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PLASTIC DEFORMATION CHARACTERISTICS OF WORN PRECIPITATION-HARDENED ALUMINIUM ALLOYS

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ABSTRACT

Characterisation of the plastic deformation of two types of precipitation-hardened aluminium alloys; A2124 and A6092 against M2 steel was carried out using a block-on-ring configuration. The wear test was used under dry sliding condition at ~1m/s over the load range; 23-140N. Detailed microscopy was performed with the aid of scanning electron microscope (SEM) to determine the sub-surface structural evolution and local worn surface topography. The formation of a mechanical mixed layer (MML) due to repeated sliding generically, leads to a significant difference in wear response since the properties of the layers differ from those of the bulk. In this work, the absolute hardness values of the MML were very high compared to the bulk hardness of the underlying material with the A2124 exhibiting the greatest hardening; almost a fourfold increase over the bulk hardness. Finally, the relationship between the characteristics of the MMLs especially on the work hardening and the alloy type is discussed.

Keywords: precipitation-hardened, aluminium alloys, mechanical mixed layer (MML), plastic deformation, wear

INTRODUCTION

Recently, much greater attention has been paid to aluminium based metal matrix composites, which have been primarily developed to improve certain properties of alloys. These properties include improved tribological behaviour to extend the scope of their application in the manufacture of a range of components from engine parts to sports goods like helmets, golf clubs, rackets, etc. In the case of wear of aluminium alloys, there has never been a systematic investigation into the role of the matrix composition. Whether lubricated or dry sliding, there is evidence that substantial work hardening occurs at the worn surface [1-4]. In this respect, there is no data as to whether a 2xxx series alloys is superior to a 6xxx series alloys, despite that both were strengthened by the same hardening method. Thus, in this study, two types of aluminium alloys; A2124 and A6092 were chosen. The first alloy was A6092, which is an Al-Mg-Si precipitation-hardening alloy. The second alloy was A2124, which is an Al-Cu-Mg alloy that is also hardened by precipitation, but with a greater hardening increment than the A6092. Both the A6092 and A2124 alloys were produced by powder metallurgy route in order to maximise sample homogeneity, and this was the process route for wear resistant metal matrix composites being studied in a related project [5].

The discovery of the precipitation hardening capability of aluminium alloys at the beginning of the 20th century opened up high performance applications in automobiles to aerospace. In this treatment, the second phase is precipitated within matrix phase. The hardness and strength values increase as a result of precipitation of a new precipitate due to period and heat from supersaturated solid solution [6,7].

The A2124 alloy contains copper as the prime-hardening element; in which an increase in Cu content gives a continuous increase in strength for optimum heat treatment. In the case of wear resistance it is favoured by high hardness and the presence of hard constituents. As for the A6092, the alloys obtain their increased strength by precipitation of precursors of Mg_2Si. In terms of properties, generally the extrudability and weldability are very good. Even so, 6-series alloys are not widely used in aerospace application as other precipitation strengthened alloys. Despite their superior corrosion resistance (in marine atmospheres), they cannot compete in terms of the overall balance of properties [8].

The wear mechanisms involved in this study are discussed as a function of alloy composition and the characteristics of the formed MMLs. Results of extensive SEM, coupled with 3D tomographic reconstruction and the investigation of selected sub-surface region using quantitative Energy Dispersive X-ray (EDX), are also presented.

EXPERIMENTAL

Starting materials and preparations

The chemical composition of each alloy stated in weight percentage is shown in Table 1. Both A2124 and A6092 alloys were produced by powder metallurgy route. The pre-alloyed powders with mean particle size (d_{50}) about 25µm were produced by inert gas (argon) atomisation. The powders were then cold pressed and extruded into diameter rods at extrusion ratios of 30:1.

