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A Comparative Study on Wear Properties of Highly Conductive Materials Commercially Pure Al and Cu

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Keywords:
Conductive material; Friction; Micrographs; SEM; Wear rate; Worn surfaces.

Abstract
A comparative study has been carried out on the wear behavior of commercially pure aluminium and copper of highly used conductive materials under dry sliding environment. Wear tests have been conducted using a standard pin-on-disk apparatus where Al and Cu are treated as pin samples and stainless steel as disc. An applied load of 10N is used for both specimens where the calculated contact stress is active at 0.51 MPa. Furthermore, different loads ranging from 5 to 30 N are used to investigate the other tests. The sliding velocity is considered 0.64 m/s and the sliding distance varies between 150m-3500m. The worn surfaces of the samples before and after wear are analyzed using both optical and scanning electron microscopy. The experimental results show that the wear rate of Al is three and a half times higher by weight and eleven and a half times higher by volume than that of Cu due to its inferior physical and mechanical properties. In addition the coefficient of friction of Al is 1.2 times higher than that of Cu. The worn surfaces under dry sliding condition, Al exhibits higher abrasive wear along with plastic deformation due to thermal softening as Cu has better strength compared to Al. Nevertheless, considering the economic factors and its weight, Al offers better results.

1. Introduction

Copper, iron, gold, aluminum, and silver are some of the metals that carry heat and electricity the best (Tehrani, 2021). Due to their low resistance and great conductivity, copper and aluminum are most often employed as the electrical conductors in electrical cables (Cui, *et al.*, 2017). These metals have distinct qualities that make them valuable for a variety of applications in addition to being ductile and somewhat corrosion-resistant. Major uses of these elements are in the sector of construction, packaging, electrical industry, transportation, equipment manufacturing, consumer goods and metallurgy as discussed briefly in ASM Handbook (1990). Wear characteristics of all elements are very important. Wear is the overall loss of material from a surface caused by mechanical processes such as contact with solid, liquid, or gaseous entities or relative body motion between bodies. It happens as a result of the plastic displacement of the surface and near-

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surface material as well as the dissociation of wear debris-forming particles. The range of the particle size is millimeters to nanometers (Akchurin *et al.*, 2016; Choudhry, *et al.*, 2022).

Although wear particles can result in mechanical damage, there are times when the side effects are far more significant. For example, wear during joint replacement can trigger an autoimmune response, leading to long-term joint failure (MacQuarrie *et al.*, 2004). Surface wear relies on a number of things like surface geometry, loading strength and frequency, weather characteristics and mechanical together with thermal and metallurgical properties of the material (Bhadauria et *al.*, 2020).

The choice of material for the marine and aerospace industries is of paramount importance. The materials used must have high hardness, formability, ductility, elasticity, and toughness, as well as low density and brittleness. Non-ferrous metals – For light loads, Al, Cu and their alloys are used as gear materials. Pure Al and Cu have poor wear resistance, which limits their use in various industrial applications. Improvements in the strength and wear properties of pure Al and Cu can be achieved by various methods, including the preparation of composites of them (Bharathi & kumar, 2023; Ibrahim & Aal, 2020). In order to take the necessary measures to prevent a catastrophic failure, it is essential to have an early warning system for any wear-related issues. This would allow for the calculation of the useable remaining life and facilitate the development of maintenance measures (Gupta *et al.*, 2023).

The continuous increase in the use of these elements or their alloys and the constant demand to improve the performance of their manufacturing processes follow important trends that gradually advance the development of various research fields. The demand for more robust materials with superior properties continues to grow to meet the needs of new engineering applications. When a product reaches the end of its useful life, the material is recycled and reused. Aluminum and copper are particularly desirable materials because they can be reused several times without suffering significant quality loss. Recycling of these materials also offers considerable benefits in terms of cutting pollutants that harm the environment and energy use by 95% (Soo *et al.*, 2018; Wu *et al.*, 2017).

