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The effects of pre-ageing on a thermomechanically treated 6201 aluminium alloy

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The effects of pre-ageing on the tensile properties of a thermomechanically treated 6201 aluminium alloy were examined. It was found that the pre-ageing effects can be either beneficial or detrimental depending on the amount of cold work applied prior to final ageing. The pre-ageing performed was at 135° C for 30 min. The final ageing was at 140° C for various time periods. Pre-ageing combined with 60% cold work improves the tensile properties. However, pre-ageing combined with 80% cold work shows a detrimental effect on the tensile properties of 6201 alloy. The mechanisms are explained in terms of transmission electron microscopy.

1. Introduction

It is well known that the mechanical properties of most precipitation-hardening aluminium alloys can be markedly improved by the proper application of plastic deformation during natural or artificial ageing [1–4]. Besides raising the yield and ultimate tensile strengths, thermomechanical treatments (TMT) can have beneficial effects on other properties such as fatigue strength [5], stress-corrosion resistance and fracture toughness [3, 4]. Therefore TMTs have become increasingly important in designing components for contemporary technology.

The commercial treatments utilize cold working in conjunction with ageing, including the T3, T8, T9 and T10 temper conditions, whereas the use of stepped plastic deformation, stepped ageing or combinations of these introduces a new dimension to TMT of precipitation-hardening aluminium [6–8]. An interesting variation of TMT in which step-ageing is employed is TAHA (solution treatment, quenching, pre-ageing at low to intermediate temperatures, cold working and final artificially ageing at higher temperatures). Di Russo *et al.* [2] and one of the authors [1] have shown that TAHA treatment can markedly increase the ultimate tensile strength and yield strength of Al–Zn–Mg alloys, compared to the conventional T8 or T6 treatment, while still maintaining adequate ductility. Benedyk [6] also showed the same results on Al–0.75 wt % Mg_2Si and commercial 6061 alloy. Ikeno and co-workers [9, 10] investigated the effects of pre-ageing temperature and time, cold reduction ratio and final ageing temperature on the hardness and ductility of a 6201 alloy. They found that when alloys pre-aged at 200° C were cold-rolled to 30% and aged at 150 to 300° C, the hardness was improved at ageing temperature up to 250° C. It was also suggested that the deformation during TAHA may cure the reversion effect in Al–Mg–Si alloy, and the pre-ageing treatment refines the precipitates to give a more uniform stress distribution throughout the treated material. The greater number of precipitates formed during TAHA treatment decreases the dislocation pile-up density and the pile-up stress, thereby raising the ductility.

In order to obtain a better understanding of the effects of TAHA on the tensile properties and microstructures of 6201 alloy, different processes have been carried out in this study. It is found that the effect of pre-ageing on the tensile properties of 6201 alloy can be either beneficial or detrimental depending on the amount of cold work applied. The mechanism is explained in terms of transmission electron microscopy.

2. Experimental details

6201 aluminium alloy (0.69Mg–0.65Si–0.24Fe–0.12Cu, wt %) was solution-treated at 530° C for 1 h followed by water quenching. After solution treatment some specimens were cold-rolled at room temperature to 60 or 80% reduction in thickness, followed by final ageing at 140° C for various time periods. These specimens are represented by THA. Other specimens were first pre-aged at 135° C for 30 min, cold-rolled at room temperature to 60 or 80% reduction in thickness followed by final ageing at 140° C for various time periods. These specimens are abbreviated to TAHA. The variation of tensile properties by changing the final ageing time was obtained using an Instron tensile test machine operating at a crosshead speed of 0.2 cm min^{-1}. The submicrostructures in TAHA specimens were compared with those of THA specimens using a Joel 100B transmission electron microscope operating at 100 kV. Thin foils for transmission

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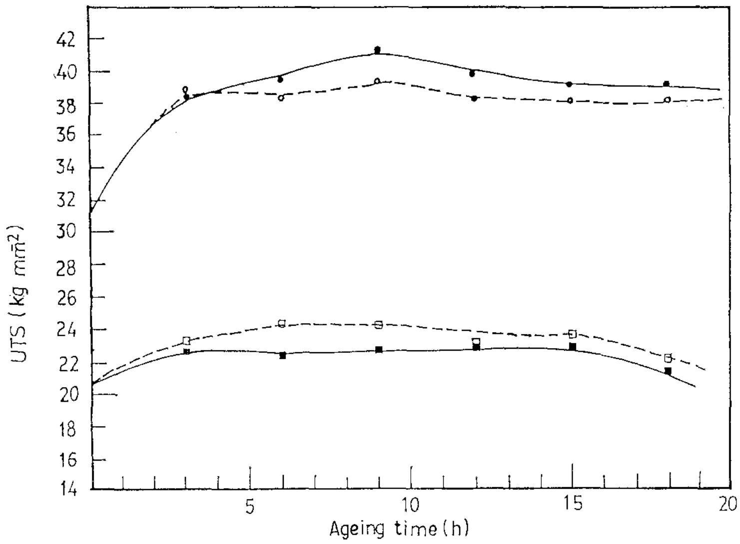

