Wear resistance of Cu–18 vol.% Nb (P/M) composites

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Abstract

Friction and wear behavior of copper matrix composites reinforced by unidirectional Nb fibers were explored using both pin-on-ring and pin on disk set-ups. Composite specimens were manufactured from a Cu–18 vol.% Nb powder mixture. Through various mechanical processes and heat treatments, this powder mixture was converted to a ‘ribbon-shaped Nb’ fiber reinforced copper composite with final average fiber thickness of about 10 nm and aspect ratio of about 30. The friction and wear properties of this composite were evaluated against gray cast iron with the hardness of 92 HRB. The effects of normal load, sliding speed and fiber orientation on the friction and wear of this composite were investigated. Steady state wear was observed upon formation of a thin film on the wear surface for all the specimens. This film formed due to the material transfer from the disk to the composite surface due to low ductility of the copper matrix. The wear rate was proportional to the sliding distance and normal load for all specimens, while specimens with fibers normal to the sliding surface showed the lowest wear rate. Moreover, the wear rate appeared to be an exponential function of the sliding speed. This was related to temperature rise at the interface of sliding surfaces and recovery of Cu matrix and possible breakage of the Nb fibers. Metallographic examination of Cu–Nb micro-fiber reinforced composite showed that when exposed to temperature greater than 600 °C, fibers start to break and spherodized. This phenomenon significantly reduces the strength of Cu–Nb composite and increases its wear rate. Some insight into the mechanisms of wear was obtained using optical and scanning electron microscopy and energy dispersive spectrometry analysis of the surface.

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1. Introduction

Combination of strength and high electrical/thermal conductivity offered by copper fiber reinforced composites has made them attractive for many applications such as high field magnet technology and electronic circuits [1–4]. Specifically, Cu matrix composites reinforced by Nb microfilaments have gained an exceptional interest among others due to their high specific strength and good electrical conductivity. These composites may be also used in design of electrical brushes, where their friction and wear properties are important design consideration. In general, metal matrix composites have enhanced wear resistance compared to un-reinforced alloys [5–9]. Various mechanisms contribute to the wear characteristics of fiber reinforced composites. The matrix material could be removed by adhesion, abrasion, and delamination, while the fibers could be removed by fiber pull out, fiber plowing, and interfacial failure [9,10]. A model for wear behavior of metal matrix composites was suggested by Nayeb-Hashemi et al. [10] which accounts for the contribution of these different wear mechanisms. The model was evaluated in conjunction with the wear test for studying the wear behavior of unidirectional graphite aluminum composite. It was concluded that in the absence of fiber pull out, the wear rate was approximately proportional to the normal load and the sliding distance. Cu–Nb composites differs from many conventional unidirectional metal matrix composites as (1) Nb fibers have a ribbon shape with an aspect ratio of about 30, (2) Nb fibers thickness is very small l–10 nm, (3) there is no chemical reaction between the Nb fiber and Cu matrix, and (4) the interfacial bond strength could be high due to the good adhesion between the copper matrix and Nb fibers with high aspect ratio. Due to the unconventional properties of Cu–Nb composites, fiber pull-out,
which is the most dominant wear mechanism in most composites, might not be significant [11–13]. On the other hand, since Nb fibers are at their elongation limit, loading of the composite may cause Nb fibers to fracture, but not necessarily to be pulled out. Furthermore, these composites lose their mechanical properties when exposed to temperature in excess of 500 °C [14]. The loss of mechanical properties has been attributed to the recovery of the significantly cold worked copper matrix which is developed during processing these composites and breakage and spheroidization of the Nb fibers.

There are commonly two methods to manufacture Cu–Nb composites. These are by uniform cooling a mixture of Cu–Nb from its liquid state (in situ method) and by powder metallurgy processing of a mixture of Cu and Nb powders (P/M). The powder metallurgy processed composites provides a much more uniform fiber distribution compared to the ‘in situ method’. Furthermore, manufacturing large size Cu–Nb composites is practical only by the powder metallurgy process due to the difficulties in maintaining uniform cooling process in the in situ process [14,15]. In powder metallurgy processing, the mixture of Cu and Nb powders is converted to Cu–Nb multi-filamentary reinforced composites via various mechanical processes and heat treatments. Fig. 1 shows a process diagram for converting the Cu–Nb powder to Cu–Nb multi-filamentary reinforced composites. Basic mechanical properties as well as the fatigue and fracture behavior of this composite were evaluated by Nayeb-Hashemi and Pourrahimi [1]. Some of the major mechanical properties of this composite are included in Table 1. Note that the ultimate tensile strength of Cu–18 vol.% Nb (P/M) composite is several times larger than that of the pure copper. While addition of Nb microfilaments highly enhances the mechanical properties of the copper matrix, it slightly reduces its electrical conductivity. The objective of this work is to study the wear behavior of Cu–Nb (P/M) by exploring the role of fiber orientation, sliding speed and applied normal load. In this study the volume fraction of Nb is kept constant and equal to 18% (Cu–18 vol.% Nb (P/M) composite). The tribological behavior of Cu–20 vol.% Nb composite produced by in situ method, evaluated by Liu et al. [11–13], is compared with the results of the current study.

