Effect of Modification of the Microstructure of a Cast Al–33%Cu Eutectic Alloy by Isothermal Heat Treatment in the Semisolid State on its Adhesive Wear Characteristics
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Abstract

The adhesive wear characteristics of an as-cast eutectic Al-33\%Cu alloy having a typical lamellar structure have been compared with that of the same alloy having a modified microstructure by the block-on-wedge wear test. The modification of the as-cast microstructure was effected by isothermal heat treatment in the semisolid state (SSH) at 560°C for 10 min followed by water quenching. The modified microstructure consisted of globules of hypereutectic \( \beta \) copper aluminides globules dispersed in the \( \alpha \)-Al matrix. During the wear test, the counter body was a EN31 steel drum of hardness Rc62. Cumulative wear loss and coefficient of friction decreased after modification of the cast structure by SSH. FESEM examination of the worn surfaces and wear debris revealed that oxidative wear was more prominent in case of the sample with the modified microstructure. However, removal of the oxide nodules, plastic deformation of the matrix, micro-cracking and delamination of the matrix accounted for the wear loss in both the cases. Conspicuous pick-up of iron, presumably by diffusion from the drum into the debris of oxide nodules, was noted in case of the cast sample. Iron pick-up was much less in the debris of the modified sample.

Keywords: Semisolid, Microstructure, Eutectic, Friction, Delamination.

Abbreviations: Semisolid heat treatment (SSH), Field emission scanning electron microscopy (FESEM), Coefficient of friction (CoF), Peeling Bedword (PB), Energy dispersive X-ray analysis (EDX).

Introduction

Broadly, the metal matrix composites may be grouped as ex-situ and in-situ composites \(^{[1-3]}\). Eutectic metal matrix composites belong to the group of in-situ composites. Heat treatment in the semisolid state offers an easy and convenient route for preparation of in-situ metal matrix composites \(^{[5-9]}\). Another approach is rolling of the alloy + dispersoids in the mushy state \(^{[10-11]}\). Eutectic alloys, which freeze at a fixed temperature, do not solidify through a mushy zone. Modification of the microstructure of such alloys either by heat treatment or mechanical treatment in the semisolid state is quite difficult. In this investigation, an attempt has still been made to convert the lamellar eutectic structure of a cast Al-33\%Cu alloy to a modified structure consisting of spheriodised copper globules.
aluminide partially dispersed in the α-Al matrix by controlled isothermal heat treatment at temperature ranges of 10-20°C above the eutectic melting point. In the next stage, the adhesive wear characteristics of the as-cast Al-33%Cu alloy was compared with that of the modified alloy by block-on-wedge wear test machine. Aluminium alloys are widely used in aerospace, defence and automobile industries. Crank cases, piston rings, transmissions cases, convertor housings are typical applications in which primarily Al-Si alloys are used. However, there is always an attempt to improve the performance of the engineering components by substituting existing materials with superior materials [12]. The present investigation is a part of an exercise to develop high strength eutectic aluminium alloy composites. The focus in the current investigation is on assessing the wear performance of the modified eutectic Al-33%Cu alloy vis-à-vis that of the cast alloy.

**Experimental Procedure**

An Al-33%Cu alloy was prepared by melting pure aluminium and pure copper wires in an induction furnace. The molten metal was solidified in the form of 30 mm bars in a metal mould. 10 mm thick samples were machined from the cast rods and heat treated isothermally in the semisolid state at 560°C and then quenched in water. The adhesive wear characteristics of the semisolid heat-treated sample were then compared with that of an as-cast sample of similar size by the block-on-wedge test. The counter body was made of EN31 hardened steel of hardness Rc62. The wear debris was collected. The microstructures of the as-cast and the heat-treated samples are illustrated in Fig 1 and Fig 3 respectively. EDX analysis of Al-33%Cu alloy heat-treated at 560°C for 6 min and then water quenched is shown in Fig 2.

**Results and Discussion**

The coefficient of friction (CoF) is calculated as follows:

\[ \mu = \frac{F_f}{F_n} \]

where \( F_f \) is average friction force and \( F_n \) is applied normal load. The value of cumulative wear (W) and coefficient of friction (CoF) obtained, are given in Table-2.

Partial melting and resolidification largely removed the lamellar structure; typical lamellar structure analysis of Al-33%Cu alloy heat-treated at 560°C for 6 min and then water quenched is shown in Fig 2.

**Table-1: Wear Test Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding velocity</td>
<td>1.86 m/s</td>
</tr>
<tr>
<td>Normal load</td>
<td>50 N</td>
</tr>
<tr>
<td>Time</td>
<td>30 min</td>
</tr>
</tbody>
</table>

The working diagram of the multistation tribotester is shown in Fig 4. The wear test parameters are given in Table-1.

