Effect of fibre–matrix–binder interactions on the matrix composition and age-hardening behaviour of 6061-based MMCs

D. J. TOWLE, C. M. FRIEND
Materials Technology Group, Cranfield Institute of Technology, Shrivenham Campus, Swindon, UK

Reactions between magnesium, alumina fibre and silica binder, during the manufacture of 6061 metal matrix composite (MMC) by the pressure infiltration technique, have been investigated for their effect on the structure, composition and age-hardening response of the MMC with increasing infiltration distance. The structure and composition were examined using optical and scanning electron microscopy, and electron probe microanalysis. The age-hardening behaviour, of both the MMC and unreinforced alloy, was determined using hardness measurements. There was a progressive depletion of magnesium in the MMC with increasing infiltration distance, which was particularly marked when the silica binder content exceeded 1 wt % (in a 20% Vf preform). This has been explained in terms of a reaction which results in the formation of an oxide at the fibre/matrix interface and a release of silicon into the matrix. The depletion of magnesium was associated with a reduction in the age-hardening response of the MMC, consistent with predicted behaviour based on the Al-Mg2Si pseudo-binary phase diagram. In spite of these effects, the overall ageing behaviour of the MMC was enhanced compared with the unreinforced alloy, showing both higher peak-aged hardnsses and enhanced ageing kinetics, particularly at lower ageing temperatures.

1. Introduction

When metal matrix composites (MMC) are fabricated with heat-treatable aluminium alloy matrices, similar ageing characteristics might be expected for both composite and unreinforced material, after allowing for the strengthening increment produced by the reinforcement employed in the composite. However, in practice these composites do not always realize their potential strengths and can even exhibit impaired strengthening when compared with the unreinforced alloy. The kinetics of ageing can also be different and both enhanced and retarded behaviour has been exhibited in different MMC systems.

Some aspects of the ageing behaviour of MMC can be explained by treating the reinforcement as an inert object of a specific shape, size and volume fraction but of different thermal expansion coefficient to the surrounding matrix [1]. In such models the large thermal strain produced in the matrix around the reinforcement is accommodated by either elastic or plastic deformation [2]. Either process can result in a modified response during ageing although the latter process appears to be the most important, in which the ageing behaviour is affected by the increased dislocation densities in the matrix around the reinforcement. It is also important to consider the chemical properties of the reinforcement and matrix and the possible reactions which can occur between these two components of the composite [3,4]. Such reactions could effectively remove chemical species from the matrix by producing reaction products which do not dissolve during solution treatment. These reactions are most severe when the alloy is molten and consequently they are also likely to be influenced by the particular manufacturing process employed to produce the MMC [5].

In the pressure infiltration method for producing MMC a preform consisting of a fibre array is infiltrated by a superheated molten metal. The contact time between the melt and the reinforcement is relatively short due to the rapid solidification of the melt (typically about 1 min). Longer contact times are usual in other methods of MMC manufacture, for example contact times of about 15 min are used for the compocasting technique (at 600/650 °C) [4]. However, in the pressure infiltration technique the alloy may also be several hundred degrees above its upper melting temperature at the onset of infiltration increasing the possibility for reactions between the melt and reinforcement. In addition, the preforms usually contain a reagent such as colloidal or precipitated silica (at a concentration of approximately 2–5 wt % reinforcement) to mechanically bind the fibre array. There exists, therefore, the possibility of complex reactions between the metal matrix, binder and reinforcement. Evidence of matrix–reinforcement and matrix–reinforcement–binder reactions has been shown in several investigations on MMC in particular those based on aluminium alloys containing magnesium [4–6]. However, there is some inconsistency in these
investigations as to the effect of such reactions on the ageing behaviour of MMCs when the matrix alloy contains magnesium as a constituent of an age-hardening phase. One investigation on 6061 MMC has shown an impaired hardening response, compared with the unreinforced alloy [7]. However, two other similar investigations have suggested that the depletion of matrix magnesium was not sufficient to affect the normal age-hardening behaviour of the composite [5, 8], provided the magnesium content of the alloy was sufficiently high [8].

