Study of the wear behaviour of Al-4.5% Cu-3.4% Fe in situ composite: Effect of thermal and mechanical processing

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Study of the wear behaviour of Al–4.5% Cu–3.4% Fe in situ composite: Effect of thermal and mechanical processing

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Abstract

Al–Cu-based MMCs reinforced by Al–Fe intermetallics are investigated for their wear behaviour. The composite (Al–4.5 mass% Cu–3.4 mass% Fe) was produced by solidification processing where the Al–Fe-based intermetallic formed in situ in a matrix of mainly Al–Cu alloy. The effects of thermal and mechanical processing, viz., as-cast condition, solution treatment, aging and hot rolling on the wear behaviour of the composites were examined. The composites were characterized by optical microscopy, SEM, microhardness measurements and X-ray diffraction. The wear behaviour of the composites was studied in a pin-on-disc type wear apparatus.

The as-cast in situ composite exhibited the highest wear rate. The wear rate of the (cast + solution treated + aged) composite was about 4.5 times and that of the (rolled + solution treated + aged) composite about 9.5 times lower than the wear rate of the as-cast composite. Hot-rolling + solution treatment + ageing of the MMC was found to yield the lowest wear rate among all processing conditions investigated. Worn surface revealed that mainly abrasive wear took place in all cases. The extent of abrasive wear was largest in the as-cast MMC as evidenced by deep groves on the worn surface as well as by the highest weight loss. Dark patches of presumably transfer layer were found in some cases, particularly on the (rolled + solution treated + aged) samples. Attempt has been made to relate the wear behaviour of the in situ MMC to their microstructures and to the microhardness of the matrix and the reinforcing phase.

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Keywords: Al–Cu–Fe in situ composite; Wear; Thermal and mechanical processing

1. Introduction

Metal–matrix composites (MMC) are of great interest in recent years as they can offer a better combination of properties not attainable in conventional alloys. Al-based MMCs have been attracting a lot of attention particularly for their desirable combination of high stiffness and low specific gravity. Recently, tribological properties of Al-MMCs have also drawn much interest. Most of the Al-MMCs studied so far are produced by ex situ techniques (in which the reinforcing particles are added to the matrix ex situ). On the other hand, in situ technique, in which the reinforcing particles are precipitated from within the alloy during solidification processing, can offer certain advantages, viz., ease of processing, low cost and uniformity in the distribution of the reinforcing phase. In the present work, in situ Al–4.5 mass% Cu–3.4 mass% Fe MMCs have been produced by solidification processing.

In the Al–Fe system, an intermetallic phase Al₃Fe exists under equilibrium that can act as the in situ reinforcing phase [1,2]. The addition of copper to the system offers the probability of an age hardenable matrix that is expected to improve further the properties of the material [3]. After casting, the Al–4.5 mass% Cu–3.4 mass% Fe MMCs are treated thermally and mechanically to modify their microstructures. Tribological properties of MMCs so treated are studied under dry sliding conditions. It has been shown that the microstructure of the MMCs has a great influence on their tribological behaviour. The properties of Al–4.5% Cu–3.4% Fe composites are also compared with that of the base Al–4.5% Cu alloy.

2. Experimental

Commercially pure aluminium was melted in a graphite crucible and was superheated to about 850 °C to which electrolytic copper was added. The melt
Table 1
Details of thermal and mechanical treatment conditions used

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Details of the conditions used</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-cast condition</td>
<td>For composite: cast in a cast iron mould preheated to 550 °C. For alloy: cast in a cast iron mould (not preheated)</td>
</tr>
<tr>
<td>Solution treatment</td>
<td>Heating at 580 °C for 2 h followed by quenching in iced brine</td>
</tr>
<tr>
<td>Solution treatment followed by aging</td>
<td>Heating at 580 °C for 2 h followed by quenching in iced brine and then aging at 215 °C for 5 h</td>
</tr>
<tr>
<td>Rolling</td>
<td>Cast samples pre-heated at 545 °C, hot rolled followed by cooling in a furnace from about 450 °C</td>
</tr>
<tr>
<td>Hot rolling followed by solution treatment and aging</td>
<td>Cast samples pre-heated at 545 °C, hot rolled followed by cooling in a furnace from about 450 °C. Heating at 580 °C for 2 h followed by quenching in iced brine and the aging at 215 °C for 5 h</td>
</tr>
</tbody>
</table>

