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Tensile and fatigue properties of a thermomechanically treated 7475 aluminium alloy

M. T. JAHN, JIN LUO
Department of Mechanical Engineering, California State University Long Beach, Long Beach, California, USA

High-purity Al–Zn–Mg alloy was thermomechanically treated. The process included solution treatment, pre-ageing, cold-working by rolling and final ageing. Pre-ageing was carried out at 100° C (TAHA1) and room temperature (TAHA2). Experimental results indicated that the TAHA1 process improved the tensile strength significantly while the TAHA2 process improved the fatigue life more substantially. Fatigue crack initiation sites were examined carefully by scanning electron microscopy. A correlation between fatigue crack initiation, fatigue striation, tearing ridge, dimple distribution and fatigue life was observed. The experimental results are discussed in terms of substructure and are also compared with the tensile and fatigue properties of a thermomechanically treated 7075 Al–Zn–Mg alloy which were previously reported by one of the authors.

1. Introduction

The application of high-strength Al–Zn–Mg (7000 series) alloys has been widely accepted in airframe construction owing to their superior performance in many aspects including high strength-to-weight ratio, low cost and good formability. However, although their tensile properties are significantly better than for other series of aluminium alloys, the advantage in fatigue behaviour has not been as significant. In order to improve the tensile properties and fatigue behaviour at the same time, many approaches have been developed in the last three decades [1–9]. McEvily and co-workers [1, 2] found that while cold work prior to ageing increased the tensile strength of Al–Zn–Mg alloys slightly, the fatigue and stress–corrosion lives were improved substantially. In Ostermann's work [3] an increase of 25% in the 10 million cycles-to-failure stress level in 7075 aluminium alloy was achieved by a thermomechanical treatment (TMT). In 1973 Di Russo *et al.* [4] developed an interesting variation of TMT, called the TAHA process, in which step ageing was employed. By this process they were able to obtain better strength, ductility and fatigue properties. Rack and Krenzer [5] 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 [6, 7] that a desirable microstructure for good fatigue properties is fine equiaxed grains with a uniform dislocation distribution which is strongly locked by fine precipates.

In their research on pure aluminium, Jahn *et al.* [8] suggested that the formation of substructure by TMT can improve both tensile and fatigue properties, due to the fact that the strain distribution within grains is more uniform and that the stress gradient at grain boundaries is reduced. In a recent study of 7075 Al–Zn–Mg alloy, Jahn and Jen [9] were able to achieve an improvement in yield strength by 10% and in fatigue life by 26% due to appropriate TAHA processes. In this work we concentrated on the influence and correlation of pre-ageing temperature and final ageing time with the tensile and fatigue properties of a 7475 Al–Zn–Mg alloy, a purified version of 7075 aluminium alloy. Room-temperature pre-ageing was included in this study to provide more uniform nucleation sites for finer precipitate. A comparison of this study with previous work [9] was made to investigate how purity affected the effect of TAHA processes on Al–Zn–Mg alloys. In addition, a close examination of fatigue crack initiation through scanning electron microscopy, which was not included in previous work [9], has been carried out in this study to obtain a better understanding of fatigue behaviour.

2. Experimental details

The investigated material was a 7475 aluminium alloy, a high-purity Al–Zn–Mg alloy with a strict control of iron and silicon contents. The as-received material was in plate form with a thickness of 0.08 in. (2 mm) under T-761 condition. The composition of the material is given in Table I. The thermomechanical processes were very similar to those described in previous work [9].

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)

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TABLE I Chemical composition of the investigated 7475 aluminium alloy

Element	Content (wt %)
Zinc	5.804
Magnesium	2.277
Copper	1.75
Chromium	0.194
Nickel	0.005
Manganese	0.006
Silicon	0.020
Iron	0.084
Tin	0.002
Titanium	0.024
Aluminium	Balance

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 465° 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 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 85% of the specimen's tensile strength was used, and R (stress ratio) = 0.12. The surface of the 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 AMR-1000 scanning electron microscope (SEM) with an operating voltage of 20 kV and a filament current of 60 to 80 μm.