Table 1 Chemical composition of precipitation hardened aluminium alloys (%wt)

Elements	***A2124***	***A6092***
Si	<0.05	0.31 ± 0.02%
Fe	0.04 ± 0.02%	0.05 ± 0.02%
Cu	4.42 ± 0.04%	1.01 ± 0.02%
Mn	0.94 ± 0.02%	<0.02
Mg	1.35 ± 0.02%	1.05 ± 0.02%
Zn	<0.02	<0.02
Cr	<0.02	<0.02
Ti	<0.01	<0.01
Ni	<0.02	<0.02

The wear test

The sliding wear tests were carried out using a multi-purpose wear and friction tester with a block-on-ring configuration. Under unlubricated sliding conditions, the wear test is performed at four different loads; 23, 42, 91 and 140N, which applied via cantilever beam and with a fixed sliding speed of ~1m/s at room temperature. Pin specimens with Vickers microhardness of $115Hv_{1kgf}$ (A2124) and $72Hv_{1kgf}$ (A6092) were prepared by sectioning across the transverse direction of the extruded material at 12.8 mm intervals and then grinding/polishing to a 1 µm polished finish. The counterface was a flat M2 tool steel ring, hardened to 705 Hv_{20kgf} and also polished to a 1 µm polished finish, giving R_a values between 0.1-0.2 µm. Detailed analysis of the worn surface and the cross section was carried out using SEM operating in the range of 7-20 kV. These images were also used to obtain stereo pairs at 16^o tilt to each other. MeX software, from Alicona, allowed tomographic reconstruction of surface topography from these images, proving depth profiles.
Quantitative EDS values reported are an average of 10 analyses from different regions of MMLs. The specimens were nickel coated prior to the longitudinally sectioning, to protect the original surface and limit the charging effects from the mounting medium in the SEM. The solution was heated up and kept at 90% with deposition rate of 15µm/hr. The coated samples were then sectioned by a slow cutting speed with excess coolant to maintain a minimum heat between the pin and the cutting tool. The near surface deformed structure was revealed by etching at room temperature in 8% sodium hydroxide (NaOH) aqueous solution.

Hardness profiles

The hardness of bulk materials prior to the wear test, microhardness measurement was carried out to quantify the work hardening at the subsurface regions. The measurements as a function of depth below the worn surface were carried out using a Mitutoyo MVK G1 microhardness tester with a Vickers indentor at a load of 25gf for 15 seconds. The hardness of the mixed layer at and near surface regions was also measured using the same device.

RESULTS AND DISCUSSION

Tomographic reconstruction

Figure 1 shows the tomographic reconstruction of tilted SEM stereo pairs which gives information about specific height distributions over the worn surface. A greater height difference was observed in the A6092 where craters extended as deep as 50 µm. On the basis of present analysis, microgrooves and plastic deformation with wear particle morphology indicate both adhesive and microploughing wear. The severity of these deformed appearances was found to scale with wear variables, i.e; sliding distance and applied load, which is consistent with other literatures [1,4].

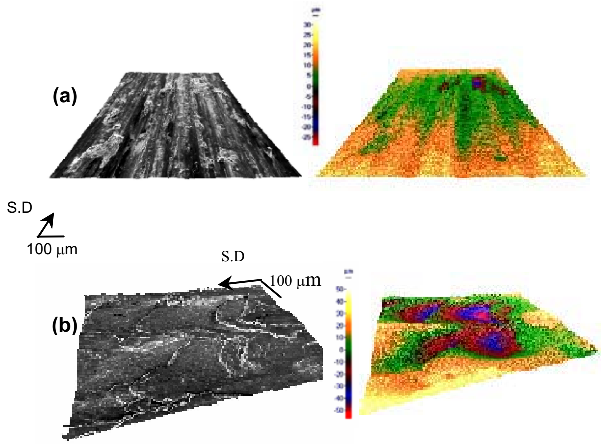

Fig. 1.: Digital Elevation Models of (a) A2124 and (b) A6092 alloy worn surface against M2 at 140N showing the texture image. S.D represents the sliding direction.

