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Effects of TAHA treatments on the fatigue life of a 7075 aluminium alloy

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The effects of TAHA treatments including pre-ageing, plastic deformation and final-ageing on the fatigue life of a 7075 Al–Zn–Mg alloy were investigated. Pre-ageing was carried out at 100° C (TAHA1) and room temperature (TAHA2). Experimental results indicated that the improvement in fatigue life due to TAHA1 and TAHA2 was at least 19.5 and 26%, respectively, when compared to the conventional T–6 treatment. Scanning electron microscopy showed that fracture features such as dimple distribution, fatigue striation, tearing ridge and platelets could be correlated with fatigue behaviour. The correlation between the peak fatigue life, peak elongation, residual stress and substructure, such as subcell and precipitate, is also discussed.

1. Introduction

Due to its high strength to weight ratio, low cost and good formability, 7075 Al–Zn–Mg alloy is a popular choice of material for application in lightweight structures and subsonic aircraft systems. Unfortunately, though, the use of high-strength 7075 Al–Zn–Mg alloy is limited by its relatively poor fatigue properties. In order to improve its fatigue strength, several thermomechanical treatment (TMT) processes have been tried [1, 2]. In 1973 Di Russo *et al.* [3] developed an interesting variation of TMT, called the TAHA process, in which step ageing was employed. By this process one obtained better strength, ductility and fatigue properties. Rack *et al.* [4] suggested that pre-ageing may refine the precipitates, and that plastic deformation during the TAHA process may cure the reversion effect in Al–Zn–Mg alloy such that a more uniform stress distribution can be obtained. It was also suggested [5, 6] that a desirable microstructure for good fatigue properties is fine aquiaxed grains with a uniform dislocation distribution which is strongly locked by fine precipitates. However, some investigators [7–9] believed that the TAHA process did not appear to offer much potential for improving the fatigue strength of 7075 Al–Zn–Mg alloy.

In this work we concentrated on the influence and correlation of pre-ageing temperature with the tensile and fatigue properties of a 7075 Al–Zn–Mg alloy. We tried a new TAHA process which includes solid solution treatment, pre-ageing at room temperature, and plastic deformation by cold rolling followed by final ageing. We believed that the fatigue properties would be greatly improved by the room-temperature pre-ageing, which provides more uniform nucleation sites for finer precipitates. The T–6 treatment, and the conventional TAHA process in which the pre-ageing was carried out at 100° C, were also performed in this investigation in order to compare with the results of this new TAHA process.

2. Experimental details

The starting material for this investigation was 7075–T6 plate which was produced from continuous rolling by the Kaiser Aluminum Co. (Pleasanton, California). The chemical composition is given in Table I. Three different treating processes were carried out to change the property of the aluminium alloy for comparison. They were: (a) solution treatment → water quenching → pre-ageing at 100° C for 1 h → cold rolling → final ageing, called TAHA1; (b) solution treatment → water quenching → pre-ageing at room temperature for 30 days → cold rolling → final ageing, called TAHA2; (c) solution treatment → water quenching → final ageing, called CT (conventional treatment). Solution treatment was performed at 460° C for 1.5 h. Cold rolling was carried out at room temperature by a rolling mill with three passes to 14% reduction in thickness. Final ageing was performed at 130° C for various times to obtain under-aged, peak-aged and over-aged condition. A numerical index in front of the name of the process indicates the time (in hours) of final ageing. For instance, 5TAHA2 represents a specimen which was treated by the TAHA2 process with a final ageing time of 5 h.

Tensile and fatigue tests were performed on an MTS (Minneapolis, Minnesota) Model 906–87 system. The load control system was used for the tensile test. The yield strength (YS) was taken from a 0.2% offset on the stress–strain curve. Elongation was determined by measuring the increment of the gauge length after fracture. For the fatigue test a cyclic tension–tension stress in which the maximum stress was 90% of the specimen's tensile strength was used, giving R (stress ratio) = 0.9. The surface of the

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TABLE I Chemical composition of the 7075 Al alloy used for investigation

Element	Content (wt %)
Fe	0.20
Zn	5.17
Ti	0.04
Mg	2.21
Cu	1.41
Cr	0.22
Si	0.12
Mn	0.10
Ni	Nil
Al	Remainder

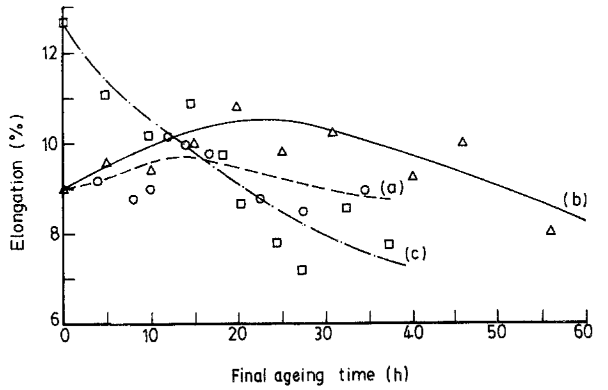

Figure 2 The variation of elongation with respect to the final ageing time for (a) TAHA1, (b) TAHA2 and (c) CT specimens.

fatigue specimen was polished to a mirror-like condition before the test. The microstructure was examined through an Olympus optical microscope. The fractography of the fatigue-fractured surface was investigated by an ARM–10000 scanning electron microscope (SEM) with an operating voltage of 20 kV and a filament current of 60 to 80 μm.

