The Formation of Mechanically Mixed Layer during Dry Sliding of Cu-15wt%Ni-8wt%Sn Bronze

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Abstract

Dry sliding wear of Cu–15Ni–8Sn (in wt%) bronze, against a stainless steel 440C counter surface is investigated in air and flowing Ar gas, using a pin-on-disc tester. The microstructure of the mechanically mixed layer formed during wear, has been characterized at the nanoscale level with an aim to identify its genesis and to establish its role in controlling the wear.

Introduction

During the sliding of two solid bodies, under friction and load, chemical composition of the near surface is modified, due to the interaction with the counter face material and the environment. This layer is termed as transfer layer or Mechanically-Mixed Layer (MML) and has characteristically distinct chemical composition and microstructure. The transfer layer can be continuous or patchy. The importance of this layer on affecting the friction of the sliding bodies and their wear rate, has been well acknowledged [1]. Debris generated during the wear process originates mostly from the transfer layer. Previous studies on pure Cu have shown, that transfer layers are a few microns thick and consist of nanocrystalline grains [2]. During a tribological process, the transfer layer is believed to be constantly in the process of making and breaking under steady state conditions. Despite the numerous past studies invoking the importance of transfer layer, there remains a poor understanding of MML, especially with regard to their microstructure and their formation. Further, it remains unclear whether the transfer layer is a part of the existing bodies or is formed by the debris particles, by the process of compaction on the sliding surface.

In the present work, the formation of the transfer layer, in a spinodally decomposed Cu-15wt%Ni-8wt%Sn bronze alloy (henceforth referred to as CuNiSn alloy) [3] has been studied. Microstructures of subsurface layers formed during wear were characterized up to nanoscale level by conventional and analytical Transmission Electron Microscopy (TEM), including energy dispersive spectroscopy and Electron Energy Loss Spectroscopy (EELS). The wear behavior of the bronze was interpreted in the light of microstructural changes, occurring in the surface during the wear process.

Experimental procedure

Wear tests of the CuNiSn alloy (~ 31 HRC hardness) were carried out, using a pin-on-disc tester against a martensitically hardened stainless steel (SS) 440 C disc (~ 60 HRC hardness). Details of the testing procedure are mentioned in [3,4]. The wear rates were estimated by direct measurement of the weight loss of the pin, to an accuracy of ± 0.1 mg as well as from the linear displacement versus time data plot, recorded in-situ by a Linear Variable Displacement Transducer (LVDT). TEM
samples of the worn pin were prepared as per the procedure described in ref. [4].

Results and Discussion

Wear Behaviour

Table 1 gives the weight loss, the coefficient of friction ($\mu$) and the wear coefficient ($K$) for the worn CuNiSn alloy. At 10 Kgf load and 0.25 m/s sliding speed under air, severe wear of the pin against the SS 440C counter surface started, right at the beginning of the experiment. In flowing Ar atmosphere, under the same test conditions, the wear rate reduced by about 75% while it reduced further by about 50%, with a reduction of the sliding speed from 0.25 m/s to 0.10 m/s. The coefficient of friction versus time curves showed similar characteristic, throughout all the tests [3] – a negligibly short transient period followed by a steady-state period with only one type of transfer mechanism. Moreover, the value of friction coefficient was around 0.3 for all experiments, carried out against the SS counter surface. This suggested that similar wear mechanisms operated during these tests. A steady state coefficient of friction suggested, that there was only one mechanism of transfer and wear. However, in the self-mated tribological system, the wear rate increased significantly. The weight-loss increased by about 250% over the SS-mated system when tested in air at the sliding speed of 0.25 m/s under 10 Kgf load (Table 1).

Microstructure

Cross section microscopy of the worn pin revealed a Severely Plastically Deformed Layer (SPDL), capped by a thin MML (about 2 to 3 micron thick), separating the outer surface and the SPD layer. TEM characterization of the MML revealed it to be a nanocomposite comprised of equiaxed Cu-rich bronze grains and (Fe,Cr)$_2$O$_3$-based oxide grains (Fig. 1). The MML was formed by the mechanical mixing of debris particles from both the bodies, viz., the bronze pin and the SS 440C counter face surface. Oxidation seemed to have played an important role, since the oxide particles generated from the SS counter face surface appeared to stabilize the MML. When a similar experiment, with the same loading conditions, was done under flowing Ar atmosphere, the wear rate reduced by about 75% while it reduced further by about 50%, with a reduction of the sliding speed from 0.25 m/s to 0.10 m/s. The coefficient of friction versus time curves showed similar characteristic, throughout all the tests [3] – a negligibly short transient period followed by a steady-state period with only one type of transfer mechanism. Moreover, the value of friction coefficient was around 0.3 for all experiments, carried out against the SS counter surface. This suggested that similar wear mechanisms operated during these tests. A steady state coefficient of friction suggested, that there was only one mechanism of transfer and wear. However, in the self-mated tribological system, the wear rate increased significantly. The weight-loss increased by about 250% over the SS-mated system when tested in air at the sliding speed of 0.25 m/s under 10 Kgf load (Table 1).

