High current density copper-on-copper sliding electrical contacts at low sliding velocities

J.A. Bares a,+, N. Argibay b, N. Mauntler b, G.J. Dudder a, S.S. Perry a, G.R. Bourne a, W.G. Sawyer b

a Dept. of Materials Science and Engineering, University of Florida, Gainesville, FL 32611, USA
b Dept. of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32611, USA

ABSTRACT

Metal fiber brushes are of interest in many high current density applications due to their high conductivity and low wear rates in humid environments. The frictional properties and wear behavior of a copper fiber brush sliding against a copper counterface in humid environments under high current densities (180 A/cm²) were investigated at low sliding velocities (10 mm/s). A linear reciprocating tribometer integrated with a scanning white light interferometer was used to acquire volume loss measurements of the copper counterface. Counterface wear was found to be independent of both the direction of current flow and the presence of current. X-ray photoelectron spectroscopy (XPS) showed carbonate species in all wear tracks after testing in humidified carbon dioxide. Only slight differences in the relative amounts of oxide on the counterface wear tracks were observed. Effects of water adsorption on friction coefficient and contact resistance were studied by varying the temperature of the counterface while maintaining a constant ambient temperature and humidity in carbon dioxide and argon environments. As sample temperature increased above the ambient temperature, both friction coefficient and contact resistance increased. Friction coefficient was lower for the carbon dioxide environment, which may be related to the presence of the carbonate species in the wear track region.

1. Introduction

Many practical applications require low wear, low electrical loss brushes for current collection [1,2]. High sliding velocities and high current densities are typically used to achieve maximum power transfer and efficiency in these applications. A number of prospective brush materials have been compared in a review by McNab [3]. Monolithic graphite and metal–graphite composite brushes, while sufficient for low current density applications, have high contact resistance and are inefficient at high current densities. Liquid metal current collectors, which use sodium potassium and low-melting point bismuth-based alloys, can operate at higher current densities and higher sliding speeds than solid brushes, but concerns exist over chemical compatibility and handling of highly reactive liquid metals [4–6]. Current high power electric motor research efforts have focused on lightly loaded metal fiber brushes, generally in humid non-air environments [7–13].

Humidified carbon dioxide environments have previously been shown to be effective at reducing friction and wear of metal–graphite composite brushes [14–16]. In high current applications, graphite-containing brushes generate large temperature rises because of Ohmic heating. Compared to metal–graphite composite brushes, metal fiber brushes have much lower bulk resistivities. Metal fiber brushes provide a large number of independent contact spots through which current can flow, whereas monolithic brushes are limited to a small number of contact spots randomly distributed across the surface. Successful implementation of humidified carbon dioxide environments with metal–graphite brushes led to its use with metal fiber brushes. Non-oxidizing environments, such as carbon dioxide, prevent excessive oxidation of freshly exposed material at the sliding interface, which reduces contact resistance and improves electrical efficiency. Water adsorption onto the sliding surfaces acts as a lubricating boundary layer, limiting adhesion in the metal–on-metal contact.

In sliding electrical contact systems, it has commonly been observed that positively biased brushes (electron flow impinging on brush surface) wear at a higher rate than negatively biased brushes (electron flow leaving brush surface) [17–21]. Differing theories exist on the origin of the brush wear rate anisotropy. Boyer et al. [17] hypothesized that brush wear was electrochemically driven—the direction of the electric field activated oxidation at the positive brush while oxidation at the negative brush was inhibited. Paulmier et al. [19] concluded that polarity effects were related to oxidation rates, based on Auger electron spectroscopy results which showed higher concentrations of oxygen on the positively biased copper surface. Lee [22] proposed that the adsorption of
polar molecules, such as water, from the environment was influenced by the direction of current flow, and differences in adsorption behavior may account for differences in friction, wear, and voltage drop.

A majority of existing data has focused extensively on brush wear. This study attempted to characterize rotor surface evolution by examining friction, wear, and contact resistance of copper flats in reciprocating sliding contact with a copper fiber brush in humidified environments.