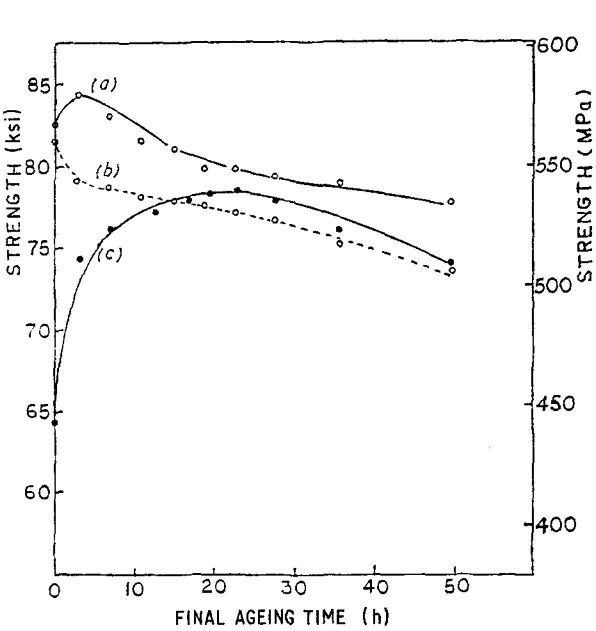

Figure 1 The variation of tensile strength with respect to the final ageing time for (a) TAHA1, (b) TAHA2 and (c) CT specimens.

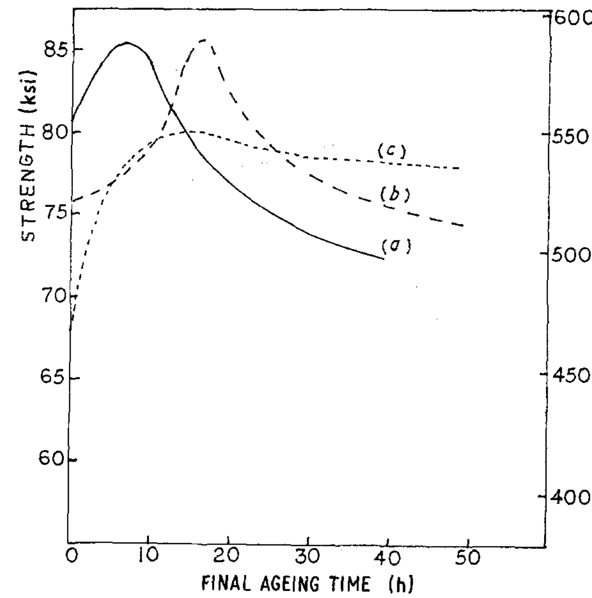

Figure 2 The variation of tensile strength with respect to the final ageing time for 7075 aluminium alloy specimens [9]: (a) TAHA1, (b) TAHA2 and (c) CT.

3. Results and discussion

The relationships between the tensile strength and the final ageing times for specimens TAHA1, TAHA2 and CT are shown in Fig. 1. Curves (a) and (c), representing the tensile strength of specimens TAHA1 and CT, are typical ageing curves which show regions of under-ageing, peak-ageing and over-ageing. The ageing curve of the TAHA2 specimen (Curve (b)) is somewhat different from the conventional ageing curve. The strength of the TAHA2 specimen decreased monotonically as the final ageing time was increased. No occurrence of peak ageing was observed. For comparison, the ageing curves for TAHA1, TAHA2 and CT specimens of 7075 aluminium alloy as reported by Jahn and Jen [9] are shown in Fig. 2 by Curves (a), (b) and (c), respectively. Since the 7475 alloy investigated in this study is a high-purity Al–Zn–Mg alloy which can be annealed more readily than 7075 alloy, the smaller peak in Curve (a) of Fig. 1 as compared to Curve (a) of Fig. 2 and the lack of peak in Curve (b) of Fig. 1 are understandable, since during ageing annealing softening also occurred due to the fact that TAHA1 and TAHA2 specimens were cold-worked before final ageing. The relationship between the yield strength and the final ageing time for TAHA1, TAHA2 and CT specimens is shown in Fig. 3 by Curves (a), (b) and (c), respectively. The behaviour is similar to the ageing–time dependence of tensile strength. The curves representing the elongation of TAHA1, TAHA2 and CT specimens against the final ageing time are shown in Fig. 4 by Curves (a), (b) and (c), respectively. The ductility, represented by elongation as shown in Fig. 4, of 7475 aluminium alloy is somewhat better than the ductility of 7075 alloy reported by Jahn and Jen [9]. Since 7475 alloy is a high-purity version of 7075 alloy, the higher ductility and higher toughness are expected.