was stirred manually to homogenize the solution. Required amount of very low carbon steel chips (as the source of iron) was added to superheated melt. The melt was stirred for about 10 min to ensure the dissolution of iron and homogenization of the melt. The temperature of the melt was lowered to about 750 °C before pouring it into a cast iron mould preheated to 550 °C. The melt of composition Al–4.5 mass% Cu–3.4 mass% Fe was thus allowed to solidify under slow cooling condition. During solidification Al–Fe-based intermetallic particles precipitated in situ to yield a metal matrix composite. For comparison, an Al–4.5 mass% Cu alloy was prepared and cast in a cast iron mould.

The cast in situ composite and the alloy were subjected to different treatments. The cast composite and the alloy were solution treated as well as (solution treated + aged). A portion of the cast composite was also hot rolled. The rolled composite was further subjected to solution treatment and ageing. Details of the thermal and mechanical treatment conditions investigated can be found in Table 1. The samples thus prepared were characterized by optical microscopy, scanning electron microscopy, X-ray diffraction and microhardness measurements. All the samples were subjected to tribological investigations using a pin-on-disc type apparatus under dry sliding conditions in the ambient air at room temperature.

For the wear study, the composite and the alloy were machined to cylindrical pin of 5.5 mm diameter and 15 mm length. Medium carbon steels discs of 14 mm thickness and 103 mm diameter were used as the counter body during the tests. The average hardness of the counter body was RC 50. The pin was pressed against the disc under a constant load of 15 N. The disc was rotated at 1000 rpm, which gave a linear speed of 2.14 m s⁻¹ at the wear track. For each experiment, a new pin and a new disc were used. Test duration ranged from 0.5 to 2.5 h. Before the tests both the pin and the disc were degreased, clean and dried with acetone. After the wear tests, the worn surfaces of the pins were examined by optical microscopy. The wear rates of the samples were calculated from weight loss measurements.

3. Results and discussion

Fig. 1a shows the wear rate of as-cast and heat-treated Al–4.5 Cu–3.4 Fe composites as a function of sliding distance. The wear rate increases rapidly during the running-in period, which is followed by a gradual increase in the wear rate. The rate of wear is found to be the highest in the case of the as-cast sample. Upon solution treatment, the wear rate is found to decrease dramatically. When the solution treated sample is aged, a further reduction of wear rate results.

Fig. 1b depicts the wear rate of the as-cast as well as (cast + solution treated + aged) Al–4.5 Cu alloy. It is observed that solution treatment and aging of the alloy result in a small decrease in the wear rate. A comparison of Fig. 1a and b shows that in the as-cast state both Al–4.5 Cu–3.4 Fe composite and the Al–4.5 Cu alloy exhibit wear rates that are of similar order of magnitude. In fact at longer sliding distances, the alloy shows a lower wear rate. The decrease in wear rate caused by solution treatment and aging is much more pronounced in the case of Al–4.5 Cu–3.4 Fe than in Al–4.5 Cu.

The variation of wear rate of the rolled composite is shown in Fig. 1c. When compared with the as-cast composite (Fig. 1a), it is seen that rolling brings about a substantial decrease in the wear rate of the composite. Solution treatment and aging of the rolled composite resulted in a further decrease in wear rate. It is seen in Fig. 1 that the (rolling + solution treating + aging) of the composite yields the lowest wear rates in the present investigation.
Table 2
Wear rate of the samples at a sliding distance of 19.27 × 10³ m