2. Experimental procedure

A copper fiber brush on copper flat sliding contact was investigated in a linear reciprocating test geometry under a humidified carbon dioxide environment. The tribometer was placed inside an acrylic environment chamber, which allowed for precise control of operating environment. Carbon dioxide gas was bubbled through a heated water bath to create a high humidity operating environment. A humidity meter and oxygen meter were used to continuously monitor water and oxygen levels inside the chamber. The test environment was maintained at approximately 95% relative humidity and less than 100 ppm of oxygen. The copper fiber brush consisted of a wire mesh bundled into a 3-mm diameter cylinder and soldered at one end. The diameter of an individual brush fiber was approximately 60 \(\mu\)m. The copper counterface was polished to a final surface roughness of less than 50 nm. After polishing, the counterface was cleaned by sonicating twice each in methylene chloride, acetone, and methanol for 5 min apiece, using fresh solvent for each cleaning. The counterface was bolted to a copper sample holder, as depicted in Fig. 1, and the sample holder assembly was clamped to a copper cooling stage. A programmable temperature controlled water circulator supplied water to the stage to set the sample temperature. A thermocouple was attached to the sample holder to measure sample temperature. Unless specified otherwise, the sample temperature was maintained approximately 1–2 °C below the ambient temperature.

Current was sourced through the brush/counterface contact using a 0–100 A, 0–10 V DC power supply. Voltage measurement and current supply wires were soldered to the copper wire brush, and the complementary voltage and current wires were bolted to the copper sample holder to complete the electrical circuit. As shown in Fig. 1, the brush holder was attached to a six-channel multi-axis load cell (JR3, Inc.; 100 N maximum load) used to measure both the normal forces and frictional forces. The load cell was separated from the electrical contact by an insulating polyetheretherketone bracket, and the entire load cell assembly was mounted to a double leaf spring flexure. Normal load was applied by adjusting the vertical stage micrometer, causing the leaf spring flexure to deflect. The linear stage was driven by a stepper motor with a speed range of 0–140 mm/s and a positioning accuracy of 1.5 \(\mu\)m. Testing conditions were as follows:

- normal load = 1.0 N (nominal pressure of 1.4 \(\times\) 10^5 Pa),
- current density = 180 A/cm^2,
- sliding velocity = 10 mm/s and
- track length = 5 mm.

A schematic of the counterface wear track is shown in Fig. 2 with an example of the velocity profile for a single cycle. Brief periods of acceleration and deceleration occurred at the end points of the track. Only data from the steady-state velocity regime was analyzed. Current flow from the counterface to the brush was identified as the positive counterface condition; current flow from the brush to the counterface was identified as the negative counterface condition. Samples were run-in under no-current for 15,000 cycles. Current was cycled in increments of 10,000 cycles, up to 45,000 cycles. Testing was then repeated with current flow in the opposite direction.
Fig. 2. Velocity profile for a single reciprocation cycle (top) in relation to a schematic drawing of the top view of the counterface wear track (bottom). Track length was 5 mm in the sliding direction. Overlapping non-contact interferometry measurements, denoted by the shaded region, were made at the midpoint of the track, transverse to the sliding direction.

The tribometer was integrated with a scanning white light interferometer (SWLI; Zygo NewView 5032) to make interrupted topography measurements of the counterface wear track after every change in current. A representative section at the midpoint of the wear track was scanned perpendicular to the sliding direction, as indicated by the shaded region in Fig. 2. Volume loss was calculated by subtracting the discretized surface height data of the wear track profiles from the profile of the original polished surface. Wear track height values greater than the height of the original surface were excluded from volume calculations because of the inability to distinguish brush wear debris from counterface material pileup. Wear track regions were characterized using scanning electron microscopy (SEM) and focused ion beam (FIB) milling to create transverse cross sections of the near-surface region within the wear tracks.

A set of three samples were dedicated specifically to X-ray photoelectron spectroscopy (XPS) analysis. The copper counterface was bolted to a custom designed stainless steel XPS platen, and the assembly was clamped to the cooling stage. The XPS platen underwent the same cleaning procedure as previously detailed for the copper counterface. The no-current, positive counterface, and negative counterface conditions were investigated; normal load, current density, sliding velocity, and track length remained the same. After completion of wear testing, the counterface/platen assembly was removed from the test chamber and transported under dry nitrogen to the XPS chamber for analysis.

Effects of sample temperature on friction coefficient and contact resistance were studied, under the same operating conditions as previously described, in humidified carbon dioxide and humidified argon environments. The difference in temperature between the sample (copper counterface) and the environment will be referred to as the subcool. The temperature of the water circulated through the cooling stage was varied while the ambient temperature (26 °C) and humidity (95% RH) remained approximately constant. A total of five different subcoolings were investigated: −4, 0, +4, +8, and +12 °C. Each temperature was maintained for 2000 cycles. A current density of 7 A/cm² (negative counterface) was used to minimize heating of the sample. Normal load, friction coefficient, and voltage drop were recorded for each cycle.