The present work was undertaken to address these inconsistencies. The interaction effects present in a 6061 matrix MMC have been investigated with the aim of identifying their influence on the ageing behaviour.

2. Experimental procedure

2.1. Composite fabrication

The MMC employed in this work was based exclusively on a 6061 matrix (nominally Al-1% Mg-0.6%Si) reinforced with Saffil fibres, of approximate composition 95% δ-alumina and 5% silica. Two types of preform were used, one of which was commercially available and the other was manufactured in house by a standard technique [9]. Both types contained nominal fibre fractions of 20%, $V_f$. The preforms manufactured in-house contained variable silica binder contents which ranged from 0%-5% as shown in Table I. No details of silica content were available for the commercially supplied preforms but these were expected to lie in the range 0%-5%. The table also shows the preform thickness after infiltration and the resulting fibre fractions of the MMC.

The preforms were infiltrated under metallostatic pressure in a preheated cylindrical die as described previously [7, 10], using a melt temperature between 950 and 1000°C, and a die temperature between 350 and 400°C. All the MMCs were sound, with little evidence of porosity and there was little or no crushing of the preforms during infiltration except for the cast containing 0% silica (which was 20 mm thick prior to infiltration).

2.2. Ageing measurements

Hardness specimens (~10 mm x 10 mm x 30 mm) were cut parallel to the axis of the cylindrical casting, so that they contained both the reinforced and unreinforced alloy in a single specimen. The solution treatment employed for the specimens was 550°C for 1 h. After solution treatment, the specimens were first water quenched and then transferred to liquid nitrogen prior to ageing. Isothermal ageing was performed at temperatures of 140, 160 and 178°C.

Hardness was characterized by Vickers Hardness, $H_v$, using a 10 kg load. Approximately ten regularly spaced readings were taken over the full thickness of the MMC. Approximately four readings were taken in the unreinforced region commencing at the interface with the MMC. These two data sets were then averaged to construct the appropriate ageing curves. The specimens used to produce each ageing curve were all taken from the same cast and a separate specimen was used for each ageing time. Although this latter procedure produced some specimen to specimen scatter, an ageing curve could be produced which was characteristic of the whole cast. Selected specimens corresponding to the peak-aged condition were also measured by Rockwell Hardness, $H_{R_p}$, for comparison of the present results with previously published data on the age-hardening behaviour of other 6061 MMC systems.

2.3. Microstructural characterization

Optical microscopy was carried out on selected MMC specimens to examine both qualitatively and quantitatively the distribution of the fibre reinforcement. The distribution and type of second phases within the MMC was also examined. Scanning electron microscopy with energy dispersive X-ray analysis was employed to characterize the second phases identified by optical microscopy. More detailed examination of the magnesium and silicon contents in the region of fibre interfaces, and the distribution of these elements within the MMC was performed by wavelength dispersive X-ray analysis in an electron probe microanalyser. For the latter examination a probe diameter of approximately 5 μm was located in fibre-free regions in the top, centre and bottom of the MMC. Three composition measurements were conducted at each position.

3. Results

3.1. Optical microscopy

The structure of all the MMCs was typical of composites fabricated by the pressure infiltration of fibre preforms. During preforming the fibres are laid down in a mat-like structure and this results in a "two-dimensional planar random" morphology of fibres which is altered little during melt infiltration. In addition there was some clumping of fibres which gave micro variations in fibre density ranging from high to low or even zero fibre regions. This structure and the local variation in fibre distribution are illustrated in Fig. 1 which shows that the fibre-free regions were approximately 50 μm in size. In addition to these effects, Cast 2 also showed some fine planar delaminations within the composite which were parallel to the top surface (i.e. normal to the axis of the cylindrical