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Wear Characteristic of Several Commercial Wrought Aluminium Alloys Against Tool Steel

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ABSTRACT

Aluminium alloys are increasingly being used in tribological applications, often in composite form, but to date no systematic work has been undertaken on optimising the matrix composition. In particular, it is not clear whether a work-hardened, a precipitation hardened or dispersion hardened matrix is optimum. Accordingly, the dry sliding wear behaviour of four aluminium alloys (A2124, A6092 (both precipitation hardened), A3004 (dispersion hardened) and A5056 (work hardened) was investigated against an M2 steel counterface in the load range 23-140N and at a fixed sliding speed of 1 ms^{-1}. Severe wear was observed for all alloys, with domination of transfer of Fe from the counterface for all alloys, which resulted in the formation of a mechanically mixed layer. The relationship between alloy composition, deformation below worn surface and wear resistance is discussed.

Keywords: Dry sliding, wrought aluminium alloy, depth of deformation, mechanically mixed layer (MML)

ABSTRAK

Kegunaan aloi aluminium yang seringkali ditemui dalam bentuk komposit kian meningkat digunakan di dalam aplikasi tribologi. Walaubagaimanapun, sehingga kini tiada penyelidikan yang sistematik dilakukan untuk mengoptimumkan komposisi matriks. Dalam hal ini, khususnya, adalah tidak jelas samada matriks yang diperkuatkan oleh pengerasan kerja, mendakan ataupun serakan yang lebih optimum. Oleh itu, kelakuan penggelongsoran haus kering bagi empat aloi aluminium (A2124, A6092 (kedua-duanya melalui pengerasan mendakan), A3004 (pengerasan serakan) dan A5056 (pengerasan kerja)) disiasat melalui pergeseran terhadap gegelang keluli M2 di dalam julat beban 23-140N pada kelajuan penggelongsoran tetap, 1 ms^{-1}. Kesan haus yang teruk telah dicerap pada kesemua aloi, dengan dominasi pemindahan Fe daripada gegelang ke atas aloi menghasilkan pembentukan lapisan campuran mekanikal. Hubungan antara komposisi aloi, ubah bentuk di bawah permukaan haus dan rintangan haus juga dibincangkan.

Katakunci: Gelangsar kering, aloi aluminium tempawan, kedalaman ubah bentuk, lapisan campuran mekanikal (LCM)

INTRODUCTION

Aluminium alloys are attractive alternatives to ferrous materials for tribological applications due to their low density and high thermal conductivity. However, their uses have been limited by their inferior strength, rigidity and wear resistance (Odani 1994). 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. Applications requiring enhanced friction and wear performances, include brake rotors, engine blocks and cylinder liners, connecting rods and pistons, gears, valves, pulleys, suspension components, etc (Noguchi & Fukizawa 1993).

Despite numerous reports (Ghazali et al. 2005; Perrin & Rainforth 1997 & Rainforth 2000) on the wear behaviour of Al alloys, there has never been a systematic investigation on the role of the matrix composition. Whether lubricated or dry sliding, there is evidence that substantial work hardening occurs at the worn surface. Thus, in this respect, a work hardening alloy (such as A5056) may have advantages over a precipitation hardened alloy, since the latter may exhibit low work hardening rates through the shearing of precipitates by dislocations, which is a work softening mechanism. In addition to work hardening, the adhesion between contact surfaces usually results in transfer and mechanical mixing. This appears to occur for the boundary lubricated condition as well as in dry wear (Rainforth 2000). Moreover, the result of matrix/reinforcement bonding in aluminium based MMCs is often undesirable as it may induce reduced ductility and fracture toughness (Diaz et al. 1996). Thus, in determining the effect of different combinations of matrix alloy and reinforcement, one must first study the performance of the matrix material itself.

This study seeks to determine the effect of Al-alloy composition on dry wear behaviour against a ferrous counterface. In particular, the effect of alloy composition on work hardening behaviour was investigated. Furthermore, the effect of the alloy composition on the formation of the MML and its consequent effect on wear rate were also examined.