<table>
<thead>
<tr>
<th>Alloy Treatment condition</th>
<th>Wear rate (×10⁻¹² m³ m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Al–4.5 Cu–3.4 Fe composite</td>
<td>As-cast</td>
</tr>
<tr>
<td>Cast + solution treated</td>
<td>0.52</td>
</tr>
<tr>
<td>Cast + solution treated + aged</td>
<td>0.38</td>
</tr>
<tr>
<td>Cast Al–4.5 Cu alloy</td>
<td>As-cast</td>
</tr>
<tr>
<td>Cast + solution treated + aged</td>
<td>1.25</td>
</tr>
<tr>
<td>Rolled Al–4.5 Cu–3.4 Fe composite</td>
<td>Rolled</td>
</tr>
<tr>
<td>Rolled + solution treated + aged</td>
<td>0.18</td>
</tr>
</tbody>
</table>

The wear rates of all the materials at a sliding distance of 19.27 × 10³ m are given in Table 2. It can be derived from the table that the wear rate of (cast + solution treated + aged) composite is about 4.5 times lower than that of the as-cast composite. The wear rate of the (rolled + solution treated + aged) composite is about 9.5 times lower than that of the as-cast composite.

Fig. 2 shows the micrographs of the worn composite samples in the as cast (cast + solution treated + aged) and (rolled + solution treated + aged) conditions. The micrographs show the presence of deep grooves and valleys on the worn surface of all samples, suggesting that mainly abrasive wear is operative in all cases. The extent of abrasive wear damage was found to be the highest on the as-cast composite, as was evidenced by the presence of deeper grooves under the microscope as well as by the highest weight loss. Dark patches presumably of transfer layer were found in some cases, particularly on the worn surface of the (rolled + solution treated + aged) sample.

The optical micrographs of the composite samples obtained under different treatment conditions are presented in Fig. 3. In the as-cast state, the composite is found to contain large needles of second phase particles in the matrix. These needles have been identified principally as the Al₃Fe phase [3]. The matrix of the as-cast sample is expected to contain Al–Cu–Fe solid solution and the CuAl₂ phase [1,2,4]. No detectable change in the arrangement and shape of the needles of Al₃Fe is observed upon solution treatment and aging. Rolling is found to result in a drastic change in the microstructure of the composite. The large needles of Al₃Fe are broken down and spheroidized into smaller and more equiaxed particles. The microhardnesses of the matrix and particle of different samples are given in Table 3. The microhardness of the matrix is seen to increase as the composite is solution treated as well as aged. Rolling also results in an increase in the hardness of the matrix.

The matrix hardness increases to a large extent when the rolled composite is solution treated and aged. This is thought to be due to the presence of more uniform distribution of finer Al–Cu-based intermediate precipitates, as the deformed matrix provides more numerous and well distributed nucleation sites. The measured microhardness values show more scatter in the case of the second phase. In spite of the scatter, the microhardness of the needles in the cast composites shows a certain increase upon solution treatment as well as aging. A problem was encountered while measuring the hardness of the small globular precipitates of the rolled specimens. It was difficult to locate the indentation exactly on the globules. While all other reported microhardness values are the average of six to eight measurements, the microhardness of the globules are the average of only two measurements. While the accuracy of the measurements may not be very high, it nevertheless suggests that the globular precipitates in the rolled composite possibly have a higher hardness than the original needle-shaped precipitates of the cast
Fig. 3. Optical micrographs of the Al–4.5 Cu–3.4 Fe composite in the (a) as-cast, (b) cast + solution treated + aged, (c) rolled, and (d) rolled + solution treated + aged conditions (300×).

Table 3
Hardness of matrix and particles, Vickers (HV)

<table>
<thead>
<tr>
<th>Vickers microhardness (HV) of cast Al–4.5 Cu–3.4 Fe composite</th>
<th>Vickers microhardness (HV) of cast Al–4.5 Cu alloy</th>
<th>Vickers microhardness (HV) of rolled Al–4.5 Cu–3.4 Fe composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-cast Matrix 106 ± 2 Needles 788 ± 248</td>
<td>As-cast Matrix 96 ± 5</td>
<td>Rolled Matrix 171 ± 42 Globules 1334 ± 361*</td>
</tr>
<tr>
<td>Cast + solution treated Matrix 151 ± 16 Needles 838 ± 99</td>
<td>Cast + solution treated Matrix 153 ± 15</td>
<td>Rolled + solution treated + aged Matrix 438 ± 80 Globules 2143 ± 61*</td>
</tr>
</tbody>
</table>
composite. The microhardness of the matrix of the composite is higher than that of the corresponding Al–Cu alloy.