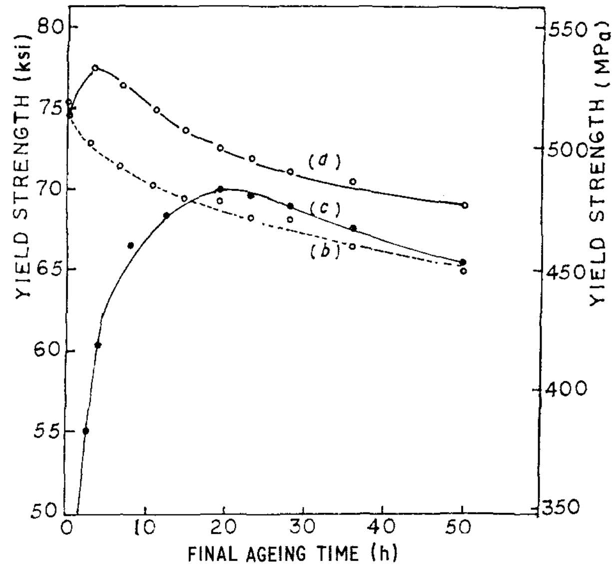

Figure 3 The variation of yield strength with respect to the final ageing time for (a) TAHA1, (b) TAHA2 and (c) CT specimens.

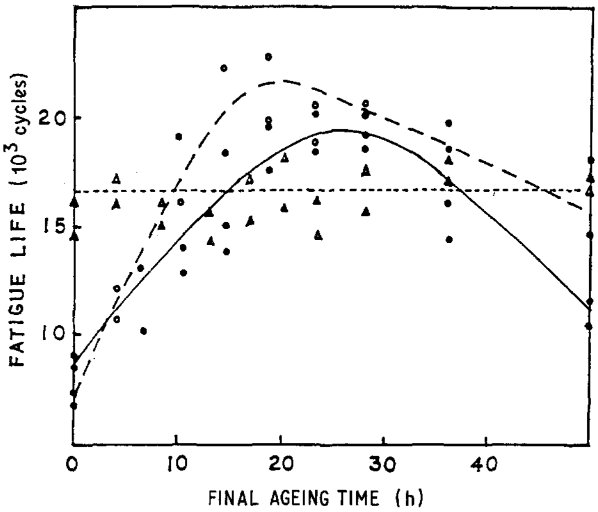

Figure 5 The variation of fatigue life with respect to the final ageing time for (●, ——) TAHA1, (○, – – –) TAHA2 and (▲, - - -) CT specimens.