Nevertheless, there is a paucity of reports on the friction and wear behavior of commercially pure Al and Cu. The main intention of this research is to evaluate the wear performance of these two highly conductive commercially pure Al and Cu materials under the same sliding environment. Pin-on-disk wear testing is a common screening tool for quantifying the wear rate or performance of any material. Therefore, as part of the study, comparisons are carried out in terms of weight and volume, as well as wear rates in relation to the coefficient of friction. Cost advantages and material gravimetric analysis are also designed for best performance.

2. Material and Methods

Market available pure aluminium and copper were melted in a crucible made out of graphite using a fire from natural gaspit furnace. The analysis of the chemical composition of two cast samples was carried out using spectrochemical methods, as depicted in Table 1.

Table 1: Weight percentage chemical compositionof the two samples

	Zn	Pb	Sn	Fe	Ni	Al	Si	Mn	P	Cr	Cu
Al	0.0553	0.0065	0.0017	0.1806	0.0000	Bal	0.2101	0.0034	0.0001	0.0030	0.0022
Cu	0.0030	0.0005	0.0009	0.0005	0.0002	0.0003	0.0007	0.0002	0.0002	0.0001	Bal

Casting of Al and Cu was done at 750 °C and 1150 °C in a metal mould of mild steel, size was155 mm x 45 mm x 35 mm as preheated at 250 °C. The appropriate flux cover was used for preventing oxidation during melting. To prepare the mechanical and wear test samples, the cast alloy was first machined to a size of 145 x 40 x 32 mm to remove the oxide layer. Then the bar was cold rolled by 80% with a 10HP rolling mill where the 40 mm thick portion under gone to 8 mm. Cold rolled Al and Cu samples were machined into sizes of 14 mm in length and 5 mm in diameter for the wear study. Using the Digital Micro Vickers Hardness Tester with 1 kg load and 10 second dwell time, the hardness of both samples was determined.A sample size of 25x 25x 5 mm with finish surface was prepared for this measurement. Density was calculated considering the mass and volume of the two samples. Tensile testing was carried out according to ASTM specification in an Instron testing machine using 10^{-3}/s strain rate. The tensile sample's gauge length was taken to be 25 mm.The following ASTM standard G99-05 examined the frictional and wear behavior of those Al and Cu samples in a pin-on disc type wear apparatus (ASTM G99-05, 2010). The counter surface disc material was maid up of 309s stainless steel having hardness and roughness around HRB 95 and 0.40 µm respectively. Load of 10 N was used for all the samples in dry sliding condition where the calculated contact pressure active at 0.51 MPa. Moreover, load was incremented 5 to 30 N in other experiments. During the test, the disc was rotated at 250 rpm on a track of 49 mm diameter at the sliding speed of 0.64 m/s with variable sliding distances ranging from 150 m to 3500 m. The ambient conditions for all tests were 22 °C and 70% humidity and thedry sliding conditions were applied to the specimens.At least nine tests were completed for every one material. The measured weight loss (ΔW) and volume loss (ΔV) were used to calculate the wear rate, the distance run (*S.D.*) and the applied load (L) on the samples during the test (Kaiser & Kaiser, 2020). The track diameter and disc rotation speed were used to determine the sliding distances. For calculating the friction coefficient (μ), reading from the load cell (F) was normalized by applied load, L. The following equations express mathematical relationships for obtaining the weight loss, specific wear rate (S.W.R.)along with coefficient of friction:

$$\Delta W = W_{initial} - W_{final} \quad (1)$$

$$S.W.R. = \frac{\Delta W}{S.D. \times L} \quad (2)$$

$$\Delta V = V_{initial} - V_{final} \quad (3)$$

$$S.W.R. = \frac{\Delta V}{S.D. \times L} \quad (4)$$

$$\mu = \frac{F}{L} \quad (5)$$

The samples microstructure were observed using a Versamet-II-Microscope and conventional metallographic methods. Ultra-high-resolution JEOL scanning electron microscope with an energy dispersive X-ray analyzer (Model: Link AN - 10000) attached was used for the SEM investigation and EDX analysis. Before being polished with alumina. Keller's reagent was used to chemically etch aluminum, and the conventional 1:1 ratio of ammonium hydroxide and hydrogen peroxide was used to chemically etch copper. Figure 1 displays some images of the experimental setup, counter disc, and prepared sample.