Fig. 4 shows the XRD patterns of the as-cast as well as (cast + solution treated + aged) composites. The pattern mainly shows the presence of aluminium peaks. No peak belonging to aluminium–copper or aluminium–iron compounds could be identified. This is thought to be due to the fact that the most prominent peak(s) of different aluminium–copper and aluminium–iron compounds coincides with some of the aluminium peaks [5].

In the Al–Cu system, the as-cast microstructure is expected to consist of Al-rich solid solution containing about 0.2% Cu and precipitates of the brittle Cu–Al2 phase [4]. The cast microstructure in the Al–Fe system comprises large precipitates of Al3Fe in an eutectic mixture of Al/Al3Fe [1–3]. The cast Al–Cu–Fe composite is thus expected to consist of precipitates of Al3Fe phase in a matrix that is basically a mixture of Al/Al3Fe eutectic and the Cu–Al2 phase. Cu and Fe are also likely to be present in small amount in Al as solutes. Solution treatment will cause the dissolution of the brittle Cu–Al2 phase in the matrix, thus improving its toughness. Aging of the solution treated samples will result in the precipitation of metastable Al–Cu phases [6] in the matrix leading to strengthening. With this microstructural information in mind, the wear resistance of the differently treated composites and the alloy can be compared.

It is seen in Fig. 1 that the wear resistance of the as-cast Al–4.5 Cu–3.4 Fe composite is not any better than that of the Al–4.5 Cu alloy. In fact at longer sliding distances, the wear resistance of the as-cast alloy is better (Table 2). The poor properties of the as-cast composite and the alloy are thought to be mainly due to the presence of the deleterious CuAl2 phase in the matrix. Solution treatment that causes the dissolution of the harmful CuAl2 results in an improvement in wear resistance, particularly of the composite. Such treatment also increases the hardness of both matrix and the Al3Fe precipitate that is expected to lead to improved abrasive wear resistance [7].

It has been observed that rolling of the composite brings about two major changes: (a) reduction in the size and a change in the shape of the reinforcing particles and (b) an increase in the hardness of both matrix and particle as compared with the corresponding cast composite. The dependence of wear rate on the size of the reinforcing particles in Al-based MMCs has been studied in the past. Both an increase [8,9] and a decrease [10,11] in wear resistance with an increase in particle size have been observed depending upon particle size range, load etc. In present case, the needle shaped particles in the as-cast composite are rather large. The fragmentation and spheroidization of the needles into smaller particles by rolling is seen to contribute to improved wear resistance. Fracture surface of the as-cast and rolled composite revealed a large difference in the SEM. The as-cast composite showed brittle fracture through the needle and the matrix, while, the presence of dimples on the fractured rolled composite indicate considerable ductility in this sample. This improved overall ductility/toughness of the rolled material is also expected to contribute to improved wear resistance.

4. Conclusions

The wear resistance of in situ Al–4.5 mass% Cu–3.4 mass% Fe composite under different conditions, viz., as-cast, solution treated, aged and rolled is studied and compared with that of the base Al–4.5 mass% Cu alloy. Abrasive wear has been identified as the main wear mechanism in all the samples tested against hardened medium carbon steel. In the as-cast condition, the wear resistance of the composite is similar to that of the alloy. However, solution treatment, as well as aging, results in a dramatic improvement in the wear resistance of the cast composite as compared to that of the alloy. Solution treatment + aging improves the wear resistance of the composite by about 4.9 times over that of the as-cast composite. Composite so treated has about 3.3 times better wear resistance than the corresponding Al–Cu base alloy. Rolling + solution treatment + aging of the composite yields the maximum improvement in wear resistance, about 9.5 times as compared with the as-cast composite. The presence of the reinforcing Al3Fe phase in the composite and its strengthened matrix as well as the fragmentation and spheroidization the Al3Fe particles by hot rolling are suggested to contribute to its better wear resistance.

References


