FRACTURE AND FATIGUE OF Al_2O_3-BASED MICROSPHERE / 6061-T6 ALUMINIUM METAL MATRIX COMPOSITE

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ABSTRACT

The fracture and fatigue behaviour and mechanical properties of COMRAL-85™, a 6061 aluminium-magnesium-silicon alloy reinforced with 20 volume percent Al_2O_3-based polycrystalline ceramic microspheres, and manufactured by a liquid metallurgy route, have been investigated. Fracture toughness tests were performed using short bar and short rod (chevron-notch) specimens machined from extruded 19mm diameter rod, heat treated to the T6 condition. The fracture toughness in the R-L orientation was found to be lower than in the C-R or L-R orientations owing to the presence of particle-free bands in the extrusion direction. All values were considerably less than the toughness of the monolithic matrix alloy. Fatigue testing was conducted on both notched and smooth round bar specimens of COMRAL-85, Al 6061-T6 and six powder metallurgy composites with particle volume fractions ranging between 5 and 30 percent. The fatigue threshold results were very similar for all the composites, being lower than for the matrix alloy. S-N data revealed that the powder metallurgy composites gave longer fatigue lives than the matrix alloy, whereas COMRAL-85 exhibited a reduced fatigue life.

KEYWORDS

Aluminium metal matrix composite, COMRAL-85, Al 6061-T6, alumina-based microsphere, particulate reinforcement, fracture toughness, fatigue threshold, S-N curve.

INTRODUCTION

Aluminium metal matrix composites (MMC's) are potentially attractive materials for aerospace and automotive applications because of their higher specific stiffness and strength, as well as better wear resistance, than unreinforced aluminium alloys. Particulate metal matrix composites (PMMC's) are especially of interest owing to the low cost of the raw materials and fabrication processes required, making them suitable for applications involving relatively high volume production. Their improved properties result from the addition of hard ceramic particles, the size, shape, volume fraction and distribution of which critically affect the mechanical behaviour of the composite. However, PMMC's suffer from the disadvantages of having lower ductility and toughness than the corresponding unreinforced alloys, factors which limit their usefulness in practice.

The PMMC used in this study was COMRAL-85™ (Comalco microsphere reinforced aluminium) produced by a liquid metallurgy route through the addition of a ceramic microsphere particulate (Couper and Xia, 1991; Xia, 1991) and extruded in the form of 19mm diameter rod. COMRAL-85 consists of an aluminium alloy 6061 matrix, the composition limits of which are given in Table 1, containing 20 volume percent of Micral (microsphere alumina). The Micral reinforcement (Xia, 1991) is a fine-grained, polycrystalline ceramic containing two principal phases, mullite ($3Al_2O_3.2SiO_2$) and corundum (α-Al_2O_3), with a size range of 1-40μm (average size 20μm).

Table 1. Composition limits of aluminium 6061 matrix alloy (wt%).

Si	Fe	Cu	Mn	Mg	Cr
0.4-0.8	0.7 max	0.15-0.40	0.15 max	0.8-1.2	0.04-0.35
Zn	Ti	Others (each)		Others (total)	Balance
0.25 max	0.15 max	0.05 max		0.15 max	Al

EXPERIMENTAL

The COMRAL-85™ MMC used in this study was manufactured by a liquid metallurgy route and supplied by Comalco as extruded 19mm diameter rod. The extruded rod was heat-treated to the T6 condition, more specifically, solution treated at 530°C for 90 minutes followed by pre-aging at 175°C for 8 hours. The optical microstructure of COMRAL-85 is shown in Fig. 1, from which it is apparent that the particle distribution is reasonably homogeneous. In addition, composites containing various volume percentages of particles (namely 5%, 10%, 15%, 20%, 25% and 30% - designated as PM5, PM10, PM15, PM20, PM25 and PM30 respectively) were produced by a powder metallurgy route.