Fig. 1. (A) Process flow diagram of P/M processing of Cu–Nb composites. (B) Sample of Cu–Nb powder mixture. (C) Deformation of Nb powder to ribbon shape cross-section fibers. (D) Multiple restacking of Cu–Nb multi-filamentary composite wire for developing a large size wire. See Ref. [1] for details.
Table 1
Mechanical properties of Cu–18 vol.% Nb (P/M) composite in the fiber direction
(\(E\) = Young’s modulus; \(\text{UTS}\) = ultimate tensile strength; \(K_{IC}\), mode I fracture toughness for crack direction normal to the fiber direction)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E)</td>
<td>113</td>
</tr>
<tr>
<td>Yield strength</td>
<td>820</td>
</tr>
<tr>
<td>(\text{UTS})</td>
<td>1035(^\text{a})</td>
</tr>
<tr>
<td>True fracture strain</td>
<td>0.4</td>
</tr>
<tr>
<td>(K_{IC})</td>
<td>23.4</td>
</tr>
</tbody>
</table>

\(^\text{a}\) The reported value of \(\text{UTS}\) is for intermediate industrial scale composites, which is used in the current study. For laboratory scale composites, \(\text{UTS} = 1.6\) GPa. See Ref. [14] for details.

2. Experimental investigations

To study the role of fiber orientation on the tribological behavior of Cu–18 vol.% Nb (P/M) composite, three types of specimens were prepared from the Cu–Nb composite wire with diameter of 3 mm, manufactured from Cu–Nb powder and using the processing method shown in Fig. 1 and described in [14]. The Cu–Nb wire used in preparing wear specimens were at the drawability limit of Nb (Nb microfilaments with the thickness of 5–10 nm). The wear specimens were categorized based on the composite fiber orientation relative to the wear surface and sliding direction (i) FNS: fibers normal to the sliding surface, (ii) FPS: fibers parallel to both sliding surface and sliding direction, (iii) FTS: fibers parallel to the sliding surface, but normal to the sliding direction (see Fig. 2A). In wear experiments on composites with fibers normal to the counter face (FNS), cylindrical specimens with diameter of 3 mm and height of 2 mm were used as a pin on the pin-on-ring setup. The specimen was glued to a SEM mount using a high strength adhesive. This method allowed us to mount and dismount this assembly easily in the wear test set-up. The specimens for FPS and FTS tests were rectangular specimens with the cross-sectional area of 3.3 mm × 2.14 mm and height of 2 mm. These specimens were prepared by placing a cylindrical Cu–Nb composite wire in an epoxy mount. The specimens were then grinded using 600 grit SiC paper and polished with 0.05 μm alumina powder in order to get a flat surface along the length of the wire composite. This procedure was repeated until two parallel flat surfaces were achieved. The epoxy was then resolved in acetone and the specimens were cleaned in an ultrasonic bath. The specimens were glued to SEM mounts prior to wear experiments.

The wear characteristics of three types of Cu–18 vol.% Nb (P/M) composite specimens were examined against gray cast iron disk with the diameter of 20 cm and thickness of 5 mm and hardness of 92 HRB. For the wear test, both pin-on-ring and pin on disk tribometers were employed. Fig. 2B shows a schematic diagram of the pin on the ring set-up. For the pin on ring setup, the specimens were in contact with the rotating cylindrical surface of the disk and for pin on disk set-up the specimens were in contact with the flat surface of the disk. Both, friction force and normal load were monitored continuously using a double flexi-