3. Results and discussion

Friction coefficient and contact resistance data for the brush/counterface contact in humidified carbon dioxide are shown in Fig. 3 (constant subcool of 1–2 °C). For the initial 15,000 cycles of no-current sliding, friction coefficient displayed a run-in behavior—peaking at a value of approximately 0.35 before gradually decreasing and stabilizing at a value of approximately 0.24. At a current density of 180 A/cm², the negative counterface sliding pair maintained a friction coefficient of approximately 0.24, and further changes in current did not cause significant deviations from this value. The positive counterface exhibited noticeable changes in friction coefficient at the current transitions, and a general trend of increasing friction with time during periods of constant current was observed. Around cycle 20,000, the positive counterface friction coefficient increased rapidly. The increase in friction coefficient occurred over the same time span as an inadvertent increase in sample temperature caused by a mechanical failure in the chilled water supply system. The measured temperature increase is shown in the inset graph of Fig. 3. Contact resistance, shown in the upper portion of Fig. 3, was approximately the same for the positive and negative configurations, with values ranging from 2 to 3 mΩ. Resistance values between cycles 15,000 and 25,000 were slightly higher than values between cycles 35,000 and 45,000.
Fig. 3. Contact resistance (upper left) and friction coefficient (lower left) plotted versus cycle number for positively biased counterface and negatively biased counterface conditions in humidified carbon dioxide and constant subcool of 1–2 °C. Highlighted region (right) shows inadvertent increase in positive counterface surface temperature between cycles 20,000 and 25,000.

Line profiles of the original polished counterface (cycle 0) and wear track after subsequent sliding are shown in Fig. 4. Surface profiles were recorded after each interval of constant current sliding. The positive counterface, shown on the right of Fig. 4, had a lower initial surface roughness (quantified as the average surface roughness; Ra) than the negative counterface; however, after the initial no-current run-in, the relative changes in surface roughness for the positive and negative counterfaces were approximately the same per 10,000 cycle increment. Friction coefficient did not change significantly as the wear track roughness increased. Because the wear track roughness appears to continue to increase up to cycle 45,000, there is an opportunity for long-term testing to determine the upper limit of rotor surface roughness.

By comparing each wear track line profile to the original surface profile, the material volume loss can be calculated. The total volume loss (Vol) was calculated by summing the change in volume (ΔVol) over all pixels in the scan area (l) according to Eq. (1.1):

\[ Vol = \sum_{i} \Delta Vol_i \]  

(1.1)

The volume loss per pixel can be found by determining the change in surface height over some number of cycles of sliding and multiplying the height change by the pixel area as shown in Eq. (1.2), where \( h_{i,n} \) is the height of pixel \( i \) at cycle \( n \), \( h_{i,n+m} \) is the height of pixel \( i \) at cycle \( n+m \), and Δx and Δy are the lateral dimensions of the pixel:

\[ \Delta Vol_i = [h_{i,n} - h_{i,n+m}] \Delta x \Delta y \]  

(1.2)

The calculated volume loss is plotted against sliding distance in Fig. 5. The wear rate for a constant current region is the volume loss divided by the product of the normal load (1.0 N) and sliding distance. The volume loss plotted in Fig. 5 was measured only in

Fig. 4. Line profiles transverse to wear track sliding direction acquired at cycles 0 (top), 15,000, 25,000, 35,000, and 45,000 (bottom). Profiles for the negative counterface are shown on the left, and profiles for the positive counterface are shown on the right. Average roughness (Ra) values were calculated for each line profile. Location of scan area on sample surface is indicated by the shaded area in Fig. 2.
the scan area, as depicted in Fig. 2; therefore, wear rates were calculated based on the sliding distance across the scan area rather than the total sliding distance shown on the x-axis of Fig. 5. By normalizing the volumetric wear rate (units of mm³/Nm) to the scan area, a linear wear rate (m/m) was calculated for comparison with the literature values for typical brush wear rates. As shown in Table 1, the highest wear rates – approximately $2 \times 10^{-6}$ mm³/Nm – occurred during the no-current run-in. After run-in, no significant change in wear rate was observed when alternating between 0 and 180 A/cm². Additionally, the direction of current flow did not significantly affect the magnitude of the wear rates. Under current flow, the negative counterface wear rates were $5.7 \times 10^{-7}$ and $6.9 \times 10^{-7}$ mm³/Nm, while the positive counterface wear rates were $2.6 \times 10^{-7}$ and $8.8 \times 10^{-7}$ mm³/Nm. Further studies are needed to investigate these trends over larger sliding distances.