The results of fatigue tests are given in Fig. 5. For the conventional specimens (CT) the fatigue life remained almost constant (about 16 000 cycles) despite the change in final ageing time. However, there is a peak in the curves for TAHA1 and TAHA2. The peak fatigue lives for TAHA1 and TAHA2 were 17 900 and 20 000 cycles which occurred at 25 and 20 h final ageing, respectively. As compared to CT specimens, the TAHA processes improved the peak fatigue lives by 12 and 25%. In TAHA processes, plastic deformation may produce much residual stress in the case of OTAHA1 and OTAHA2. The residual stress may lead to poor elongation and poor fatigue life, which is consistent with our experimental results (Figs 4 and 5). Once final ageing has started, the residual stress will be gradually released so that the elongation and fatigue life will be improved. After some final ageing time the residual stress will be released and a homogeneous substructure with uniformly distributed fine precipitate will be obtained such that the specimens (25TAHA1 and 20TAHA2 in this case) will possess good elongation and peak fatigue life. This is in good agreement with our experimental results as can be seen from the comparison of Figs 4 and 5. In general, the improvement in peak fatigue life of 7475 aluminium alloy (12% for TAHA1 and 25% for TAHA2) due to TAHA processes was slightly less significant than that obtained in 7075 alloy (19.5% for TAHA1 and 26.3% for TAHA2). This can be understood by the fact that the CT specimen of 7475 alloy possessed a much better fatigue life than the CT specimen of 7075 alloy. The better fatigue life of the 7475 CT specimen compared with the 7075 CT specimen is attributed to its higher purity and higher toughness.

The fatigue process consists of three stages. They are fatigue crack initiation, fatigue crack propagation and overload fracture. Since the morphology at the boundary of the fracture surface and the free surface could give valuable information about fatigue crack initiation, these boundaries were carefully investigated by scanning electron microscopy. Fig. 6 shows the morphology at the vicinity of the boundary between fracture and free surfaces of an as-solution-treated CT specimen. The right-lower part of Fig. 6 indicates slip bands on the free surface. The left-upper half shows the fracture surface. At the boundary the cracks along slip bands open up and serve as crack initiation sites for the as-solution-treated CT

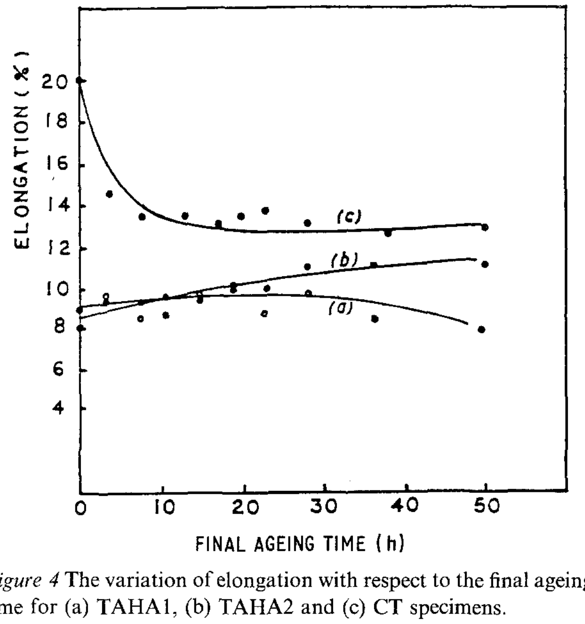

Figure 4 The variation of elongation with respect to the final ageing time for (a) TAHA1, (b) TAHA2 and (c) CT specimens.

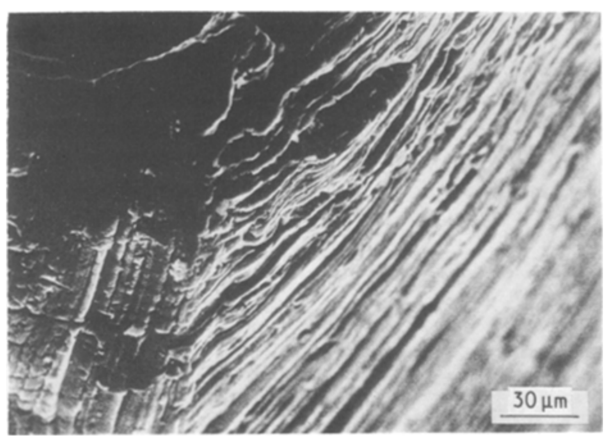

Figure 6 Scanning electron micrograph at the boundary of free surface and fracture surface of as-solution-treated CT specimen.