Table 1: Table summarizing experimental conditions and the data extracted from the wear experiments

<table>
<thead>
<tr>
<th>Expt. No.</th>
<th>Counter face Disc Material</th>
<th>Load (kgf)</th>
<th>Sliding Speed (m/s)</th>
<th>Time (s)</th>
<th>Environment</th>
<th>Coeff. Of Friction</th>
<th>Weight Loss (gm)</th>
<th>Wear Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>SS 440C</td>
<td>10.0</td>
<td>0.25</td>
<td>9000</td>
<td>Air</td>
<td>0.279</td>
<td>0.1311</td>
<td>6.42x10$^{-6}$</td>
</tr>
<tr>
<td>2.</td>
<td>SS 440C</td>
<td>10.0</td>
<td>0.25</td>
<td>9000</td>
<td>Argon</td>
<td>0.343</td>
<td>0.0321</td>
<td>1.57x10$^{-5}$</td>
</tr>
<tr>
<td>3.</td>
<td>SS 440C</td>
<td>10.0</td>
<td>0.10</td>
<td>9000</td>
<td>Argon</td>
<td>0.294</td>
<td>0.0151</td>
<td>1.85x10$^{-5}$</td>
</tr>
<tr>
<td>4.</td>
<td>Cu-Ni-Sn</td>
<td>10.0</td>
<td>0.25</td>
<td>9000</td>
<td>Air</td>
<td>0.517</td>
<td>0.3228</td>
<td>1.58x10$^{-4}$</td>
</tr>
</tbody>
</table>

Fig. 1: (a) Bright field and (b) Dark field TEM micrographs of the subsurface layers formed in CuNiSn bronze worn in air against a SS 440C counter face.
Ar atmosphere, the MML formed was observed to be patchy (Fig. 2). In addition, when the source of Fe₂O₃ particles generation was removed and the experiment was done with a self-mated bronze disc, the surface was devoid of MML subsurface layer. The pin showed the formation of SPDL only. These finding have been published separately [4]. The SPDL consisted of a Cu-Ni-Sn solid solution with elongated nanograins, due to extensive dislocation glide and twinning. Since the wear rate in self-mated system had increased significantly, it was concluded that the formation of the MML had improved significantly the wear resistance of the bronze against SS 440C.

The bronze phase in the MML, had the tendency to phase separate Cu and (Ni + Fe₂O₃) phases. The decomposed phases in the MML were studied in detail, using core-energy-loss spectroscopy. This is illustrated in Fig. 3, which shows EELS line scan across the MML/SPDL interface. Details for the interpretation of the spectra can be found in ref. [5]. Evidently, the separation of the bronze phase into Ni-rich and Ni-lean particles within the MML could be seen in the histogram. Further, the Ni-rich particles also contained Fe (from the (Fe,Cr)₂O₃ particles). Length scale of this decomposition was about 20 nm (Fig. 3). In contrast, no such decomposition was found in the SPDL. The drastic change in composition and microstructural features across the MML/SPDL established, that MML was not part of the original (pin) body and must have formed by mechanical mixing and compaction of the debris from the two bodies. This was because, a continuous change of microstructural features across the interface would have been observed, if the MML was a part of the original body.

These investigations have also demonstrated, that the formation of a MML in the present context was beneficial in reducing the wear rate and this was most beneficial, when it was very thin and patchy. The MML played a role very similar to that of a solid lubricant. The presence of such an MML has advantages over an external solid
lubricant, since it rebuilds continuously and it forms everywhere along the contacting interfaces.

Conclusions

On the basis of nanoscale structural and chemical characterization of the transfer layer and its underlying material formed during the dry sliding of Cu-Ni-Sn bronze, it can be concluded that: (i) the transfer layer was not a part of the main body - a commonly held concept; and (ii) the formation of mechanically mixed layer, reduces the wear rate drastically.

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References