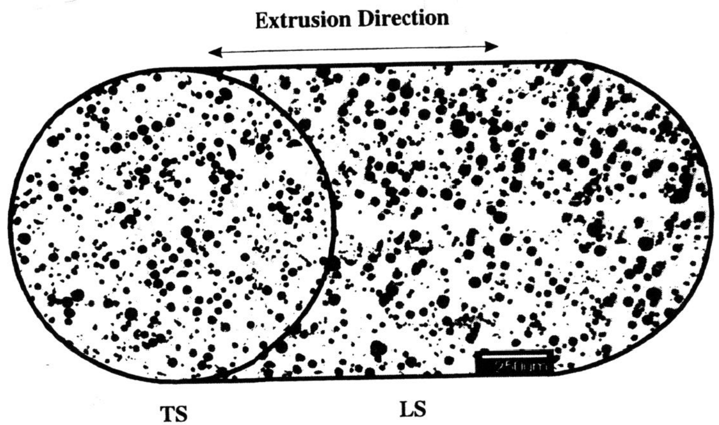

Fig. 1. Optical microstructure of extruded COMRAL-85™ rod (un-etched).

Mechanical properties were determined for the composites and unreinforced Al 6061 alloy extruded to the same diameter and heat-treated to the same schedule. Yield strength, tensile strength and percent elongation were measured on three specimens for each material in accordance with ASTM E8M-91 (ASTM, 1991). Young's modulus was determined using the ultrasonic resonance technique (Couper *et al.*, 1990). The particle size distributions on the fracture surface and on a metallographic section were also investigated with the aid of a Microvideomat 2 image analyser.

Fracture toughness testing was conducted on COMRAL-85 using short rod and short bar (chevron-notch) specimens in accordance with ASTM E1304-89 (ASTM, 1989). The geometry of these specimens and the orientations selected for the study are shown in Fig. 2. Three short rod specimens of R-L orientation with 19mm diameter section, six short bar specimens of L-R orientation 8mm square, and six specimens of C-R orientation also 8mm square, were tested. Results which were invalid due to the p (plasticity) criterion as a result of macroscopic residual stress, which may have been introduced into the specimen via machining, were corrected using the equation provided by Barker (1981).

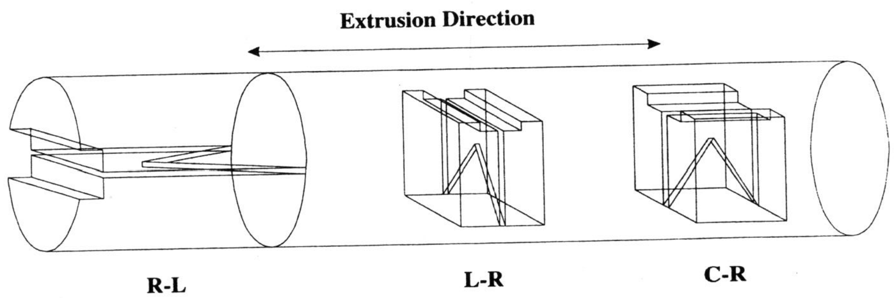

Fig. 2. Geometry and orientation of short rod and short bar fracture toughness specimens.

Fatigue testing was carried out on smooth round bar specimens of COMRAL-85, Al 6061-T6 and the powder metallurgy composites in accordance with ASTM E466-82 (ASTM, 1982). Specimens were of 3mm diameter and 25mm gauge length. Cyclic loading was with a stress ratio R of -1 and a run-out condition of 10^7 cycles. The results of these tests were then plotted as S-N curves. Fatigue threshold data were generated using notched round bar specimens 5mm in diameter (3mm diameter at the notch) using an increasing load technique, with R = -1 and a run-out of $2x10^6$ cycles.

RESULTS AND DISCUSSION

Table 2 contains the results of the tensile tests and other mechanical property data. It is clear that the addition of the ceramic reinforcement leads to an increase in Young's modulus, yield strength and ultimate tensile strength, but a significant decrease in the percent elongation. Figure 3 shows a comparison of the particle size distribution between that found on a polished plane surface chosen at random from the bulk material and that found on the fracture surface for COMRAL-85. The graph shows that there are more particles in all size ranges (except the very small ones) on the fracture surface than in the bulk material, suggesting that the particles play a significant role in the fracture process. The absence of many small particles on the fracture surface indicates that the crack avoids these.