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Fig. 2. (A) Definition of fiber orientation. FNS: fibers are normal to the sliding (contact) plane, FPS: fibers are parallel both to the sliding plane and direction, FTS: fibers are parallel to the sliding plane and normal to the sliding direction. V and \(F_N\) denote the sliding speed and applied normal load, respectively. (B) Schematic diagram of the tribo-system. (C) Typical measured time histories of normal and horizontal (friction) forces.
ble arm with attached strain gages. The choice of the pin on ring set-up was based on desire not to trap wear particles between contact surfaces. Full bridge strain gage set-up was used to continuously monitor the friction force and normal load. The strain gages were calibrated prior to the wear experiments. In addition to the pin-on-ring setup some experiments were performed using pin on disk set-up. The choice of the experimental set-up did not affect the collected data. A typical time trace of experimentally measured normal and friction forces is shown in Fig. 2C. The friction force displays a trend of variation between two well-defined maximum and minimum as shown in Fig. 2C. A possible explanation for the variation of friction force observed in various experiments is provided by Cockerham et al. [16]. In this study, we evaluated the coefficient of kinetic friction based on the mean value of the maximum and minimum of the friction force measured during the stick-slip motion, as suggested by Bowden and Tabor [17]. The normal applied load was varied in the range of 1.96–6.87 N while the sliding speed was varied in the range of 0.15–2.3 m/s. The wear rate was evaluated by periodically halting the experiment and cleaning the specimen and measuring the weight of the specimen using a digital scale with accuracy of 0.1 mg. The surface of the specimens was examined both by using optical microscopy and a scanning electron microscope equipped with energy dispersive spectrometry (EDS) analysis at 100 kV to gain insight into the wear mechanisms.

3. Results and discussion

Fig. 3 shows optical microscopy images of FPS and FTS composite specimens and the gray cast iron counterpart after 1 h of wear test at the sliding speed and normal load of 1.1 m/s and 4.90 N, respectively. The optical microscopy shows the material transfer from the disk to the pin and from the pin to the cast iron counter face. The results showed that the steady state wear rate was achieved upon formation of thin layers at the sliding interface which composed of copper, Nb and cast iron particles. EDS analysis of the interface material of the pin confirmed the material transfer from the disk to the pin. This could be due to the burial of wear particles in copper matrix and transfer of the copper and Nb to the graphite regions in the cast iron. Table 2 shows the results of the EDS analysis for composite specimens with various fiber orientations. The formation of this thin film begins at early stage of the experiment. The film formed on the gray cast iron counterpart was mostly composed of copper with very little Nb particles. Since the copper matrix is relatively softer than the Nb fibers, it can be easily removed from the composite either by adhe-
The results show that the wear volume is proportional to the sliding distance.

Fig. 4 shows the variation of wear volume versus the sliding distance for specimens with different fiber orientations. In this set of experiments, the sliding speed and normal load were 1.9 m/s and 4.90 N, respectively. The specimen with FNS orientation had the highest level of wear resistance, followed by the specimens with FTS orientation. For the composite specimens with FNS orientation, the applied force does not induce significant shear stresses at the matrix/fiber interface, decreasing the probability of fiber fracture and the subsequent fiber pull out. These results are consistent with the results reported for in situ processed Cu–Nb composite [11,12]. The wear volume was proportional to the sliding distance in accordance with the classical wear theory. Furthermore, the results indicate the wear rate is proportional to sliding distance for various applied load, Fig. 5.

The effects of sliding speed on the friction and wear volume of Cu–Nb composites for all fiber orientations were investigated for sliding speed in the range of 1.2–2.3 m/s. The results indicate that the wear volume may not only depend on the sliding distance but may also be an exponential function of the sliding speed, Fig. 6. This may be due to development of localized high temperature at the interface of the pin and its counter face, which could lead to recovery of the Cu matrix from a significant cold work during manufacturing processing of the composite (wire drawing) and breakage and spheroidization of Nb fibers. Our previous study revealed that by exposing Cu–Nb composite to temperature in excess of 600 °C, the Nb fibers start to break and spheroidized resulting in loss of composite strength [14]. Since wear is inversely proportional to the strength of the material, the exponential increase in wear rate with increasing the sliding speed could be related to the increase in local temperature at higher sliding speed. This was further confirmed by observation of formation of Nb particles in a form of spheres on the wear surface. Fig. 7 shows fiber morphology prior to exposure of the composite specimen to high temperature and after its exposure to temperature greater than 600 °C. The results show that Nb fibers start to break and spheroidized after exposure to high temperature. We tried to measure the temperature at the interface of the pin and disk, however, no reliable data was obtained. The contact temperature was estimated through a simple energy balance relation \( W = mc \Delta T \), where \( W \) is the frictional work, \( m \) the specimen mass, \( c \) the specific heat and \( \Delta T \) is the temperature rise. Since our specimens were glued to the SEM mount with an adhesive with a very low conductivity, it can be assumed that the glued surface acts as an insulated surface. The heat transfer from the specimen to the disk at the contact point can also be neglected because of the oxidation. The heat transfer through convection is also negligible. Based on sliding distance of 100 m before any wear measurements, this simple calculations yields the temperature of more than 600 °C for the
Fig. 7. Longitudinal cross-sections of the 3 mm diameter Cu–Nb composite (A) at the final stage of manufacturing. (B) After one hour exposure to 950 °C showing fiber breakage and spheroidization.