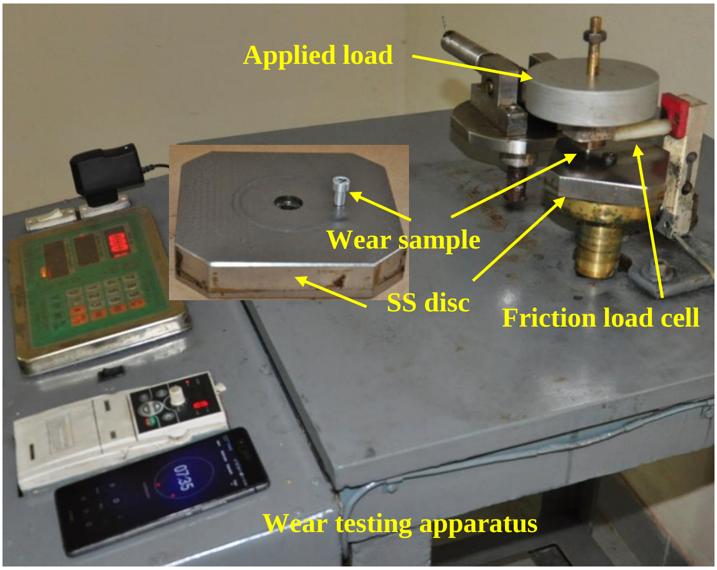

Figure 1: Representation of a wear testing setup with a wear sample and a stainless steel friction disc.

3. Results and Discussion

3.1 Physical and Mechanical Properties

Experimental values of physical and mechanical characteristics,including density, hardness, tensile strength and elongation of both commercially pure highly conductive Al and Cu are plotted through the bar chart in Figure 2. From the chart it may be supposed that the density of both Al and Cu are fully complying with well established results. Some deviation is observed due to presents of different impurities due to melting. The chemical composition defined withinside the experimental section in Table 1 showed that each component contains trace amounts of foreign materials such as Fe, Si, Ni, Cu, Mn, and Cr that come from the melting surroundings of refractory linings of furnaces, ladles, furnaces or launders. In case of micro hardness, both Al and Cu display relatively higher values as these are 80% deformed conditions.Cold deformed samples consists of additional dislocations inside the material which makes more strengthen the material. In addition, trace impurities form various intermetallicsthat increase strength somewhat (Kaiser, 2020; Ovalle *et al.*, 2023).

Similar behavior also displayed in case of tensile strength. The percentages of elongation also reflected by showing lower values for the deformation. At a glance, it is observed from the chart that all the properties like density, microhardness, ultimate tensile strength and the percentages elongation of break of Al are lower than those of Cu (Kazanas, 1979).

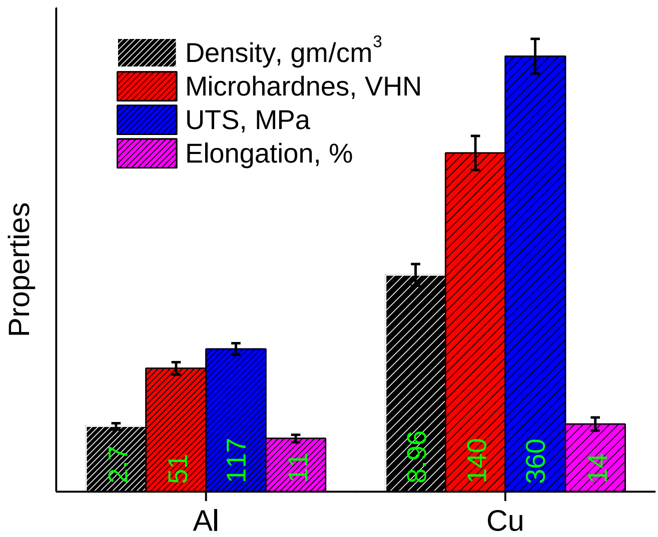

Figure 2: Physical and Mechanical characteristicsof commercially pure Al and Cu.

