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Effect of thermal ageing on hardness, tensile and impact properties of an alumina microsphere-reinforced aluminium metal-matrix composite

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Thermal ageing studies have been carried out with an alumina microsphere-reinforced 6061 aluminium metal-metrix composite (MMC). A solution treatment temperature of 530 °C for 1.5 h and ageing temperature 175 °C with ageing time ranging between 0 and 12 h have been used. It was observed that the hardness achieves a peak value in about 8 h; the ultimate tensile strength shows an increase with increasing ageing time, and reaches a plateau at about 10 h. On the other hand, elongation to failure and impact properties show a sharp decline at approximately 4 h of ageing time. Also, a limited amount of experiments using 175 °C/8 h ageing after solution treatment at 510, 490, 470 and 430 °C for 1.5 h show that the hardness of the MMC deceases steadily as the solution treatment temperature is decreased.

1. Introduction

Metal-matrix composites (MMCs) are receiving increasing attention as engineering materials. However their properties, such as strength, toughness, wear and corrosion resistance, rely on a number of factors. The state of the matrix is very important, because any thermal or mechanical treatment can affect the properties, as can the type of alloy chosen to be the matrix in the first place, and the production process. Other parameters such as the reinforcing phase, its chemical nature, whether it is continuous or discontinuous, how much is added, and in what manner it has been incorporated into the body as a whole, are important considerations.

Whilst addition of the reinforcing phase in the case of continuously fibre-reinforced MMCs gives the highest improvement in strength, work by McDanels [1], however, has shown that for discontinuously reinforced aluminium composites, the most important factor to affect the strength of MMCs is the matrix material. The 6061 alloy, which has been used as a matrix material by a number of researchers, can develop optimum strength after a T-6 temper.

It has been reported that thermal ageing of composites increases the strength, but it also decreases the ductility [2–4]. This is in character with aluminium alloys in general. However, it has been suggested that in thermal ageing, the response of the composite varies quite markedly from that of the control alloy which makes up the matrix, in that the composite can age more quickly and attain a higher peak strength [5]. For a $6061/SiC_{(P)}$ particulate composite, it has been reported that at higher temperatures the composite aged faster, whilst at lower temperatures the plain alloy aged faster. This was also the case for 6061 reinforced with Al_2O_3 particles [3]. The transition temperature, was found in both cases to be 190 °C. This was explained as representing the nucleation differences of the hardening precipitates.

This explanation given for the differences in ageing responses of materials lies in the reaction of the composite to thermal cycling. As the composites are quenched from their thermal treatment, the difference in thermal expansion coefficient for the matrix and the reinforcement creates thermal stresses, which in turn increases the dislocation density [5]. The dislocations are favoured sites for precipitation nucleation and growth, with the result that more precipitates can grow, earlier. This was also reported by Salvo *et al.* [3], who showed that aged composites have more and finer precipitates for ageing at a certain temperature and time, in relation to the unreinforced alloy. It was also found that changing the nature of the reinforcement from SiC to Al_2O_3 did not produce any major changes to the ageing response, as these two reinforcement materials have very similar thermal expansion coefficients.

In the work presented here, ageing studies have been carried out on specimens of Al_2O_3 particulate-reinforced 6061 aluminium alloy, and the effects of ageing on the hardness, tensile and impact properties of the composite have been determined.

2. Experimental procedure

The material studied was Comral-85 containing 20% microspherical Al_2O_3 particles in 6061 aluminium [6], produced by Comalco Research Centre, Thomastown, Victoria, Australia. The materials provided were in the form of (a) 19 mm diameter extruded rod and (b) 12.5 mm thick, 75 mm wide rolled plates; a typical microstructure of Comral-85 is shown in Fig. 1. The average size of the particles is, according to the supplier, approximately 20 μm. Specimens for hardness and tensile testing were obtained from the rods, while Charpy impact specimens were machined from the plate.

The thermal ageing treatment employed in the programme was to heat the specimens to T-6 temper, which consisted of the following steps:

(a) solution treat at 530 °C for 1.5 h,
(b) quench in water to ambient temperature,
(c) maintain at room temperature for 20 h (pre-ageing),
(d) Thermally age at 175 °C as a function of time up to 12 h, the optimum time for 6061 being 8 h.