The uncertainty in the wear volume, $\Delta V$, was calculated according to Eq. (1.3):

$$\Delta V^2 = I(\Delta x \Delta y)^2 u(h_{i,n})^2 + I(\Delta x \Delta y)^2 u(h_{i,n+m})$$  \hspace{1cm} (1.3)

The uncertainty in the height measurement is not dependent on the cycle number; therefore, $u(h_{i,n})$ is equivalent to $u(h_{i,n+m})$, and Eq. (1.3) can be written as follows:

$$\Delta V^2 = 2I(\Delta x \Delta y)^2 u^2(h)$$  \hspace{1cm} (1.4)

For this particular scanning white light interferometer, the uncertainty in the surface height measurement, $u(h)$, was conservatively estimated to be 10 nm. Given that the total number of pixels was $2.15 \times 10^6$ and the area per pixel was 2.03 μm², the uncertainty in volume loss was calculated to be $4.2 \times 10^{-8}$ mm³. Referring to Fig. 5, the uncertainty is approximately three orders of magnitude below the measured volume losses and, thus, too small to be depicted on the plot.

Other studies of sliding electrical contacts performed at higher sliding velocities showed that, in general, positively biased brushes wore at a higher rate than negatively biased brushes [17–21]. The current analysis focused on quantifying wear of the counterface rather than the brush, which makes it difficult to draw comparisons. The sliding velocity used in this study was several orders of magnitude below what is typically used in high current brush research and in high current motor and generator applications. However, dynamic effects, which may induce arcing at high sliding velocities, are much less prominent at low sliding velocities.

Examination of the worn counterfaces was performed using scanning electron microscopy. Fig. 6 shows SEM micrographs of the counterface wear tracks for both the positive and negative current flow directions. The SEM images were taken near the midpoint of the track, similar to the profilometry scan location. Detached debris particles (not shown) were observed primarily at the end points of the wear track. Focused ion beam milling was used to investigate the wear track subsurface grain structure. A platinum layer was deposited on the area of interest prior to milling to protect surface features from ion beam damage. A trench approximately 10 μm wide was milled transverse to the sliding direction using the ion beam. The lower micrographs of Fig. 6 show the grain structure of the near-surface region within the wear track. The positive and negative counterfaces show similar amounts of subsurface deformation, but nothing to distinguish between the different directions of current flow.

For XPS analysis, three copper counterface samples were tested under the following current conditions: no-current, positive counterface, and negative counterface. As seen in the representative C 1s spectrum of Fig. 7(a), a range of carbonaceous species were detected within the wear tracks of all three samples. The amorphous carbon peak at 284.6 eV is attributed to adventitious carbon, which likely accumulated on the surface during brief exposure to the ambient environment [23]. Carbon–oxygen species including CO₂ and CO₃ are evident through the resolved peak intensities between 286 and 290 eV [24–26]. Based on previous studies, methoxy and formate species may also contribute intensity within this energy range; however, these are not spectroscopically distinguished [24,27,28]. In addition, a –CF₂– species is detected both inside and outside of the wear track on all samples through the peak intensity appearing near 292 eV [23]. Subsequent analysis of the brush material showed significantly higher concentrations of the –CF₂– species. It has been hypothesized that a fluorinated grease was used during the drawing process for the wire of the copper brush, and remnants of the grease transferred to the counterface during sliding. In Fig. 7(b), Cu 2p₃/2 spectra, normalized by total integrated Cu intensity, are shown for the wear track region of the three samples. These spectra are
Fig. 6. SEM micrographs of copper counterface wear tracks—positive on the left (a) and negative on the right (b). Upper micrographs show the worn counterface surface after 45,000 cycles of sliding. Lower micrographs show cross sections of wear track surfaces, transverse to sliding direction, created by FIB milling.

Fig. 7. XPS results obtained from within counterface wear tracks. (a) The carbon 1s spectra for the wear track of the no-current sample is exemplary of that obtained from all counterface. Each indicated the presence of carbonates as well as contamination by a ¬CF2¬ species. (b) The copper 2p3/2 spectra for no-current (solid), positive counterface (dash), and negative counterface (dash-dot) indicate the primary presence of metallic copper. (c) The copper L3M45M45 Auger spectra for no-current (solid), positive counterface (dash), and negative counterface (dash-dot) indicate the presence of both metallic and cuprous copper.
dominated by intensity attributable to metallic copper and Cu$_2$O, although the documented 0.2 eV peak shift between the two prevents a quantitative assessment of their relative presence [23,29]. The Cu LMM Auger spectra for all three counterface conditions are shown in Fig. 7(c). Transitions corresponding to metallic copper appear at a kinetic energy of 918.8 eV and those of Cu$_2$O at 916.5 eV [23,29]. Although the spectra appear similar, upon differentiation, the peak-to-peak height ratios of Cu$_2$O to Cu are noticeably dissimilar. The no-current and negative counterfaces have ratio values of 1.1 and 1.2, respectively, whereas the positive counterface has a ratio value of 0.6, highlighting the relative absence of Cu$_2$O species (∼932 eV) on this particular counterface [23,29].