EXPERIMENTAL

The A2124, A5056 and A6092 alloy samples were made by a powder metallurgy route. The pre-alloyed powders were produced via inert gas (argon) atomisation and were supplied with an average particle size of about 25 μm (the exact value depended on alloy composition). Following cold pressing, each powder was extruded into 8-10 mm diameter rods at an extrusion ratio range of 28:1-30:1 and temperature of 400-490°C. The A3004 was supplied by Alcan in hot-rolled slab form. The compositions of the wrought Al-alloys are given in Table 1.

The wear tests were carried out using a Cameron-Plint multi-purpose friction and wear-testing machine with a block-on-ring configuration, under dry sliding conditions. The

Table 1. Compositions of wrought aluminium alloys studied (%wt)

Alloys	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Ni	Al
A2124	<0.05	0.04 ± 0.02	4.42 ± 0.04	0.94 ± 0.02	1.35 ± 0.02	<0.02	<0.02	<0.01	<0.02	Bal.
A3004	<0.05	0.38 ± 0.02	<0.02	1.08 ± 0.02	<0.02	<0.02	<0.02	<0.01	<0.02	Bal.
A5056	<0.05	<0.02	0.05 ± 0.02	0.12 ± 0.02	4.95± 0.04	<0.02	0.09± 0.02	<0.01	<0.02	Bal.
A6092	0.31 ± 0.02	0.05 ± 0.02	1.01 ± 0.02	<0.02	1.05 ± 0.02	<0.02	<0.02	<0.01	<0.02	Bal.

tests were performed at four different loads namely, 23, 42, 91 and 140 N with a fixed sliding speed of ~1ms^{-1} at room temperature of ~22.5°C and ~30% humidity. The wear test contact surfaces of the Al-alloys were metallographically polished to a 0.25μm diamond finish. A M2 steel with hardness of 800-850HV$_{20kg}$ was used as the counterface in the form of flat ring of 10 mm width and 60 mm diameter, which was also metallographically polished prior to each test. Wear samples were cleaned with methanol and weighed to an accuracy of ± 0.001g prior to testing and at 30 minute intervals during the test. Wear debris was collected in a tray located directly beneath the sliding couple that collect all the free debris.

The worn surface was characterised by scanning electron microscopy (SEM) (Jeol JSM6400). Energy dispersive X-ray spectroscopy (EDS) was performed using an Oxford Exl system on the Jeol JSM6400. Quantitative EDS values reported were taken from an average of 10 analyses at different regions. Measurements of the thickness of the mechanically mixed layer were taken from 10 random positions along the surface of one section followed by resectioning and a further 10 random measurements. Microhardness measurements as a function of depth below the worn surface were carried out on polished specimens using a Leco hardness tester with a Vickers indenter. For each test, a load of 100g was applied for 15 seconds.

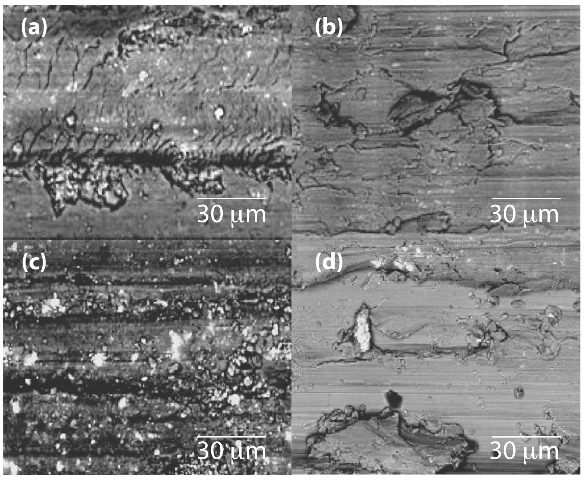


Figure 1. SEM micrographs showing
(a) cracking within the Fe-riched regions of A5056 at 140 N
(b) highest plastic deformation at the lowest loads of A3004
(c) widespread transfer of the A6092 at 23 N and
(d) protrusion (as shown by arrow) of transferred material on the worn surface of 6092 at 140 N