The heat treatment was carried out in a fluidized bed-type furnace (Fig. 2). This consisted of a vertical cylindrical bed of fine fluidized alumina particles. The fluidization ensured that the heat was evenly distributed over the entire sample. The temperature accuracy of this type of furnace was ± 1 °C.

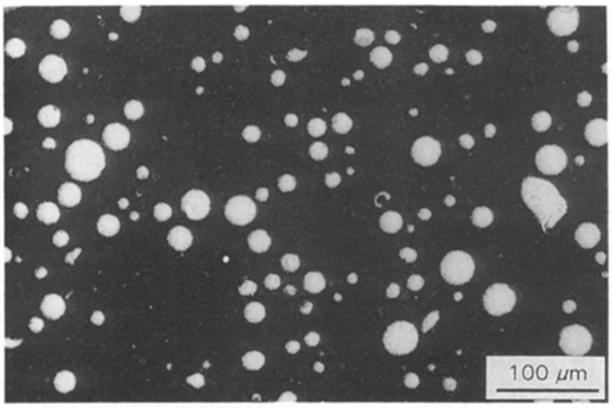


Figure 1 Al_2O_3 particles in MMC.

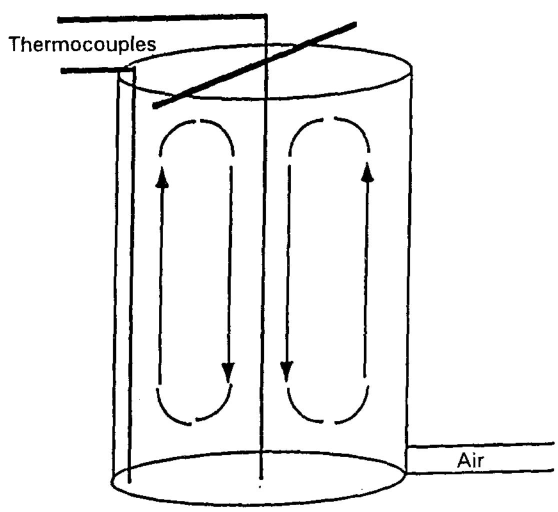


Figure 2 Schematic diagram of the fluidized bed furnace used in heat treatment.

Hardness specimens approximately 15 mm thick were sliced from the rod using a hacksaw blade. The faces were then polished to a finish suitable for hardness measurements. For these measurements, one specimen was aged at 175 °C for each of the times from 0–12 h at 1 h increments. Hardness measurements were then done by a Vickers miniload microhardness tester with a load of 50 g. Five readings were taken for each specimen and the average obtained.

Tensile test specimens following ASTM E8 Standard were machined to the dimensions given in Fig. 3. After solution treatment, the specimens were aged at 175 °C for 0–12 h at 2 h increments. An Instron model 1185 machine was used for the tensile testing. A crosshead speed of 1 mm $\min^{-1}$ was used for the tensile tests, and duplicate specimens used for every ageing time used. The elongation to failure and ultimate tensile strength (UTS) were determined as a function of the heat treatment time.

Impact specimens were machined (using conventional methods, i.e. tungsten carbide cutters) to conform to ASTM E23 type A Charpy V-notch geometry (Fig. 4). Duplicate specimens were machined in the "as-rolled" directions (y), and tested at 2 h intervals of ageing time, with five specimens machined in the "transverse" direction (x).

Fracture surfaces of tensile and impact specimens were examined in a Jeol scanning electron microscope (SEM); some limited transmission electron microscopy (TEM) was also carried out using a Jeol micro-

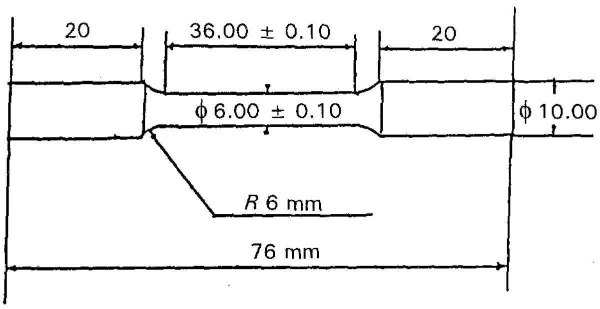


Figure 3 Configuration of tensile test specimen.