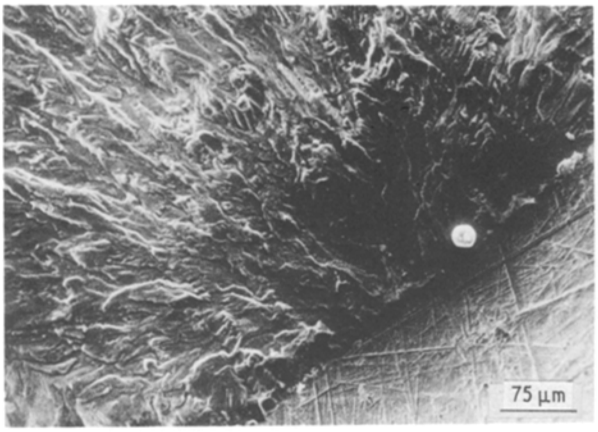

Figure 7 SEM fractography in the vicinity of the free surface for 20CT specimen.

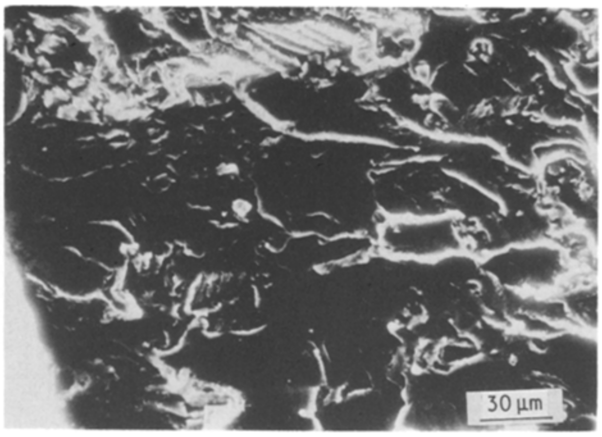

Figure 9 SEM fatigue fractography for OTAHA1 specimen.

specimen. However, no traces of slip bands were observed on the free surfaces of the other specimens. Except for the as-solution-treated CT specimen, due to final ageing and/or TMT, all specimens contained precipitates and/or dislocation tanglings which could restrict the dislocations to moving only a short distance during the fatigue process, such that no visible slip bands were observed.

Since dislocations in the as-solution-treated CT specimen are rather free to move to the surface to form slip bands, fatigue crack initiation is much easier for as-solution-treated CT specimens than for all other specimens investigated. Fig. 7 shows an SEM fractograph (close to the free surface) for the 20CT specimen which indicates that the fatigue crack initiated from an inclusion particle. The fatigue crack initiation from the particle is further confirmed by the radial zone in which the radial marks converge toward the particle as shown in Fig. 7. The particle where the fatigue crack initiates is probably Mg_2Si, since Mg_2Si is insoluble in the presence of excess magnesium for the formation of $MgZn_2$ [10]. The fatigue crack initiation was mostly observed from similar insoluble particles for CT specimens after various final ageing times. This demonstrates that even though 7475 aluminium alloy is much purer than 7075 alloy, the insoluble particles still cause fatigue crack initiation if the specimens are not thermomechanically treated. Fig. 8 shows the SEM fatigue fracture surface (very close to the free surface) for the 15TAHA2 specimen which indicates that the fatigue cracks did not initiate either at slip bands nor at insoluble particles. Fig. 8 represents the typical morphology of fatigue crack initiation for all thermomechanically treated specimens. Because an appropriate TMT process may make the precipitates finer and more uniformly distributed, the fatigue stress across the specimen will be more uniformly distributed such that the stress concentration at insoluble particles will be reduced. As a result, the fatigue crack initiation in TMT specimens was more difficult which may lead to a better fatigue life as demonstrated in this work and shown in Fig. 5.