RESULTS AND DISCUSSIONS

Wear Mechanism and The Role of The MML

The wear mechanisms observed are consistent with Archard (1953) adhesive wear characterised by plastic ploughing and transfer of material from the counterface. The difference between the worn surfaces of the alloys was also difficult to quantify, often with greater variability observed within a single sample than from sample to sample. All alloys exhibited plastic grooving, transfer and delamination from regions of transfer. Cracking within the Fe-riched regions was evident for the A5056 at 140 N (Figure 1a). The A3004 exhibited the most plastic deformation at the lowest loads as shown in Figure 1b. The evidence of recent transfer from the counterface was common and often associated with fine, loosely held particles on the surface and fine scale abrasive grooves. Figure 1c shows an example of this for the A6092 at 23 N, where this type of transfer appeared to be more widespread than for the other alloys. Backscattered electron images (BEI) in Figure 1d, showed the presence of transferred material being protruded on the worn surface.

Wear debris formation appeared to occur by two principal mechanisms, namely, the physical displacement of material from the worn surface by the ploughing action of the hard tool steel asperities, and delamination of large sheets (up to 1mm in extent at 140 N). The thickness of the delamination sheets (Figure 1) was broadly consistent with the thickness of the measured MML (Figure 2), although it could not be defined with certainty whether delamination occurred within the MML or at the MML/substrate interface. However, the longitudinal cross-sections suggested that combination of both mechanisms were the probable cause of wear.

The specific wear rate of all materials decreased with load as shown in Figure 3, indicating that the materials were effectively more wear resistant at the highest loads. This effect was most pronounced for the A3004, which showed the greatest decrease, such that, despite exhibiting the highest specific wear rate at 23 N, its wear resistance was similar to all other materials at the highest load. On the other hand, only a modest decrease in specific wear rate with load was observed for the A2124 sample.

Since the principal wear mechanism was the delamination of the MML (part or whole), it would be reasonable to expect a correlation between MML thickness and specific wear rate. This relationship is plotted in Figure 4. The specific wear rate was relatively insensitive to MML thickness for the A3004 and A5056 samples, although the specific wear rate decreased linearly with increasing MML thickness. In contrast, for the A2124 and particularly the A6092, the specific wear rate was a strong function of the MML thickness. Although a reasonable linear fit was possible for the A2124, the A6092 data was better represented by an exponential fit. Since this data did not fit the same trend as the other alloys, the experiment was repeated and measurements re-taken, but with essentially the same result. Thus, the difference in behaviour of this alloy appears to be reproducible.

Interestingly, the two alloys where the specific wear rate was relatively insensitive to MML thickness also exhibited MMLs with the least Fe content (Table 2), and the most homogeneous structure (Figure 5). Conversely, the A6092 exhibited the highest Fe content, the most