Table 2. Mechanical properties of COMRAL-85™, matrix alloy and powder metallurgy composites in heat-treated condition.

Material	σ_y (MPa)*	σ_{UTS} (MPa)	Elongation (%)	E (GPa)
COMRAL-85-T6	310	340	4†	88
Al 6061-T6	276	310	17‡	68
PM 5	333	357	9.7†	76.6
PM 10	325	351	8.2†	80.8
PM 15	323	347	6.2†	84.4
PM 20	305	339	5.3†	88.6
PM 25	320	353	3.3†	92.7
PM 30	321	345	2.5†	95.2

*0.2% offset stress
†on gauge length of 25mm on 6mm diameter tensile specimen
‡on 13mm diameter tensile specimen

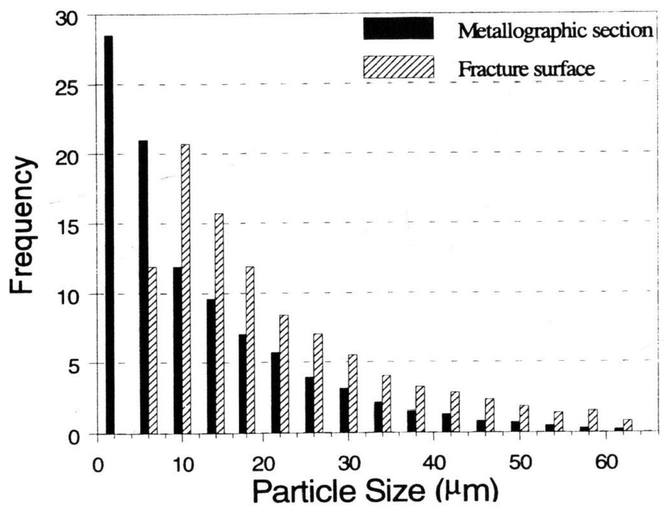

Fig. 3. Comparison of particle distribution between metallographic section and fracture surface.

The average particle size on a metallographic section from the bulk material was found to be 12.7μm, whereas the average particle size prior to blending was 20μm. The reason for this anomaly is thought to lie largely in the different methods of measurement. The latter figure is an average based on 50wt% of particles being less than a certain size, while the former was obtained from image analysis of a plane section through the material (in which a particle intersected away from its equator will appear smaller than it actually is).

The average fracture toughness values of COMRAL-85 in the L-R, C-R and R-L orientations were found to be 20.4, 20.1 and 16.7 MPa√m respectively. These results are comparable with a K_{Ic} value of 18.5 MPa√m obtained by Hadianfard *et al.* (1993) from 75mm wide by 12.5mm thick plate material using 50mm wide compact tension specimens. By comparison, K_{Ic} for monolithic Al 6061-T6 is around 33 MPa√m (Taggart *et al.*, 1976). The fracture toughness values for COMRAL-85 in the L-R and C-R orientations are similar, but that in the R-L orientation is less than the others. The possible factors contributing to this anisotropy are, firstly, the presence of particle-free bands along the extrusion direction and, secondly, anisotropy of the grain structure. Although the particle distribution is relatively homogeneous, there are some localised particle-free regions and these are elongated in cigar shapes along the extrusion direction. In the L-R orientation these particle-free bands are aligned perpendicular to the plane in which the crack propagates. Therefore, the advancing crack could be retarded by them, since they are much tougher than the bulk composite. In the C-R orientation they are aligned in the same plane as, and parallel to, the advancing crack front. As such, these particles constitute a long barrier to the propagating crack. However, in the R-L orientation the particle-free bands are aligned perpendicular to, and coplanar with, the advancing crack front, so that they would not serve to retard its propagation.