Ludema [9] investigated that plastic deformation and fracture have been one of the main causes of severe wear, which happen to be similar as those described in this work. Examinations on the worn surface also showed the presence of inhomogeneous profiles, having smoother zones that correspond to areas that had recently been in contact with the counterface, whereas the rougher zones are regions where surface delamination had occurred. This is indicative of the fact that considerable plastic deformation might have occurred on the surface. Based on these observations, it can be postulated that the wear mechanism of aluminium alloys was plastic deformation dependent.

Subsurface deformation

Figure 2 gives longitudinal microstructural features of the subsurface of the worn surfaces at different loads. In all cases, a mechanically mixed layer (MML) was present due to the repetitive sliding. However, significant differences between the MMLs of each alloy were observed. Their thickness which varied with loads suggested that the subsurface zones of the materials to the sliding and impact wear consisted of three zones [10]; the base material, the deformed intermediate region of the base material and the MMLs. The distinctive morphology of the mixed layer has led to a suggestion that its formation was due to a compression of the transfer material and the entrapped debris, which was followed by mechanical mixing during the sliding process.

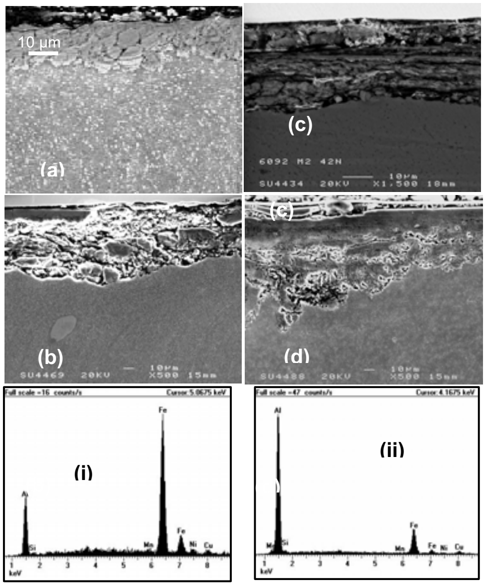

Fig. 2.: Higher magnifications of longitudinal cross-sections of A2124 at (a) 23N (b) 140N and A6092 at (c) 42N and (d) 140N. A corresponding EDS analysis of A6092 cross section at 140N against M2 are shown

The MML of the A6092 (Figure 2c and d) was heavily stratified at lower load and reached more than 70µm thick at the highest load, which was apparently a result of plastic deformation within the layer. As for the A2124, the MML thickness was moderate, fragmented and comprised of an agglomeration of smaller particles. In the present study, the MMLs were found to contain Al, Fe which proves the source of element in the MML obviously originated from the counterface. Figure 3 illustrates specific wear rates of both alloys as a function of load. The values, in the range of 0.3×10^{-4} to 2.1×10^{-4} mm^3/Nm, are generally within the severe wear regime. The specific wear rate decreased with load for both materials, indicating improved wear resistance at the higher loads.

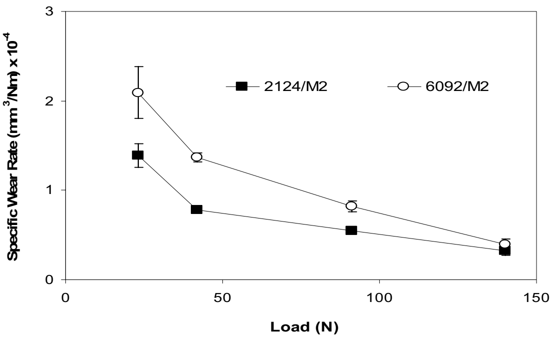

Fig. 3.: Specific wear rate of both alloys as a function of load.

Table 2 gives the composition of the MML for each alloy, which varied from point to point; the figures provided being an average of 10 readings.