3.2 Wear Behaviour

With a constant pressure of 10 N or 0.51 MPa and a velocity of 0.64 m/s under dry sliding conditions, the wear rate in terms of weight as a function of sliding distance for both Al and Cu is shown in Figure 3. At the entire distance of traveling the wear rate is always higher for Al compare to Cu. The wear rate normally of a material under dry sliding situation depends on it's density and hardness.When lumps at contact locations created by plastic deformation are removed, these results may be explained. It is already explained by the Archard's theory that wear rate inversely proportional to the hardness of the material (Archard, 1953). It is clear that the wear rate of both materials increases with increasing distance.The wear rate increasing can be attributed to the frictional heat and material softening due to the long-term close contact between the two mating surfaces. Thermal softening is caused by too much pressure and temperature onthe materials and it is also time dependent. Thus, it occurs in a superior wayif dry sliding is continued for prolonged moment in time (Khan & Kaiser, 2023; Totten, 1992). In addition, in the wear test, the formation of an intermediate oxide layer between the mating surfaces is also one of the possible reasons for improved wear resistance. As a result of long journey of wear test, there is a tendency to constant of the wear rate due to the creation of wide oxide film. Then these films control the rate of wear of the materials.

When the wear rates of the two materials are express in terms of volume deviation of this property moves higher. The results are plotted in the Figure 4, which is clealy indicated this senario. It is because of the high difference of density of Al as it is 3.3 times lower than that of Cu.

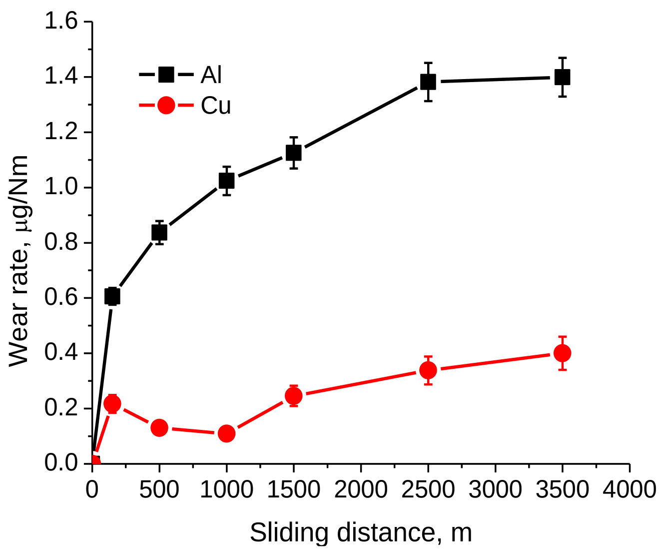

Figure 3: Distinction of the wear rate of Al and Cu in terms of weight with sliding distanc

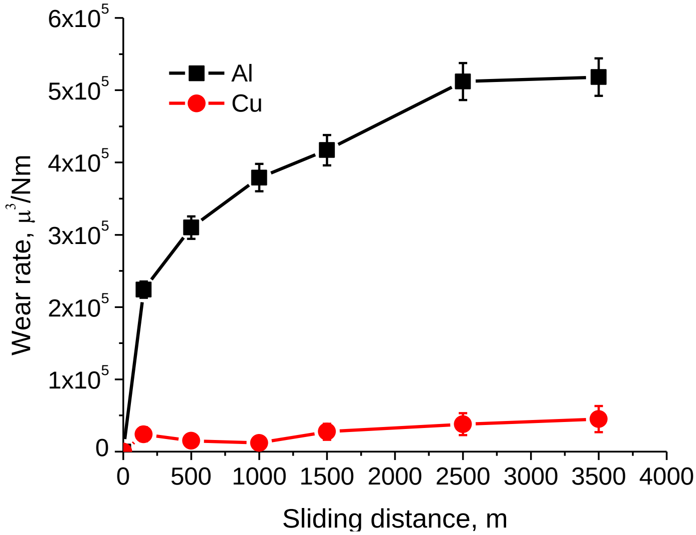

Figure 4: Distinction of the wear rate of Al and Cu in terms of volume with sliding distance.