We believe that contact surface temperature is greater than this estimated temperature. Therefore Cu matrix recovery and breakage and spheroidization of Nb fiber is a very likelihood at high sliding speed since it can be assumed that all frictional work is converted to heat to raise the specimen temperature. The effects of sliding speed have been also reported in other friction and wear experiments. For Cobalt-partially stabilized zirconia (PSZ) composites, the wear rate is shown to increase initially by increasing the sliding speed till a critical value and then decreases as the sliding speed further increases [18]. A completely opposite trend was observed for metal matrix graphite fiber composites [19]. These observations further emphasize the complex tribological behavior of fiber reinforced metal matrix composites, accentuating the need for further systematic studies.

The effect of normal load on the wear behavior of the composite was investigated for a set of specimens with fibers normal to the counter face. The results showed that for the range of applied normal load studied, the wear rate was proportional to the normal load, Fig. 8. These results are comparable with those reported for in situ processed composite with 20 vol.% Nb by Chen et al. [13]. Liu et al. [11] showed that the optimum volume percentage of Nb fibers for in situ processed Cu–Nb composites which leads to maximum wear resistance is ~20 vol.% which results in a wear rate ~2.5 times smaller than that of the pure copper. Similar qualitative observations regarding the effect of fiber volume fraction on the wear behavior of polymer matrix composites is reported in [20].

Fig. 9 presents the coefficient of friction of Cu–Nb composite specimens with different fiber orientations measured as a function of sliding time. The normal load in this set of experiment is 3.9 N and the results are presented for two sliding speeds, 0.15 and 0.35 m/s. The nominal values of coefficient of friction
for each composite specimen are also presented, which reveals a slight dependence on the fiber orientation. The FPS experiments have the highest coefficient of friction. Similar trends were observed for metal matrix graphite fiber composites by Eliezer [18]. Liu et al. [11,12] found that, FNS orientation had a higher friction coefficient than FPS orientation at low sliding speed. This was attributed to the greater energy dissipation required for orienting the normal filaments to the sliding direction towards the sliding direction. The influence of normal load on the coefficient of friction of Cu–Nb composites was also investigated. The coefficient of friction of FTS specimens was insensitive to the normal load in the range of 3–7 N, while it increased slightly for FNS and FPS specimens with increasing the normal load. In addition, the coefficient of friction of all specimens showed very little sensitivity to the sliding speed, which is consistent with observation in [11,12] for Cu–Nb in situ processed composites.

4. Conclusions

This study suggests that copper matrix composites reinforced by 18 vol.% Nb fibers not only offer high thermal/electrical conductivity and high specific strength, but also have a significantly enhanced wear resistance compared to the copper matrix. This unique material characteristic makes Cu–Nb composites an ideal material for many applications such as electrical brushes. The wear resistance of the unidirectional Nb–Cu composite depends on the orientation of fibers relative to the sliding surface and sliding direction. For all the fiber orientations considered, the wear volume was approximately proportional to the sliding distance in the range of applied normal load. This was in agreement with the classical wear theory for isotropic materials. However, the wear rate apparently was an exponential function of the sliding speed. This could be due to development of high temperature at the interface of pin and disk. The high temperature at the interface results in recovery of the Cu matrix and breakage of Nb fibers and its spheroidization, leading to loss of composite strength. The wear rate was lowest when fibers were normal to the wear surface. The wear rate of Cu–18 vol.% Nb powder metallurgy processed composite was comparable to the in situ processed Cu–20 vol.% Nb composite.

Steady state wear rate was developed upon formation of an interfacial layer at the interface of pin and disk after a short sliding distance. The interfacial layer consisted of material particles transferred from disk to the pin and from pin to the disk. In contrast to the wear rates, the friction coefficient was little sensitive to the normal load, sliding distance and sliding speed. The maximum friction coefficient was recorded for FSP specimens.

References