM gave indications of adhesion wear mechanism along with abrasion for all four high Cu based materials in dry sliding condition. Moreover, Cu-Sn alloy and Cu-Sn-Pb alloy indicated the formation of some intermetallic compounds after dry sliding.

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