3. Results and discussion

The relationships between the tensile strength (UTS) and the final ageing time are shown in Fig. 1. Figs. 1a, b and c represent the ageing curves for specimens TAHA1, TAHA2 and CT, respectively. In general, the strength increased monotonically at the early stage of ageing (under-ageing). After reaching a peak value (peak ageing) the strength decreased monotonically as the ageing time was increased (over-ageing). The peak strengths for 7TAHA1, 15TAHA2 and 18CT were 85, 85 and 81 ksi (586, 586 and 558 MPa), respectively. Compared with the conventional treatment (CT), the TAHA process gave a 5% improvement in tensile strength. The relationships between the yield strength and the final ageing time were similar to those in Fig. 1. The magnitude of the yield strength ranged from 80 to 90% of the tensile strength. The curves which plot the elongation against the final ageing time are shown in Fig. 2. A peak elongation occurred at a proper ageing time if the specimens had undergone TAHA processes. The elongation decreased monotonically with ageing time for CT specimens.

Fig. 3 demonstrates the variation of the fatigue life with respect to the final ageing time. Figs. 3a, b and c represent the fatigue curves for TAHA1, TAHA2 and CT specimens, respectively. There is a peak in all three curves. The peak in Figs. 3a and b are very clear, but the peak in Fig. 3c is somewhat ambiguous. The peak fatigue lives for 12TAHA1, 20TAHA2 and 18CT were 12 300, 13 000 and 10 300 cycles, respectively. Compared with the CT specimen, TAHA1 and TAHA2 gave an improvement in fatigue life of 19.5 and 26.3%, respectively. Comparing Fig. 3 with Figs. 1 and 2, it was found that the peak fatigue life always corresponded to the optimum combination of tensile strength and elongation. Taking TAHA2 specimens as an example, the peak fatigue life was observed for 20TAHA2, which also gave peak elongation and was very close to the peak tensile strength. In general, the combination of strength and ductility represents the toughness of the specimen. It means that the better the toughness the better the fatigue life.

It was found that all microstructures observed by optical microscopy were very similar to each other, despite different treating processes and different ageing times. The average grain size was 0.15 mm. It is clear that the effect of treating method and ageing time on the grain size is negligible. The variation of tensile and fatigue properties with respect to the process and ageing time was not due to a change of grain size. The fatigue-fractured surface in general consists of two regions, the overload fracture region and the fatigue-fracture region. Both regions were examined carefully with the SEM. The fractography of the overload

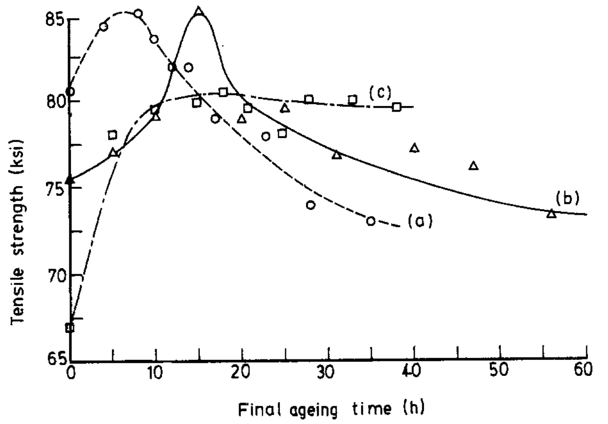

Figure 1 The variation of tensile strength with respect to the final ageing time for (a) TAHA1, (b) TAHA2 and (c) CT specimens. 1 ksi = 6.895 MPa.

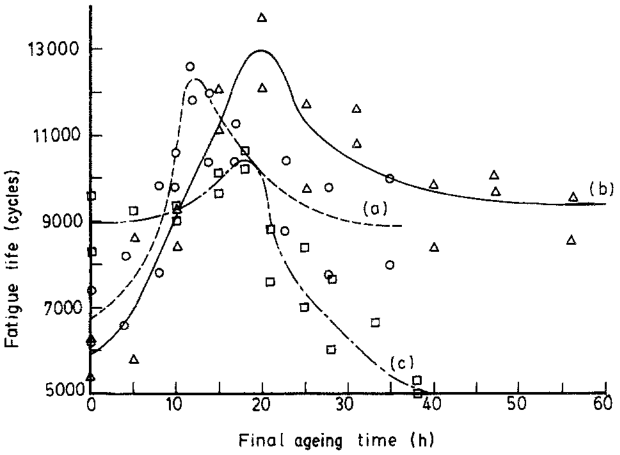

Figure 3 The variation of fatigue life with respect to the final ageing time for (a) TAHA1, (b) TAHA2 and (c) CT specimens.