**Fig 1: SEM photomicrograph of as-cast Al-33%Cu alloy**

**Fig 2: EDX analysis of an Al-33%Cu alloy heat-treated at 560°C for 6 min and then water quenched (a) Al rich α-dendrites (b) Cu rich β-dendrites**
The microstructural modification of the as-cast structure had a conspicuous effect on both the magnitude of the cumulative wear and the coefficient of friction. After modification by SSH, both cumulative wear (Fig 6) and the coefficient of friction (Fig 7) decreased.

Figure 6(a) shows that the wear was very high initially. Then it dropped sharply after 100 sec probably due to work hardening and oxidation of the matrix. It continued to drop for some more time, after about 600 sec, it started rising again. The modified sample however behaved differently. Although the wear was rather high initially, it slowed down after 400 sec as shown in Fig. 6(b). Therafter, it continued to rise at a gentle speed.

The FESEM photomicrographs show clear evidences of different modes of wear. Variation of coefficient of friction with time for as-cast and as-quenched Al-33%Cu alloy is given in Fig 7. FESEM micrograph of the wear surfaces of as-cast Al-33%Cu alloy (Fig 8(a)) shows rubbing marks, wear tracks with cracks, as well pits. Figure 8(b) shows delamination of chunks of the wear surface. A higher magnification of the modified surface shows the presence of chunks that were detached from the surface.

**Table-2: Wear Results**

<table>
<thead>
<tr>
<th>Al-33% Cu</th>
<th>Cumulative Wear (μm)</th>
<th>Average CoF</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-Cast</td>
<td>116</td>
<td>0.42</td>
</tr>
<tr>
<td>As-quenched</td>
<td>108</td>
<td>0.32</td>
</tr>
</tbody>
</table>

**Fig 3:** Microstructure of an Al-33%Cu alloy heat treated at 560°C for 10 min and then water quenched

**Fig 5:** Portion of the Al-Cu binary phase diagram

**Fig 6:** Variation of wear with time (a) as-cast Al-33%Cu alloy (b) SSH and as-quenched Al-33%Cu alloy

**Fig 4:** Block diagram of Multi Tribotester

**Fig 8:** (a) Wear surface of as-cast Al-33%Cu alloy showing rubbing marks, wear tracks with cracks, as well pits. (b) Delamination of chunks of the wear surface.
photomicrograph in Fig 8(b) also shows that the delamination occurred layer by layer. Figure 9(a) shows the wear surfaces of SSH sample. Due to SSH, the lamellar eutectic structure was altered; where copper aluminide particles were dispersed in the matrix. This sample suffered extensive oxidation during the short test as shown in Fig 9(b). Detached oxide particles and delaminated flakes formed the wear debris as shown in Fig. 10 (a&b). The volume of such oxide debris was more in the SSH sample. The SSH sample debris further shows the presence of fractured dendrites as shown in Fig. 7(b).

The EDX quantitative analysis data are tabulated and corresponding electron images and the spectra are given in Fig 11 and Fig 12 respectively. EDX analysis of the debris yielded interesting results. It is interesting to note that Fe atoms were also present in the debris of the as-cast sample as shown in Fig 11. It is most likely that Fe atoms diffused from the steel drum into the Al-Cu alloy at the high temperature generated during the wear test. The high level of oxygen in the debris confirm oxidation of surface during wear test. The data presented in Fig 11 are particularly interesting in the sense that both Al and Fe concentrations are high and nearly equal. It means that diffusion of iron resulted in the formation of mixed (Al,Fe) oxides with PB ratio much greater than 1. These oxides were pulled off under the wear load and sliding action of the drum. Hence cumulative wear, recorded in terms of the height of the test specimen, initially got reduced. The cumulative wear started rising again. The wear debris formed from the SSH sample contained only traces of Fe as shown.
Transformation of the lamellar eutectic structure into a partially globular structure resulted in a conspicuous reduction of Fe pick-up from the drum into sample surface. It probably means that the large surface areas of α-Al lamallae in the as-cast sample provide ideal interfaces for iron diffusion. The quantitative data illustrates that the oxides formed are basically mixed (Fe, Al, Cu) oxides. In the presence of Al, the oxidation of Cu is unlikely according to normal thermodynamic rules. The small amount of Cu in the oxides is mainly due to mass effect of the large proportion of Cu in the eutectic alloy. Traces of Si or Ca are common impurities in Al. Hence, the presence of minor proportion of oxides of these metals is quite possible. The present investigation opens up further scope for development of in-situ eutectic Al-alloy composites for tribological applications. The novelty of the present work may be viewed from this perspective.

**Conclusions**

- Wear of both as-cast and semisolid heat-treated Al-33%Cu alloy proceeds by rubbing, ploughing, plastic deformation and oxidation of the surface layer, peeling off of the oxide nodules and delamination of chunks from the worn surface.
- Rapid diffusion of iron from the drum into wear surface occurs during the wear test, presumably because the wear sample is heated up appreciably during the test. The oxide debris consists primarily of (Fe, Al, Cu) oxides where Cu-concentration is pretty low.
The surfaces of the delaminated flakes are also similarly oxidised.

The present investigation opens up a scope for development of in-situ Al-alloy eutectic composites for tribological applications.

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References