Figure 5 depicts influences on frictional force at various sliding distances for both Al and Cu under the aforementioned sliding condition.However, the frictional coefficient is relatively lower for Cu sample than that of Al.

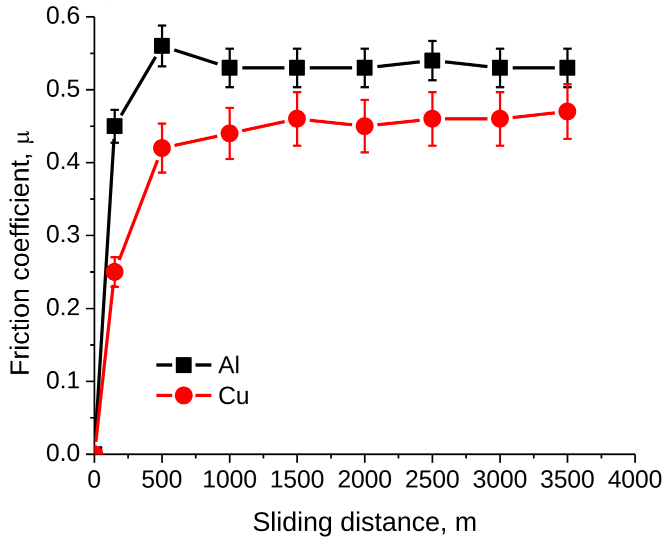

Figure 5: Friction coefficients for Al and Cu vary depending on the sliding distance

Decrease in frictional force can be attributed to better hardness and strength, as the low plastic deformation of the material at real contact areas may lead to the lack in friction coefficient (Moore & Tegart, 1952). According to earlier investigations, a localized adhesion of the worn debris to the Al surface is to blame for the increased coefficient of friction (Totten, 1992). The development of an intermediate oxide-rich layer between mating surfaces, which serves as a solid lubricant, is another factor (Malleswararao *et al*., 2020). At the initial stage the friction coefficient of the sample increases to a peak value followed by a gradual steady state value. As initially the surfaces in contact are comparatively rougher, the coefficient of friction is not steady in the beginning. Once they make the ideal connection, the result becomes nearly constant in value. Figure 6 shows the deviation in friction coefficient of both Al and Cu samples during dry sliding under different loads. The results in the figure suggested that decrease in friction coefficient might be related to the development of oxide layers. The driving force behind an increase in oxidation is an increase in temperature between the disc and pin surfaces as a result of the increasing load.Again the temperature makes the materials soften as a result coefficient of friction increases. As the lower hardness shows the higher coefficient of friction. The scatting values are a result of two opposing effects. It appears that the first effect is larger than the second, and the coefficient of friction decreases as a result (Totten, 1992).

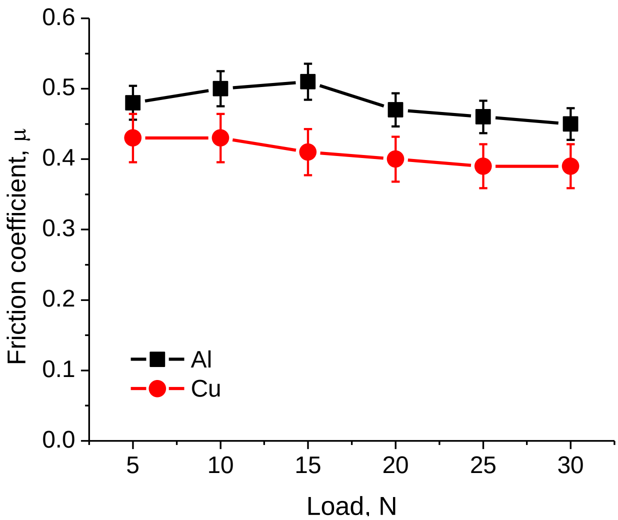

Figure 6: Deviation of friction coefficient of Al and Cu with a load applied.