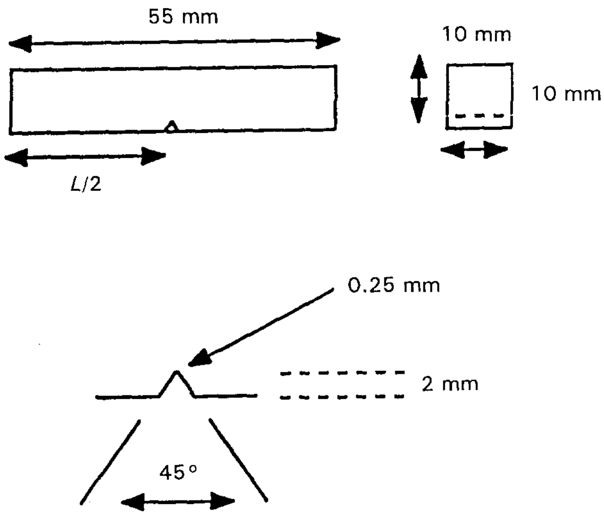


Figure 4 Charpy V-notch impact specimen geometry.

scope, to examine the effect of thermal ageing on the matrix microstructure.

In addition to the standard T-6 heat treatment, a set of experiments were also carried out where the solution treatment temperatures were less than that recommended (530 °C), and only one ageing condition, i.e. 8 h at 175 °C, was used. For these specimens only hardness measurements were undertaken. The purpose of this experiment was to examine whether a lower solution treatment temperature of the composite results in a loss of hardness, as is expected in this matrix 6061 alloy.

3. Results and discussion

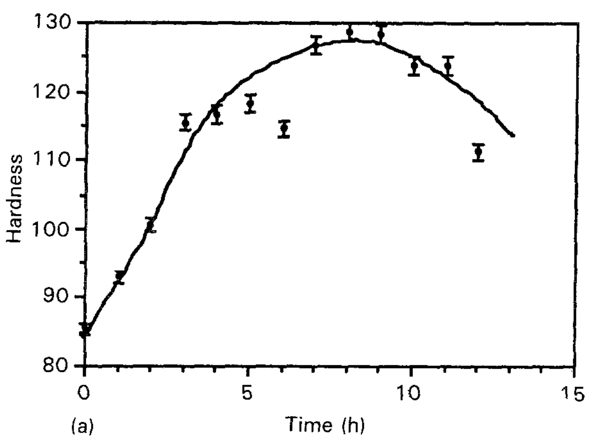
3.1. Hardness

The hardness of the composite increases as the ageing time increases (Fig. 5a), a peak hardness being achieved at about 8 h, which is about the same length of time as in unreinforced 6061. The microhardness values achieved in the composite in solution-treated and peak conditions are about 82 and 129, respectively, compared to 63 and 115 for unreinforced 6061 under similar conditions of heat treatment [7]. Normally, in particulate reinforced MMCs, especially those containing very small particles distributed in the matrix, the hardness indentation includes a number of the particles, an aspect which has been addressed elsewhere [8]. However, in the present study it was possible to make the microhardness indentation solely within the matrix (Fig. 5b). The hardness values presented in Fig. 5a can thus be considered as a true indication of the ageing response of the matrix.

3.2. Tensile properties

The tensile strength as a function of ageing time is shown in Fig. 6, where it is clear that the strength of Comral-85 is significantly improved by heat treatment. The peak strength values are almost 25% more than the value for 6061 alloy in the peak aged condition [4, 9]. The strength reaches a plateau after treatment of the composite for between 10 and 12 h. This is significant, as the peak ageing time for normal 6061 is usually 8 h. The response of the microsphere-reinforced alloy would thus appear to be slower than normal in responding on the heat treatment.

The normal mechanisms of strengthening during thermal ageing involve precipitation of Guinier–Preston (GP) zones to create stresses in the matrix and make dislocation movement more difficult. The composite at 8 h appears to have a vast network of rod-shaped GP zones (Fig. 7), as well as a small amount of Mg_2Si particles. Any further heat treatment would



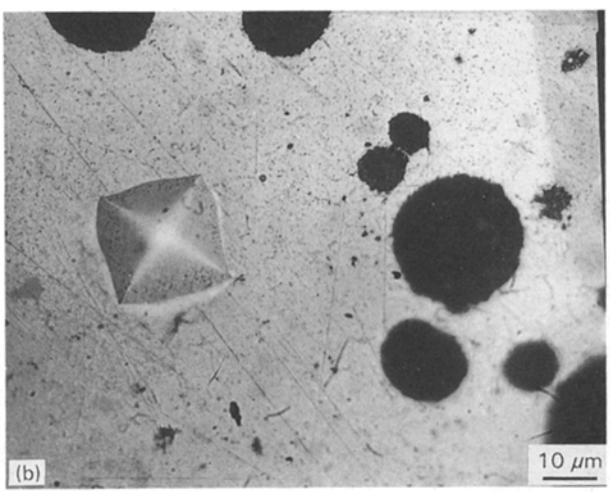


Figure 5 (a) Hardness versus ageing time at 175 °C for the composite; (b) Microhardness indentation taken in the matrix.