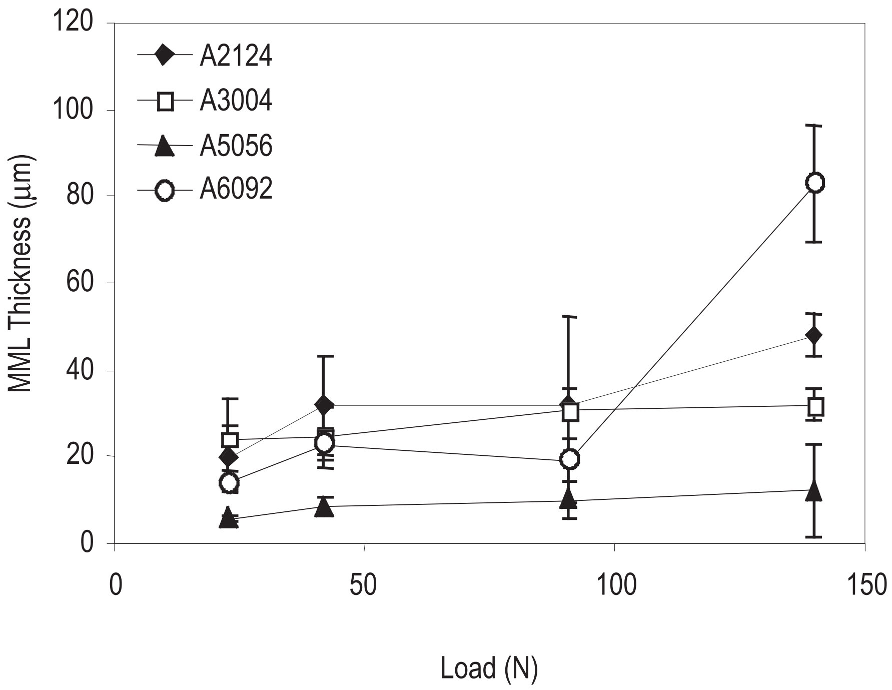


Figure 2. Thickness of the mixed layer after 10.8 km of sliding distance as a function of applied load

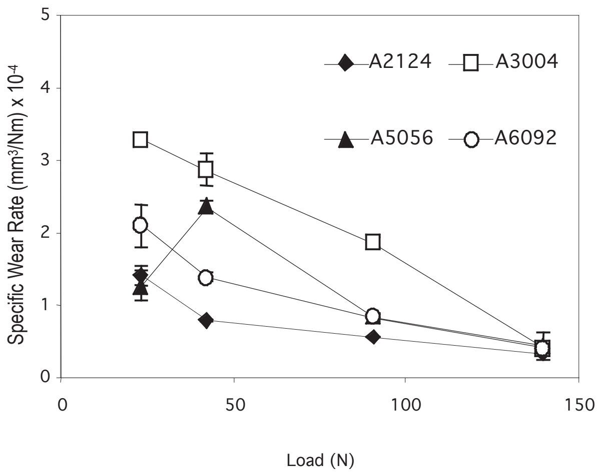


Figure 3. Specific wear rate (K′) as a function of applied load for all alloys

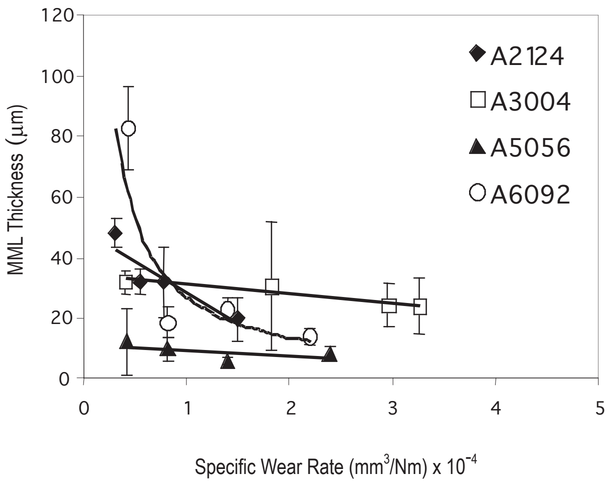


Figure 4. The relations between MML thicknesses below the worn surface and the specific wear rates

Table 2. Average quantitative EDS analysis on MML of Al-alloys

Element	Alloys							
	A2124		A3004		A5056		A6092	
	42N	140N	23N	140N	23N	140N	42N	140N
Mg	1.8	2.0	-	-	6.8	6.8	1.0	1.7
Al	85.3	73.4	94.9	95.3	80.5	86.8	61.8	79.9
Si	1.0	-	0.7	0.8	1.0	0.4	1.6	1.1
Mn	1.1	1.4	2.5	1.1		-	0.3	-
Fe	6.6	19.1	1.9	2.7	11.7	6.0	34.5	15.9
Cu	4.3	4.1	-	-	-	-	0.8	1.3