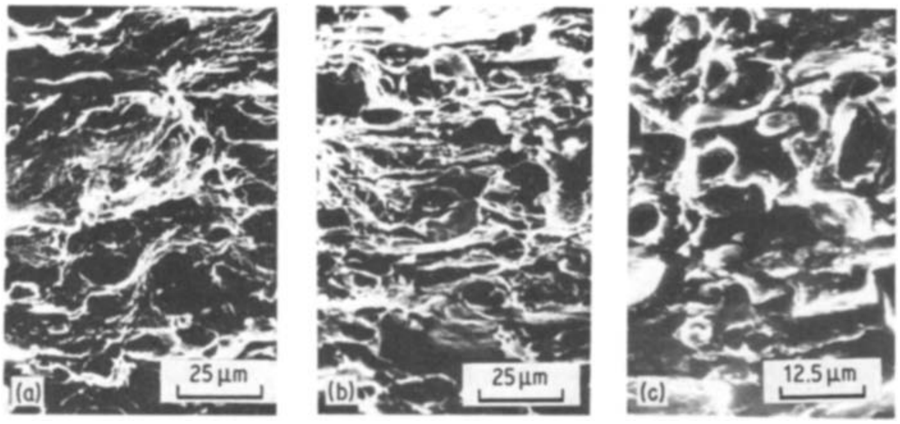

Figure 4 SEM fractography of the overload fractured region for (a) 0TAHA1 (under-aged), (b) 12TAHA1 (with peak fatigue life) and (c) 35TAHA1 (over-aged).

fracture region for TAHA1 is shown in Fig. 4. Figs. 4a, b and c represent the fractography for the under-aged, close-to-peak-aged (having peak fatigue life) and over-aged specimens, respectively.

Since the fracture surfaces were transgranular and were full of dimples, they were mostly ductile fractures. However, by careful investigation one could see that the size and distribution of the dimples were different from picture to picture. For under-aged (0TAHA1) and over-aged (35TAHA1) specimens, as shown in Figs. 4a and c, the dimples were irregular in shape and not uniform in distribution. Normally, an irregular shape of dimple arises from the fact that microvoids are easier to grow and coalesce in certain orientations. Usually, the larger dimples are voids formed at intermetallic, iron-rich or non-metallic particles. The smaller dimples result from microvoids initiated around the fine precipitates which strengthen the alloy. Since an easier growth of voids which form large and irregular dimples will make the formation of a crack easier, it leads to a structure of poor toughness in which fatigue crack propagation may be enhanced.

On the other hand, the dimples shown in Fig. 4b for a close-to-peak-aged specimen (12TAHA1) are clearer, more equiaxed and regular in shape, and finer in size. These dimples show that the precipitates in 12TAHA1 are finer in size and more uniform in distribution, which may result in better toughness and longer fatigue life. This is in good agreement with our experimental results which indicate that 12TAHA1 possessed high strength, best elongation and longest fatigue life when compared with other TAHA1 specimens. For TAHA2 specimens, the relationship between the dimple behaviour and the final ageing condition was very similar to that of TAHA1. For all CT specimens the dimples were larger, more irregular and non-uniform. This explains why the overall fatigue behaviour of CT specimens was not as good as TAHA1 and TAHA2 specimens.

For different specimens, different features of fatigue striation on the fatigue-fractured zone were observed as shown in Fig. 5. Fig. 5a indicates that the under-aged 0TAHA2 specimen which possessed poor fatigue resistance (Fig. 3b) displayed a brittle striation feature, showing short, broken and ambiguous striations with a mixture of cleavage facets. On the other hand, the SEM fractograph of 20TAHA2 which possessed the best fatigue property (Fig. 3b) displayed a ductile feature of striation, with longer, unbroken and clearer striations as shown in Fig. 5b. In addition, the absence of cleavage facets and the appearance of tearing ridges (Fig. 5b) indicate that 20TAHA2 was tougher, so that better fatigue life was expected.

The presence of tearing ridges means that there remain some unbroken zones behind the main fatigue crack front. Such unbroken zones represent tougher areas which will fracture later by tearing when a higher stress is reached. Consequently a better fatigue resistance is obtained. The fatigue striations of the over-aged 55TAHA2 were ductile and well-defined as shown in Fig. 5c, while the over-aged CT specimen demonstrated brittle striations (not shown). This is part of the reason why the fatigue lives of the over-aged TAHA2 specimens were much longer than those of the over-aged CT specimens. The correlation between the characteristics of the fatigue striation and the ageing condition for TAHA1 specimens was very similar to that of TAHA2 specimens.