3.3 Optical Microscopy

The Figure 7 displays the worn surfaces for commercially pure Al and Cu both before and after the wear test at a distance of 3500 m, sliding velocity 0.64 m/s and pressure 0.51 MPa. Prior to the wear test, polished Al and Cu samples have surfaces that are reasonably smooth compared to the others and don't show any signs of plastic deformation or drawing. They have some scratches, which might be the result of surface preparationthroughsilicon emery paper. This type of microstructure cannot provide adequate information without etchant. When both materials are tested under dry sliding conditions, numerous big wear particles, oxide debris, and particles in the same plane as the sliding motion are displayed in the picture.

Additionally, the plastic deformation and several significant fissures can be seen (Ahmed & Rahman, 2021).

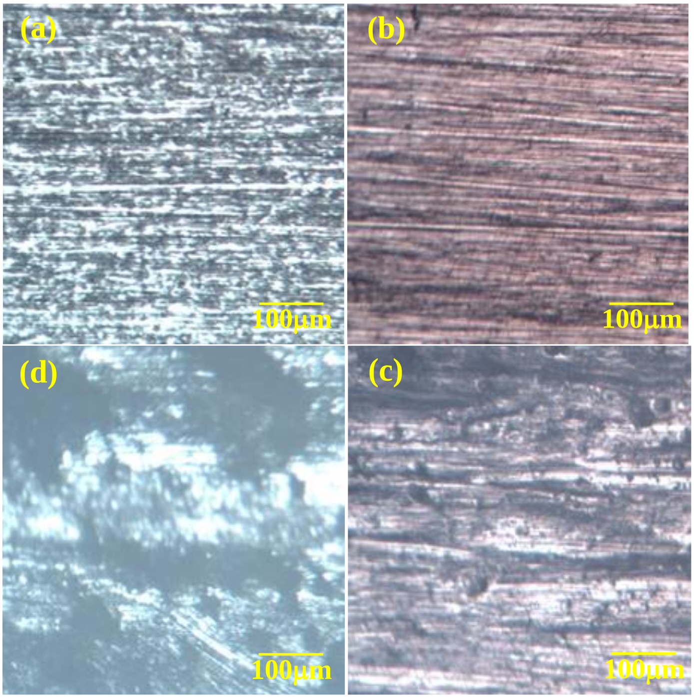

Figure 7: Before-and-after optical images of worn surfaces (a) Al, (b) Cu, and (c) Al, (d) Cu

3.4 Scanning Electron Microscopy

Just to make sure the SEM images as well as the EDX spectra are put in to show in Figure 8 of 80% cold deformed commercially pure Al and Cu. The microstructures of both the samples are mainly composed of α-Al in case of Al sample and α-Cu in case of Cu along with tiny amount of intermetallic phases (Kaiser, 2021; Rahman *et al.*, 2021). During casting a trace amount of impurities are accumulated with these elements which formed these intermetallics. The consequent EDX of the experimental samples confirms weight percentage are in this area of Al sample, 99.35% Al, 0.53% Si, 0.12 Sn, 0.02% Fe and Cu sample is 98.54% Cu, 0.83% Sn, 0.59% Pb, respectively. From the analysis it can be claimed that it obeys the spectrochemical analysis as presented in Table 1.