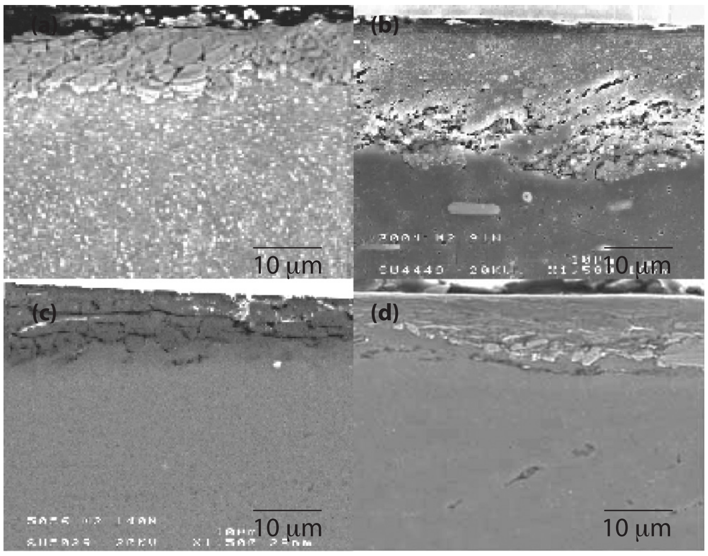


Figure 5. Higher magnifications of longitudinal cross sections of
(a) A2124 at 23 N (b) A3004 at 91 N (c) A5056 at 140 N (e) A6092 at 91 N

heterogeneous structure and the greatest influence on the specific wear rate.

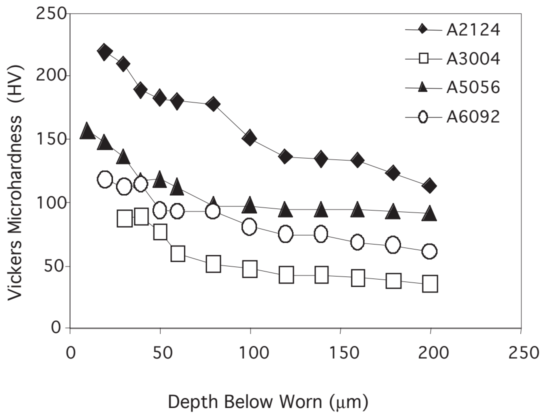
With the exception of the wear data at 42N, the A5056 alloy was slightly inferior to that of A2124. However, the surface characteristics were very different to A2124. Minimal surface hardening was observed, even though this alloy shows substantial work hardening ability in conventional cold working operations. This apparent anomaly is probably a result of frictional heating. As shown by Zhu et al. (2000), the flow stress of A5056 decreases rapidly with increase in temperature.

The thickness of the MML cannot explain the dramatic drop in specific wear rate with load observed for the A3004 alloy. The thickness of the MML is only one of several potential ways in which the MML can affect wear rate. Clearly, the mechanical properties of the MML (in particular hardness and fracture stress) and its adhesion to the substrate are contributing factors to wear. It is also clear that the alloy composition had a strong effect on the structure, thickness and composition of the MML. Repeated tests were undertaken and for each test multiple sectioning demonstrated that the results were reproducible. Therefore, the alloy composition did appear to control the extent of adhesion and material transfer in-line with the classical adhesion theory. Nevertheless, the situation was complex and other factors such as subsurface work hardening and ductility limit could have contributed to the evolution of the MML.

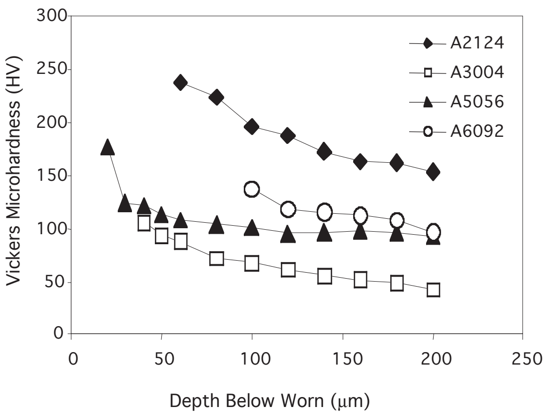
Sub Surface Deformation

Since the friction coefficient was above ~0.3 in all tests (Ghazali et al. 2005), the general form of the shear stress as a function of depth should be the same for all the tests reported here (Kapoor and Johnson 1994) and therefore the depth of deformation should be linearly related to wear rate, the true contact area and the asperity contact radius (Kuhlmann-Wilsdorf 1981).