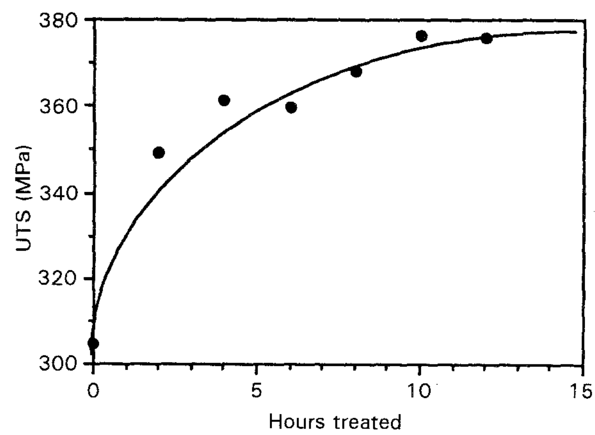


Figure 6 Ultimate tensile strength of the composite versus ageing time at 175 °C.

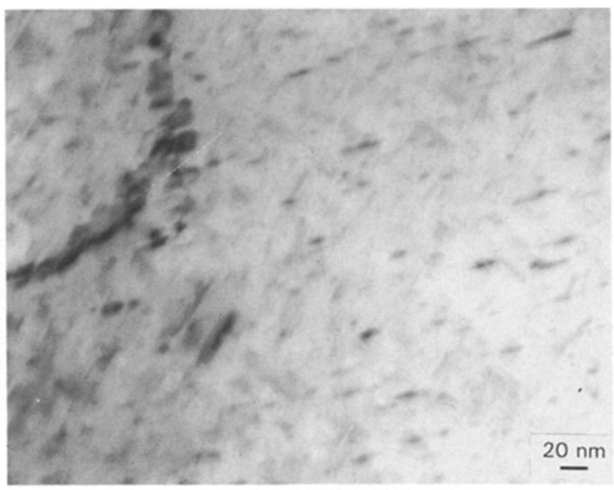


Figure 7 TEM picture of the MMC aged at 175 °C for 8 h, showing bands of dislocations.

only produce more Mg_2Si particles and decrease the strength.

The mechanism of fracture, as revealed by SEM (Figs 8 and 9), shows that fracture occurred by a mixture of microvoid coalescence and brittle failure of the particles. In some cases, particle pull-out can be seen (Fig. 10).

The elongation to failure as a function of ageing time is shown in Fig. 11. The results show a definite trend of decreased ductility with increased treatment time. If the particles were the initiator of fracture, then it would be natural to assume that the decrease in ductility arises from the increased amount of Mg_2Si that is precipitating in the matrix. A correlation could therefore be seen to exist between the rise in strength and the decrease in ductility caused by the precipitates.

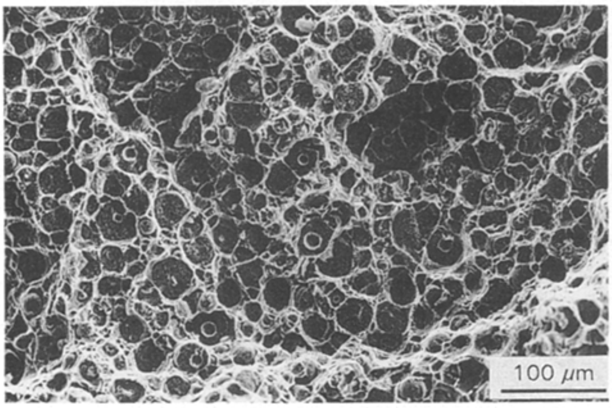


Figure 8 SEM photograph of tensile fracture surface aged 2 h at 175 °C.