Table 2 Average quantitative EDS analysis on MML of Al alloys

Element	**Alloys**			
	A2124		**A6092**	
	42N	**140N**	**42N**	**140N**
Mg	1.8 ± 0.3	2.0 ± 0.4	1.0 ± 0.1	1.7 ± 0.3
Al	85.3 ± 1.9	73.4 ± 5.9	61.8 ± 7.6	79.9 ± 5.8
Si	1.0 ± 0.5	-	1.6 ± 0.4	1.1 ± 0.3
Mn	1.1 ± 0.1	1.4 ± 0.5	0.3 ± 0.1	-
Fe	6.6 ± 1.5	19.1 ± 4.8	34.5 ± 7.8	15.9 ± 7.4
Cu	4.3 ± 0.6	4.1 ± 1.1	0.8 ± 0.2	1.3 ± 0.6

In all cases, the MML contained substantial amounts of Fe. The quantity varied from position to position, but also with load and importantly with Al-alloy. Clearly, the alloy composition has a major effect on the structure and thickness of the MML. Here, the A6092 that exhibited the thickest MML tended to exhibit higher Fe content especially at lower loads Based on the alloying element content in Table 2 and its impact on MML formation and the wear resistance, it is clear that the A2124 alloy with a high content of Cu in its MML promoted good wear resistance at both highest and lowest loads. Thus, a thin and stable MML layer as shown in the 2124 alloy was crucial, as suggested by Venkataraman and Sundararajan [11] in determining a steady state wear. Other elements tended to follow the same ratio as found with the base alloy.

Work hardening at worn surface

Figure 4 shows the Vickers micro-hardness as a function of depth below worn surface of both alloys at the highest and lowest loads. Both alloys exhibited the same basic form of work hardening, as reported by several other authors [1,3,4].

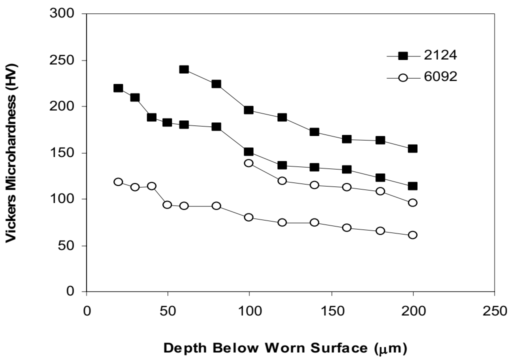

Fig. 4.: Hardness profile of alloys as a function of the deformed depth at 23N and 140N. The first datum corresponds to the depth where the first metal is found below the MML.

The near surface regions were measured to be considerably harder than the undeformed bulk material, with a maximum hardness of 230 kg/mm^2 measured at the layer underneath the MML (acted as a datum due to MMLs' brittle characterisation [11]) of A2124 alloys tested at a load of 140N, which corresponds to almost a fourfold increase over the bulk hardness of 63.93kg/mm^2 at the undeformed regions. At both loads (23N and 140N), the A2124 exhibited the greatest hardening, while, as expected, the A6092 exhibited less work hardening. The hardness at a given depth below the worn surface was found to increase with applied normal load. The A6092 exhibited generally higher wear rates for a given depth of deformation compared to A2124, although this categorisation was not a clear-cut. The absence of a linear relationship is most probably a result of the additional complexity introduced by an MML that occupied a significant portion of the total depth of deformation. The MML will have had higher stiffness and yield strength than the substrate, which would have modified the true contact area [12-14]. Moreover, the evidence in the current work suggests that the MML's properties changed with Al-alloy, as discussed above.

CONCLUSIONS

In general, the dry sliding of A2124 and A6092 alloys showed severe plastic deformation of the surface layer and the re-structuring of its microstructure. Adhesive transfer of materials (alloys) to the counterface and its back transfer between two contacting surfaces were also detected. The combination of these two types of wear leads to the formation of a mechanically mixed layer with thickness that generally increased with load. The dry sliding wear resistance of wrought aluminium alloys is also strongly influenced by alloy composition. This is a result of differences in both hardness and in chemical interaction with the counterface. The structure and thickness of the MML were strongly dependent on the aluminium alloy composition. The MMLs with high Fe content tended to be heavily stratified with thicker MMLs, while a low Fe content tended to be associated with a moderate and fragmented MML. Overall, the presence of a hard, thin and fragmented MML in A2124 alloy provides the best wear resistance than that in the A6092.

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