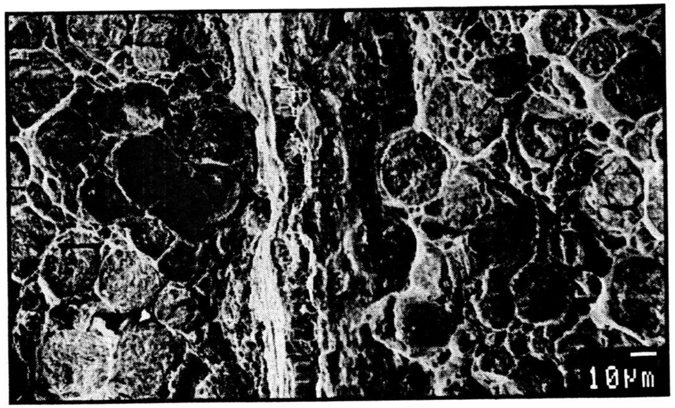

Fig. 4. SEM fractograph from central region of C-R short bar specimen showing particle-free band.

Figure 4 shows an SEM micrograph of the fracture surface. Many broken particles are revealed on the fracture surface and the volume fraction of particles is much higher than that observed in a polished section. This implies that the crack follows the broken particles. From metallographic observation of the crack path, it was found that many particles in front of the crack tip were broken and that the crack then propagates through the weakest ligament between broken particles. Particle-free bands were also apparent on the fracture surface. Based on these observations of the crack path, the existence of particle-free bands clearly has an effect on the fracture toughness value. Anisotropy of the grain structure, on the other hand, would be expected to give a higher fracture toughness in the L-R orientation than in the C-R and R-L orientations. Any such effect in the case of COMRAL-85 is therefore seen to be extremely small. Small sample t-tests conducted on the three sets of results show that the difference in toughness between the L-R and R-L orientations is definitely significant (at the 0.6% level), while the significance of the difference between values from the C-R and R-L orientations is not conclusively established (with only an 8.3% significance level).

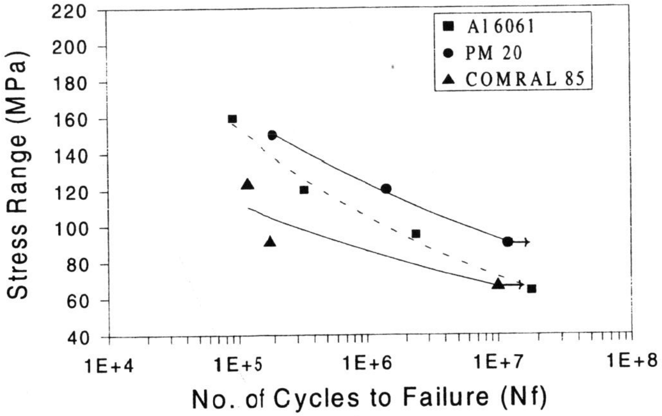

Fig. 5. S-N curves for COMRAL-85™, PM20 and Al 6061-T6.

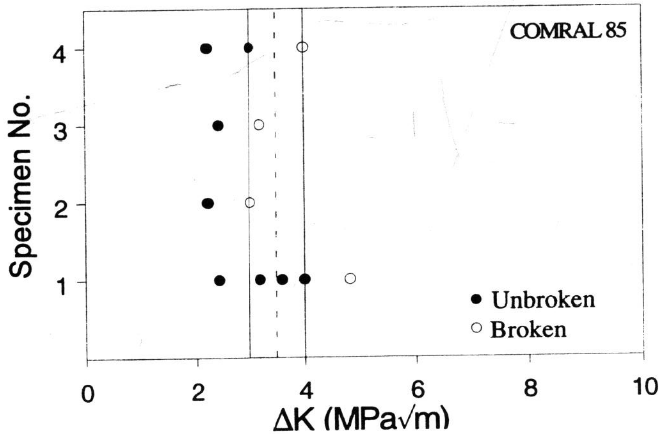

Fig. 6. Fatigue threshold for COMRAL-85™.

Figure 5 shows the S-N data and curves for COMRAL-85, PM20 and the Al 6061-T6 matrix alloy. Although the experimental data are few in number, it is apparent that the powder metallurgy composite exhibits longer fatigue lives than the monolithic matrix alloy, while the liquid metallurgy composite in general gives a shorter fatigue life. The reasons for this are not yet understood, but probably relate to differences in the nature of the particle/matrix interface.