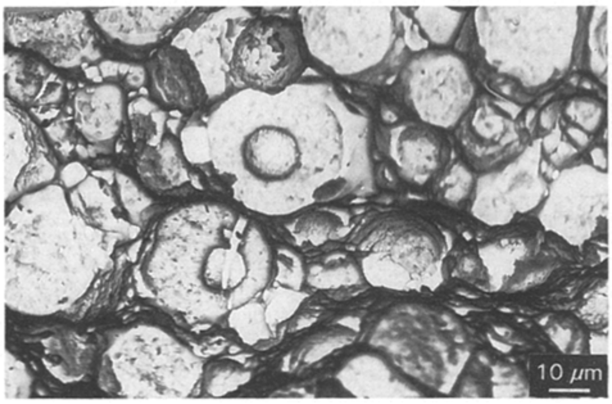


Figure 9 SEM photograph as Fig. 8 at higher magnification.

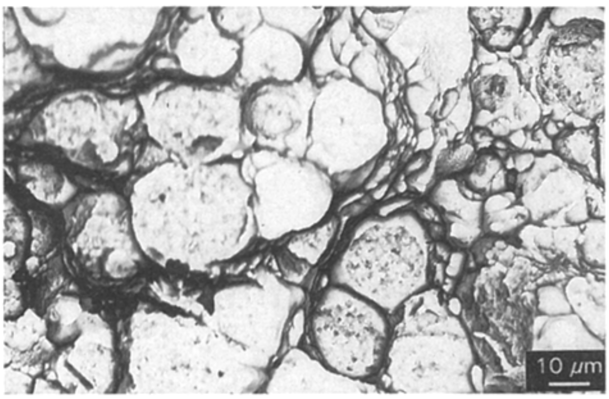


Figure 10 Fracture surface of specimen aged 2 h at 175 °C, showing particle pull-out.

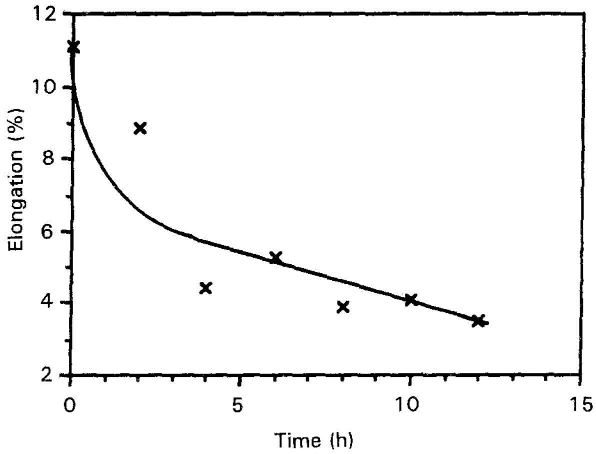


Figure 11 Elongation of failure versus time of ageing at 175 °C for the composite.

Some additional observations can be made on the tensile fracture surfaces presented in Figs 8–10. The fracture surface gives the impression that a very large portion of the surface is occupied by particles, implying apparently that the volume fraction of particles is far above the nominal 20% composition. An explanation of this is that the particles have broken preferentially to the matrix and the fracture path in uniaxial tension follows the particles, which gives the visual impression that there are more particles than there should be. Further, cracks are also seen in many of the particles on the fracture surface. It is likely that the thermal shock produced by quenching of the alloy from 530 °C to room temperature has resulted in particle cracking.

3.3. Impact resistance

A plot of impact resistance as a function of ageing time can be seen in Fig. 12. It is obvious that age hardening, even for 2 h, makes the material considerably brittle compared to the solution treated condition. The impact values for the x and y directions are not significantly different, indicating that the material is generally isotropic. The solution-treated alloy is much more ductile, possibly due to the absence of any precipitates. Consequently, the sharp decrease in ductility may be related to the first appearance of the GP zones and small embryonic precipitates. It is worth noting that the shapes of the curves for elongation versus time (Fig. 11) and impact energy versus time (Fig. 12) have a similar appearance.