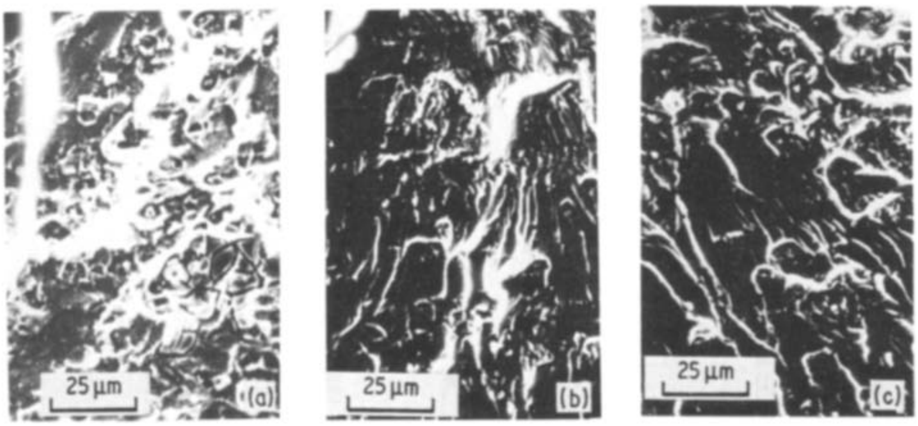

Figure 5 SEM fractography of the fatigue-fractured region for (a) 0TAHA2 (under-aged), (b) 20TAHA2 (with peak fatigue life) and (c) 55TAHA2 (over-aged).

Up to this point we have only presented the reasons why a proper TAHA treatment may lead to a better fatigue life when compared to the CT process. But the reasons why the TAHA2 process is better than the TAHA1 process are not yet explained. In trying to understand the mechanism, we need to discuss the substructure change during the TAHA process. The primary strengthening factors in TAHA are dislocation and precipitate substructure. To pre-age at a lower temperature (room temperature) and to keep for a longer time (30 days) will produce finer and denser solute clusters or precipitates which are distributed more uniformly. Following pre-ageing, plastic deformation will make the dislocations multiply and tangle with the result that a very fine and dense cellular substructure is gradually developed [10, 11]. A significant reduction in precipitate particle size and spacing would be obtained after final ageing. Since the force impeding dislocation movement is inversely proportional to the precipitate spacing, a substructure with smaller, denser and more uniformly distributed precipitate would improve the fatigue and tensile properties. This is part of the reason why the TAHA2 process may contribute to better fatigue and tensile properties than TAHA1.

In TAHA processes, plastic deformation may produce much residual stress in the case of 0TAHA1 and 0TAHA2. The residual stress may lead to poor elongation and fatigue life, which is consistent with our experimental results (Figs. 2 and 3). Once final ageing has started, the residual stress will be gradually released so that the elongation and fatigue life will be improved. At some appropriate stage of final ageing, the residual stress will be almost completely released and a homogeneous substructure with uniformly distributed fine precipitate will be obtained such that the specimens (12TAHA1 and 20TAHA2 in this case) will possess peak elongation and peak fatigue life. The elongation and fatigue life will drop after the peak value are reached, due to the coarsening of the precipitate.

4. Conclusions

1. Thermomechanical treatments on 7075 Al–Zn–Mg alloy led to beneficial effects on tensile and yield strengths when compared to the conventional CT specimens. The improvement in tensile strength was 5% at the peak condition. The improvement in yield strength was 10% for TAHA1 and 6.5% for TAHA2 at the peak condition.

2. Associated with proper final ageing in TAHA processes, fatigue life was improved by up to 26% over the conventional CT specimens if the maximum fatigue stress amplitude was 90% of the specimen's tensile strength. The improvement could be more significant if a constant stress amplitude was used for all fatigue tests.

3. For TAHA1 and TAHA2 specimens, the peak fatigue lives were not associated with the peak tensile strengths because of the residual stress produced by cold rolling. Peak fatigue lives were associated with peak elongations where the residual stress was almost completely released, and a homogeneous substructure with a uniform distribution of fine precipitate was obtained.

4. The SEM fractographs illustrated that the peak fatigue life of TAHA specimens was accompanied by ductile striation, tearing ridges and uniformly distributed dimples. Other specimens having platelets, brittle striations and non-uniformly distributed dimples on fracture surfaces were accompanied by poor fatigue life.

5. The correlation between TEM substructure and the fatigue behaviour was discussed. Transmission electron microscopy is needed in order to investigate the changes of substructure during TAHA processes.

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