In order to examine the fatigue crack propagation, different features of fatigue striation on the fatigue-fracture zone were examined. It was observed that specimens with a poor fatigue life displayed a brittle striation feature, showing short, broken and ambiguous striations with a mixture of cleavage facets, as shown in Fig. 9 for the OTAHA1 specimen which possessed a low fatigue life (7500 cycles). Specimens with good fatigue properties displayed a ductile feature of striation and tearing ridges, as shown in Fig. 10 for the 23TAHA1 specimen which possessed a peak fatigue life (18 500 cycles). The appearance of ductile striations and tearing ridges indicates a tougher material which has better resistance to fatigue crack propagation. The fractography of the overload fracture region of 7475 aluminium alloy was transgranular

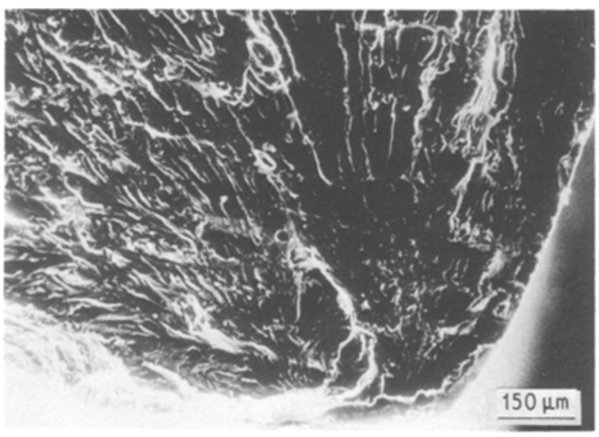

Figure 8 SEM fatigue fractography in the vicinity of the free surface for 15TAHA2 specimen.

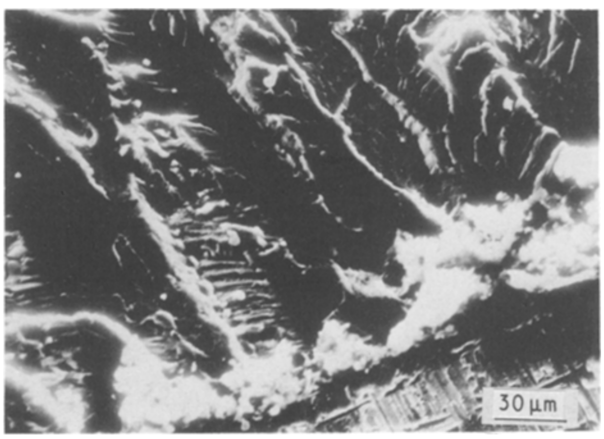

Figure 10 SEM fatigue fractography for 23TAHA1.

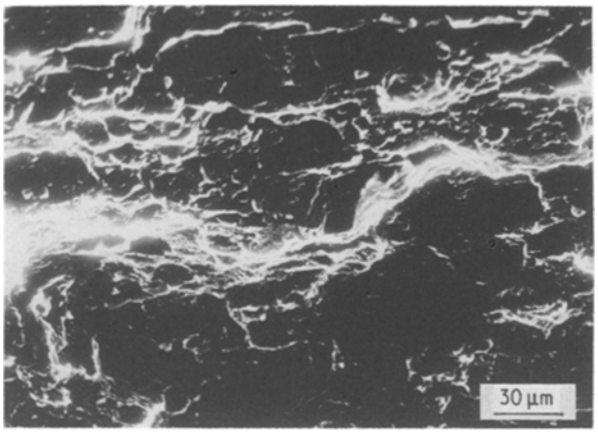

Figure 11 SEM fractography of overload region for OTAHA1 specimen.

with some dimples, representing ductile fracture. However, the size and distribution of the dimples were different from specimen to specimen. The dimples of specimens with a poor fatigue life were irregular in shape and not uniform in distribution, as shown in Fig. 11 for the OTAHA1 specimens with a low fatigue life. On the other hand, the dimples of specimens with good fatigue properties were clearer, more equiaxed and regular in shape, as shown in Fig. 12 for the 23TAHA1 specimen with a high fatigue life. These dimples show that the precipitates in specimens with a good fatigue life are more uniform in distribution, which may result in better toughness and a longer fatigue life. This is in good agreement with our experimental results.