Examination of two impact samples (Figs 13 and 14) representative of the transition region (2 h of ageing) and very brittle failure (10 h ageing) shows some difference at high magnification in the SEM. The first specimen provides some evidence of ductile failure. The matrix between the particles has drawn to some extent, although the particles are still firmly

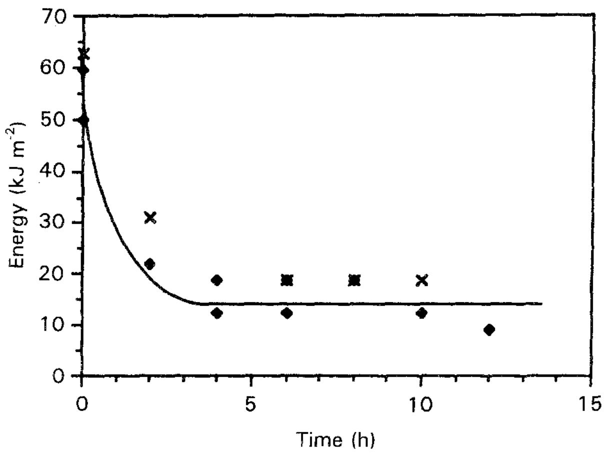


Figure 12 Charpy impact energy versus time of ageing at 175 °C for the composite.

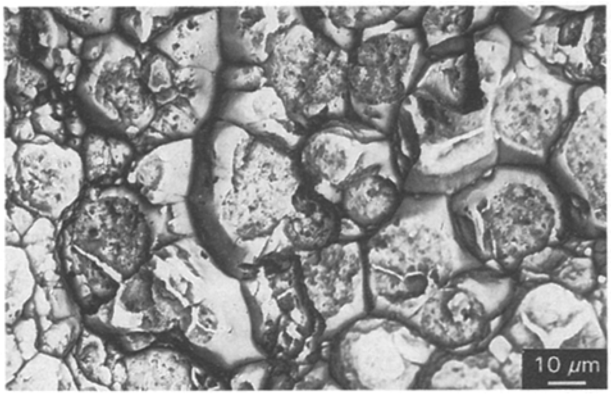


Figure 13 SEM fracture surface of an impact specimen aged for 2 h at 175 °C.

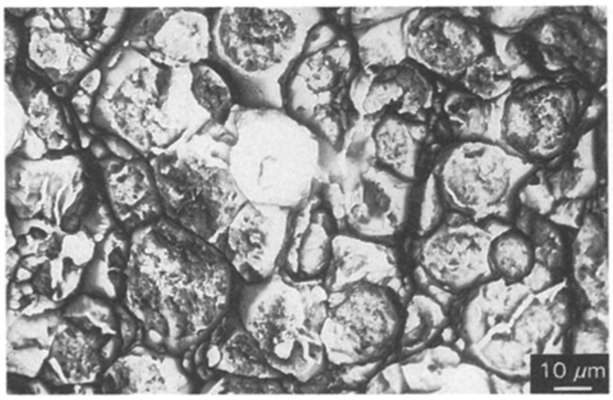


Figure 14 SEM fracture surface of an impact specimen aged for 10 h at 175 °C.

embedded in the matrix. There is evidence of microsphere cracking; however, there does not appear to be any preferential direction taken by these cracks. The sample that was aged for 10 h does not appear to have as much drawing of the matrix. This agrees qualitatively with the observed values for energy absorption, which are significantly lower. Microsphere cracking is still in evidence. In both samples the distance of the particles from the notch root does not appear to have any effect on the cracking of these particles.

TABLE I Hardness after ageing at 175 °C for 8 h from different solution treatment temperatures

Solution treatment temperature (°C)	Vickers microhardness
530 (optimum)	127
510	89
490	66
470	72
450	60
430	49

The effect on MMC hardness of ageing at 175 °C for 8 h for specimens quenched from different off-optimum solution treatment temperatures is shown in Table I. It is obvious from this table that the solution treatment temperature has a distinct effect on the microhardness of the material in the aged condition. This is expected of the unreinforced aluminium matrix and it appears, for the composite material, that the presence of the particles has not been of any considerable advantage.

4. Conclusions

(a) Thermal ageing studies of Comral-85 at 175 °C for various times (0–12 h) after solution treatment at 530 °C for 1.5 h show that peak hardness is achieved at approximately 8 h of ageing.

(b) The tensile strength of the composite generally increases as the time of ageing increases. The increase is greater during the early hours of ageing and at around 10–12 h this increase tends to taper off.

(c) The elongation to failure and impact energy show a marked reduction during the early hours of ageing, making the alloy brittle after an ageing time of approximately 2–4 h.

(d) Ageing at 175 °C for 8 h after off-optimum solution treatment temperatures indicates that there is a rapid decrease in the matrix hardness as the solution treatment temperature is decreased.

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