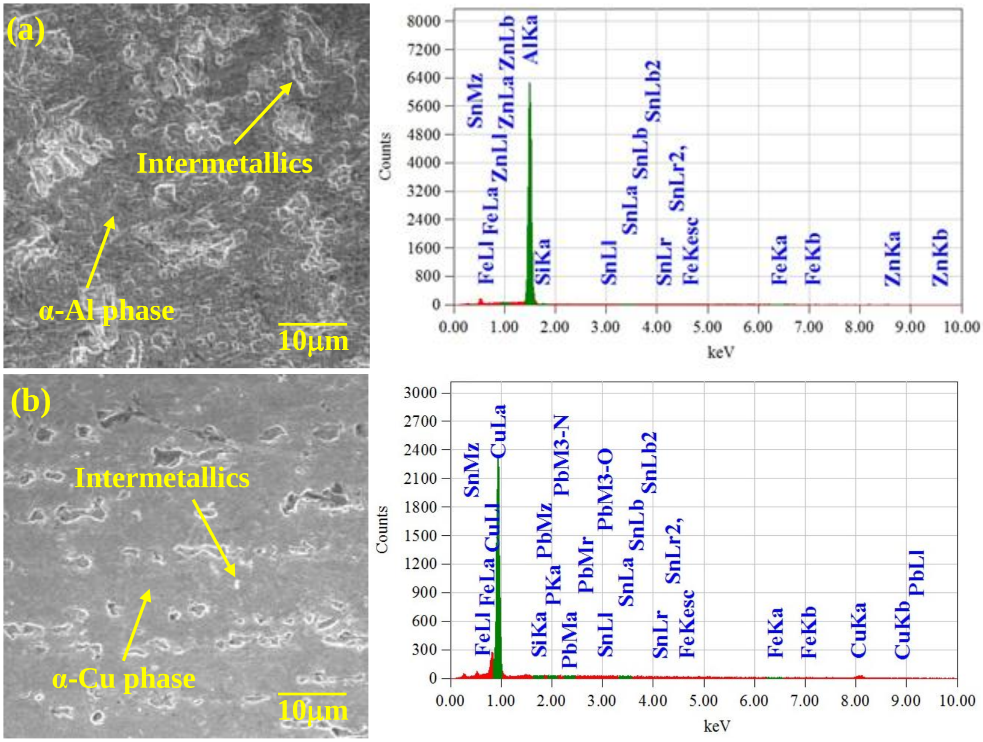

Figure 8: SEM in addition to EDX spectra of the experimental samples(a) Al and (b) Cu

SEM microphotographs of experimental Al and Cu after wear, at a distance of 3500 m are presented in Figure 9. It is used a sliding velocity of 0.64 m/s and an applied pressure of 0.51 MPa. It is unmistakably indicating abrasive wear in Al by exposing grooves brought on by the hard particles that became trapped abrading action (Figure 9a).

The extent of the roughness and the presence of grooves in the sliding direction show that the rubbing of the hard stainless steel counter surface against the softer Al matrix surface resulted in irregular micro-cutting (Wu *et al.*, 2020). Contact pressure drives the test specimen against the revolving disc in the case of Cu under the same wear environment, causing deformation, abrasion, surface fatigue, and adhesion at the sample's surface. (Figure 9b). Adhesion is the occurrence with the intention to attractive forces in close contact between two surfaces. As the motion proceeds, the junction created by the asperities on the contacting surfaces grows in size due to plastic deformation; finally, the junction shears due to its higher strength and higher temperature tolerance (Moshkovich *et al.*, 2014).