Figure 6 shows the work hardening behaviour at the worn surface of alloys, at the lowest and the highest loads, with an exception for the A3004. All alloys exhibited the same basic form of work hardening, as expected from the friction coefficient and as reported by other workers (Perrin & Rainforth 1997 & Rainforth 2000). At both loading conditions, the A2124 exhibited the greatest hardening, whereas the behaviour of the A5056 and A6092 was similar. The MML will have had higher stiffness and yield strength than the substrate, which would have modified the true contact area. Moreover, this study also suggests that the MML's properties changed with Al-alloy as discussed above.



(a)



(b)

Figure 6. Microhardness as a function of depth below the worn surface, for (a) 23 N and (b) 140 N. The first datum corresponds to the depth where the first metal is found below the MML

CONCLUSIONS

Not surprisingly, no single variable (MML thickness, degree of hardening) can account for the wear rates observed. The greatest wear resistance was exhibited by the A2124. This alloy showed the greatest initial hardness and the most surface hardening at all loads. It also exhibited the largest MML thickness, except at 140 N, where the exceptional behaviour of the A6092 occurred. The MML was largely an agglomeration of fine, fragmented particles, with a high Fe content. Thus, the combination of hard substrate and hard MML appears to be responsible for the high wear resistance.

The A6092 produced intermediate behaviour, with values of wear rates, thickness of the MML and depth of deformation to the other alloys. The exceptional increase in both MML thickness and depth of deformation at 140 N was confirmed by repeated tests. The MML in this alloy contained the highest Fe content (apparently promoted by the Si in the alloy) and was strongly stratified, a structure which appeared to promote easy crack propagation through the MML parallel to the surface.

As for the A5056, a lower specific wear rate at the highest load appeared to be associated with proportionately thinner surface damage accumulation and a more homogeneous, crack free MML. The A5056 consistently exhibited the smallest MML, and the thinnest total depth of deformation. Thus, by confining damage accumulation to a smaller depth, less wear resulted. It is also proposed that the greater homogeneity of the MML, reduced delamination sheet formation rate and/or delamination sheet thickness.

Finally the A3004, being the softest alloy, exhibited the most substantial reduction in specific wear rate with load, being the highest at 23 N of all alloys by some margin, but similar to the other materials at 140 N. Its MML contained the least amount of Fe and appeared to have the most homogeneous and crack free structure. The thickness of the MML was substantial at the lower loads, but remained approximately constant as the load increased. Similarly, the depth of deformation of this alloy was the highest, and it exhibited the least hardening at 23-91 N. However, no significant changes in deformation was observed at 140 N when compare to that of other alloys.

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REFERENCES

Archard, J.F. 1953. Contact and Rubbing of Flat Surfaces. *Journal of Applied Physics*. 24(1): 18-28.

Diaz, C., Conzalez-Carrasco, J.L. Caruana, G. & Lieblich, M. 1996. Ni_3Al Intermetallic Particles as Wear-resistant Reinforcement for Al-base Composites Processed by Powder Metallurgy. *Metallurgical And Materials Transactions A*. 27A: 3259-3266.

Ghazali, M.J., Rainforth, W.M. & Jones, H. 2004. Dry Sliding Behaviour of Some Wrought Rapidly Solidified Powder Metallurgy Aluminium Alloys. *Wear*. 259: 490-500.

Kapoor, A. & Johnson, K.L. 1994. Plastic Ratchetting as a Mechanism of Metallic Wear. *Proceedings of Royal Society of London Series A*, 445 pp. 367-381. London UK.

Kuhlmann-Wilsdorf, D. 1981. Dislocation Concepts. in Friction and Wear in D. A. Rigney (Ed.), *Fundamentals of Friction and Wear*, pp. 119-186. New York: ASM.

Noguchi, M. & Fukizawa, K. 1993. Aluminium Composite Lines Cylinders. *Advances in Materials and Processes*. 143(6): 19-21.

Odani, Y. 1994. Aluminium Alloys. *Metal Powder Report* 49: 36-40.

Perrin, C. & Rainforth, W.M. 1997. Work Hardening Behaviour at the Worn Surface of Al-Cu and Al-Si Alloys. *Wear*. 203/204: 171-179.

Rainforth, W.M. 2000. Microstructural Evolution at the Worn Surface: A Comparison of Metals and Ceramics. *Wear*. 245: 162-177.