The effect of varying subcooling on the frictional and electrical behavior of the self-mated copper system was investigated in humidified carbon dioxide and humidified argon environments. Two different gas environments were used to separate the effects of cover gas and water vapor. A current density of 7 A/cm$^2$, as opposed to 180 A/cm$^2$, was used to minimize heating of the sample and reduce temperature fluctuations at the contact. Shown in Fig. 8 are the average steady-state friction coefficient and contact resistance values for each 2000 cycle region of constant subcool. The calculated standard errors in the average friction coefficient and contact resistance values were <0.01 and ∼0.01 mΩ, respectively. The lowest friction coefficients – approximately 0.16 – were observed when the sample temperature was at or below the ambient environment temperature (negative subcool). Additionally, the lowest recorded contact resistances occurred when the subcool was at or below zero (negative). As sample temperature increased above the ambient temperature (positive subcool), friction coefficient and contact resistance increased. The trends in friction coefficient and contact resistance data in humidified carbon dioxide and humidified argon environments were similar; however, the magnitudes of the average steady-state values were slightly different. Friction coefficients in humidified argon were consistently higher than friction coefficients in humidified carbon dioxide at the same subcool. Contact resistance was also higher in humidified argon for the same subcool, but the difference was less significant as the subcool became more positive.

When the sample temperature is at or below the environment temperature, the local relative humidity and water adsorption are highest. As the sample temperature increases, friction coefficient increases due to reduced adsorption of water on the sliding surfaces. However, the observed friction increase was more pronounced in the argon environment, suggesting the chemical reactions created by the carbon dioxide cover gas aid in reducing friction. Carbonates, which were shown to form during sliding in humidified carbon dioxide by XPS, may be the primary contributor to the lower friction.

Carbon dioxide may also play a role in reducing contact resistance. One possible mechanism involves dissolved carbon dioxide in the adsorbed water layers combining with water to form carbonic acid (H$_2$CO$_3$), which has the ability to dissociate and break down Cu$_2$O residing on the surface [30]. Reducing the thickness of the oxide layer would increase the conductivity of the sliding contact. Conversely, dissolved argon in the adsorbed water layers would not react with the oxide layer and, therefore, would have no effect on the contact resistance. When the sample temperature was increased to its highest value (+12 °C subcool), the contact resistance values in Fig. 8 appeared to approach a common value. Water adsorption would also be expected to be at its lowest point at the most positive subcool. From Fig. 3, at a current density of 180 A/cm$^2$ and subcool of ∼−1 °C in humid carbon dioxide, measured contact resistance values were in the range of 2–3 mΩ. From Fig. 8(b), at a current density of 7 A/cm$^2$ and zero subcool in humid carbon dioxide, the average contact resistance was approximately 0.3 mΩ, which is significantly lower than the values measured at 180 A/cm$^2$.

Further study is needed to investigate this relationship between current density and resistance over a range of values between 7 and 180 A/cm$^2$.

4. Conclusions

Wear rates for a copper flat in a brush-on-flat reciprocating sliding geometry at low sliding velocities in humidified carbon dioxide were shown to be independent of current flow, contrary to high sliding speed studies of electrical brush wear which have shown a tendency for higher wear of the positively biased brush. XPS analysis of the wear track regions suggested the no-current and negative counterfaces had slightly higher relative amounts of Cu$_2$O compared to the positive counterface, and carbonates were found on the surfaces of all samples. Friction coefficient and contact resistance showed a strong dependence on subcool—increases in friction coefficient and resistance were observed as sample temperature increased above the ambient environment temperature in both carbon dioxide and argon. Adsorbed water layers and surface carbonates may aid in the reduction of friction in humidified carbon dioxide environments. Dissolved carbon dioxide in the adsorbed water layers may also facilitate break down of Cu$_2$O, reducing the resistance across the sliding interface.

Acknowledgements

This work was funded by the Office of Naval Research under contract number N00014-06-1-0313. The authors would like to thank Neal Sondergaard (Naval Surface Warfare Center) and Roy Dunnington (BMT Syntek) for their help and productive discussions. FIB and SEM work was performed at the Major Analytical Instrumentation Center, Department of Materials Science and Engineering, University of Florida.
References