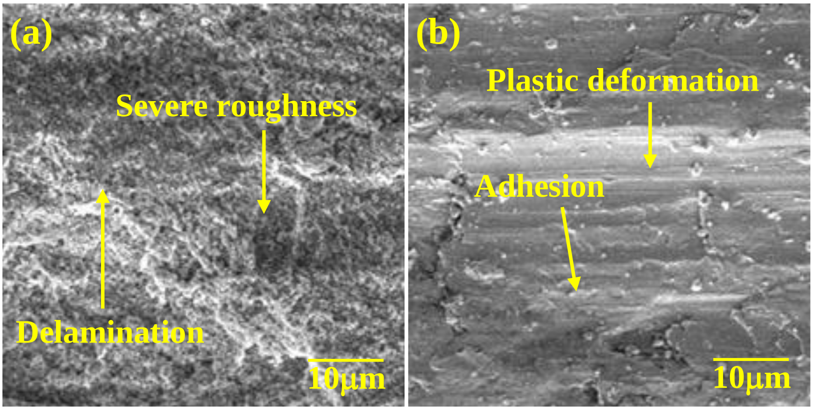

Figure 9: SEM images after the wear test of (a) Al and (b) Cuworn surfaces

The SEM images of two samples are displayed in Figure 10 to further explain the mode of fracture under tensile loading. Because Al has an FCC structure and is ductile even at low temperatures, ductility is the primary fracture mode in both specimens. The flat surfaces of the specimen halves after fracture serve as evidence that the ductile fracture occurred in a transgranular manner. During a tension experiment, void coalescence of a polycrystalline material causes this kind of fracture. Because of its higher density and FCC structure, Cu has smaller grains that have a higher grain boundary fraction in the same volume. On the fracture surface, numerous micro-voids are seen. For the Cu sample, the cavity size is also smaller. During the tensile deformation process, grain boundary sliding and pile-up are caused by an increase in grain boundary fraction and a concentration of stress near the grain boundary, which causes micro-voids to form on the fracture surface (Beevers & Honeycombe, 1962; Chen *et al.*, 2019).

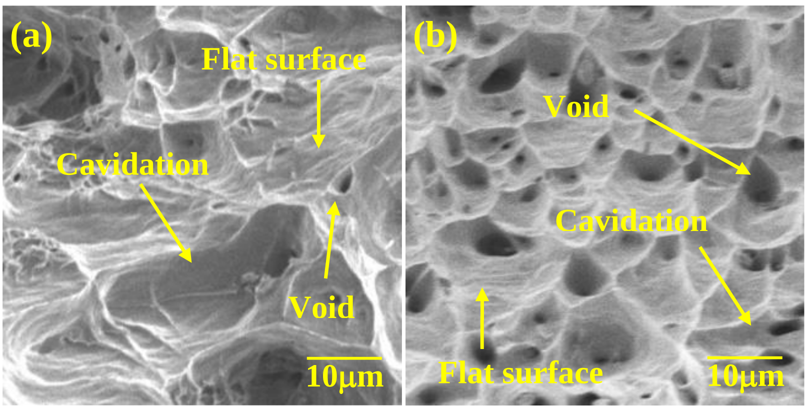

Figure 10:Fracture surfaces observed through SEM images of the of 80% cold deformed samples (a) Al and (b) Cu.

4. Conclusion

This study investigated the wear properties and made a comparison in terms of weight, volume and cost of highly conductive materials, Al and Cu. The study's findings allow for the following conclusions.

The specific wear rate of both aluminium and copper increase with sliding distance at dry sliding condition due to thermal softeningas they are heavily cold deformed. After a long gurney of wear rate tents to move the constant due to the formation of thick oxide film since it control the wear of materials.

Due to its lower physical and mechanical properties, the average wear rate for Al is 1.4 μg/Nm by weight and for Cu is 0.4 μg/Nm, which is 3.5 times higher for Al than for Cu. Here again, the wear rate of Al is $0.518\mu^3$/Nm, and that of Cu is $0.045\mu^3$/Nm, which is 11.5 times that of Cu in terms of volume.

The average friction coefficient under dry sliding conditions is 0.55 for Al and 0.45 for Cu, and owing to the inferior properties of Al, the coefficient of friction for Al is 1.2 times that of Cu.

Worn surfaces those are in dry sliding condition, Al is found with higher abrasive wear and plastic deformation due to thermal softening since its lower strength during wear compared to Cu.

The price of aluminum per kg is $2.0 and the price of copper is $8.0. From a financial perspective, the loss of Al is less than that of Cu. This is because the wear rate is 3.5 times higher than that of copper, even though the price of aluminum is 4 times lower. Considering the weight of the material, Al is more useful because it is light.

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Conflict of interest

Regarding the publication of this work, the author declares that there are no potential conflicts of interest. In addition, the author has firsthand knowledge of all ethical issues, such as plagiarism, informed consent, misconduct, data fabrication or falsification, duplicate publication or submission and redundancy.

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