The results of the fatigue threshold tests on COMRAL-85 are given in Fig. 6 from which a threshold value of 3.5±0.5 MPa√m was determined (R = -1). This is lower than the corresponding threshold value determined for Al 6061-T6 of 5.6±2.0 MPa√m. Figure 7 shows the fatigue threshold value plotted against the particle volume fraction for the powder metallurgy composites. The threshold value for PM20 is 3.5±0.3 MPa√m, the same as for COMRAL-85. It is also apparent from Fig. 7 that, apart from a significant drop on introduction of particles, the threshold value varies little with particle volume fraction. A possible explanation for this is provided by cracking of the particles in the vicinity of the notch tip on the tensile peak of the loading cycle. The stress concentration factor for a U-notch of tip radius 0.1mm in a circular shaft corresponding to the fatigue specimen geometry is calculated to be 3.83 (Peterson, 1994). Multiplying this by the peak nominal stress in the notch plane at the threshold value gives a figure in the region of 200 MPa. The strength of the particles is approximately 170 MPa (Comalco, 1990). Even allowing for some elevation of the stress level in the particles over that in the matrix near the notch, due to their higher elastic modulus, it is reasonable to propose that the particle strength alone may determine the fatigue threshold in these cases.

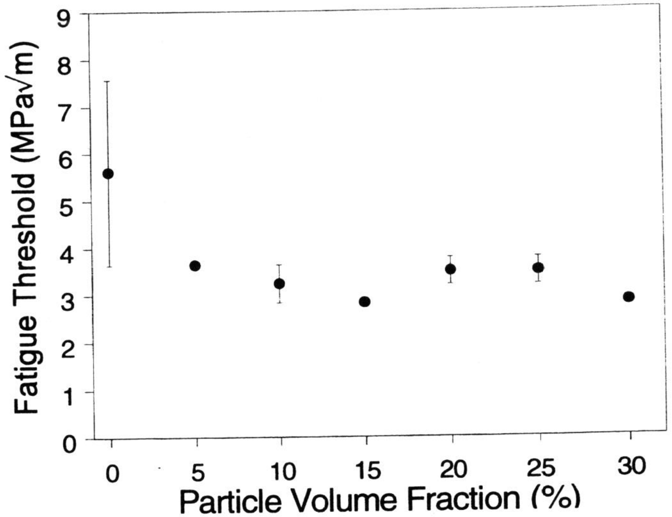

Fig. 7. Fatigue threshold versus particle volume fraction for powder metallurgy MMC's.

CONCLUSIONS

Yield stress, ultimate tensile strength, percent elongation and Young's modulus have been determined for COMRAL-85™, Al 6061-T6 and composites produced by a powder metallurgy route containing 5, 10, 15, 20, 25 and 30 volume percent of Micral reinforcement.

Short bar and short rod (chevron-notch) fracture toughness tests were performed on COMRAL-85 specimens machined from extruded 19mm diameter rod, heat treated to the T6 condition. The fracture toughness value in the R-L orientation (16.7 MPa√m) was found to be lower than in the C-R or L-R orientations (20.1 and 20.4 MPa√m respectively) owing to the presence of particle-free bands in the extrusion direction. These values are significantly lower than K_{Ic} for monolithic Al 6061-T6 (approximately 33 MPa√m).

Fatigue testing was conducted on notched and smooth round bar specimens of COMRAL-85, Al 6061-T6 and powder metallurgy composites, with stress ratio R = -1. All composites exhibited very similar fatigue threshold values (around 3.5 MPa√m) thought to be controlled by the strength of the particles, and lower than that for Al 6061-T6 (5.6 MPa√m). S-N curves were generated and showed that the powder metallurgy composites exhibited longer fatigue lives than the matrix alloy, while the liquid metallurgy composite (COMRAL-85) gave a shorter fatigue life.

ACKNOWLEDGEMENTS

This work was supported by Comalco Research Centre (15 Edgars Road, Thomastown, VIC 3074, Australia) with additional financial assistance through an Australian Research Council small grant. The help and advice provided by Drs. M. J. Couper and K. Xia of CRC as well as Dr. M. I. Ripley of the Australian Nuclear Science and Technology Organisation (Lucas Heights, NSW 2234) are gratefully acknowledged.

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