In the TAHA process, the cold work will stabilize a significant part of the precipitate nuclei formed during low-temperature pre-ageing [11]; therefore, substantial reductions in the size and spacing of precipitates could be obtained after final ageing. In addition, pre-ageing at lower temperature for an appropriate time will further produce a finer precipitate after final ageing. The reduction in precipitate size and the enhancement of uniformity in precipitate distribution due to the TAHA process has been observed in 6201 aluminium alloy by transmission electron microscopy [12]. This kind of structure possesses a better toughness; therefore the application of the TAHA process to 7475 aluminium alloy may

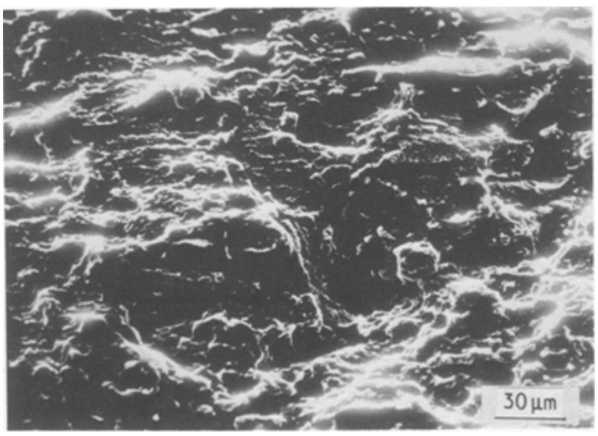

Figure 12 SEM fractography of overload region for 23TAHA1 specimen.

improve the fatigue properties more significantly than the tensile strength. Moreover, the improvement of fatigue properties by TAHA2 is greater than by TAHA1. Our experimental results showed that the improvements in tensile strength were 9 and 7% for peak-aged TAHA1 and TAHA2 specimens, respectively. The improvements in fatigue life were even better: they were 12% for TAHA1 and 25% for TAHA2. The experimental results are in good agreement with the mechanisms described above. Studies by transmission electron microscopy are required to further prove the above-mentioned mechanisms for 7475 aluminium alloy.

4. Conclusions

1. The TAHA process on 7475 Al–Zn–Mg alloy resulted in beneficial effects on the tensile and fatigue properties as compared to conventional CT specimens. The improvements in tensile strength were 9 and 7% for TAHA1 and TAHA2, respectively. The improvements in fatigue life were 12 and 25% for TAHA1 and TAHA2, respectively. It is worthwhile to note that the maximum stress in the fatigue test was 85% of the specimen's tensile strength. The improvement could be more significant if a constant stress amplitude was used for all fatigue tests.

2. For as-solution-treated CT specimen, fatigue cracks initiated at slip bands. After ageing a CT specimen, the presence of precipitates restricts the dislocation motion such that the formation of slip bands becomes more difficult. Therefore, the fatigue cracks of CT specimens after ageing initiated at insoluble particles rather than at slip bands.

3. It is suggested that TAHA processes made the precipitate finer in size and more uniform in distribution, which resulted in a more uniform stress distribution and constraints on dislocation motion. Therefore, the fatigue cracks of TAHA specimens neither initiated at slip bands nor at insoluble particles so that fatigue crack initiation was more difficult. In addition, the fatigue crack propagation inside a tougher material is also retarded. That is why the fatigue life of TAHA specimens was improved substantially when compared to conventional CT specimens.

4. It is suggested that pre-ageing at lower temperature plus cold work may introduce more precipitate nucleation sites which will lead to even finer precipitate after final ageing. The reduction in precipitate size and greater uniformity in precipitate distribution make a tougher material. Therefore, the improvement in fatigue life by the TAHA2 process was more significant than for TAHA1, even though the TAHA1 process gave a greater improvement in tensile strength.

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