Figure 1 Variations of ultimate tensile strength (140° C ageing) with respect to final-ageing times for (●) TAHA (60%), (■) TAHA (80%), (○) THA (60%) and (□) THA (80%) specimens.

electron microscopy were made by a conventional window method. The electrolyte used was a mixture of 20 ml $HClO_4$ and 80 ml methyl alcohol kept at −30° C. Thin foils were examined by bright-field, dark-field and selected-area diffraction methods.

3. Experimental results

The ultimate tensile strength (UTS) and yield strength (YS) of THA and TAHA specimens with respect to final-ageing time are shown in Figs 1 and 2. Each data point represents the average value for three specimens. The amount of scatter in strength measurements was negligible, always less than 1% from the average. Before final ageing the UTS and YS of a THA specimen are equal to that of a TAHA specimen provided the cold-work ratio of the specimen is the same. For the specimens with 60% cold-work, the peak-aged UTS and YS of TAHA specimens were greater than those of THA specimens. After peak ageing the strengths started to drop with ageing time and the differences in strengths between TAHA and THA was reduced. At peak ageing, the strengths were 41.2 kg mm^{-2} (UTS) and 38.0 kg mm^{-2} (YS) for TAHA specimens, which were about 2 kg mm^{-2} higher than those of THA specimens. The strengthening effect by the TAHA process is evident. For the specimens of 80% cold-work, the peak-aged strengths of TAHA specimens were lower than those of THA specimens. After peak ageing the strengths started to drop with ageing time and the differences in strengths between TAHA and THA were reduced. It is clear that the combination of pre-ageing (135° C, 30 min) and cold reduction (80%) has a detrimental effect on the tensile properties. The variations of elongation with respect to ageing time were very similar to each other for THA (60%), THA (80%), TAHA (60%) and TAHA (80%). Before final ageing the elongation was 9%, and then increased to 14% at peak ageing followed by slight drop with ageing time.

Transmission electron microscopy revealed that there are distinct relationships between the substructures produced by various TMT processes and the resulting tensile properties. Just after 60% cold work, the substructure in THA and TAHA specimens was a mixture of uniformly distributed high-density dislocations and elongated cells, with a high density of dislocations uniformly distributed at the cell walls as shown in Fig. 3. When the specimens (THA and TAHA) were deformed to 80% reduction, the substructure showed many recovered subgrains with random orientation as shown in Fig. 4. From bright-field, dark-field and selected-area diffraction pattern, we observed no formation of needle-shaped Guinier–Preston (GP) zones after pre-ageing. As the final

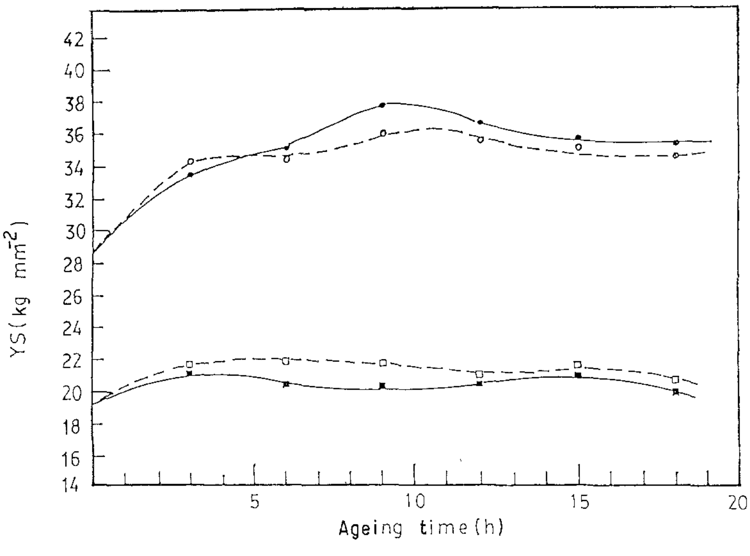

Figure 2 Variations of yield strength (140° C ageing) with respect to final-ageing times for (●) TAHA (60%), (■) TAHA (80%), (○) THA (60%) and (□) THA (80%) specimens.

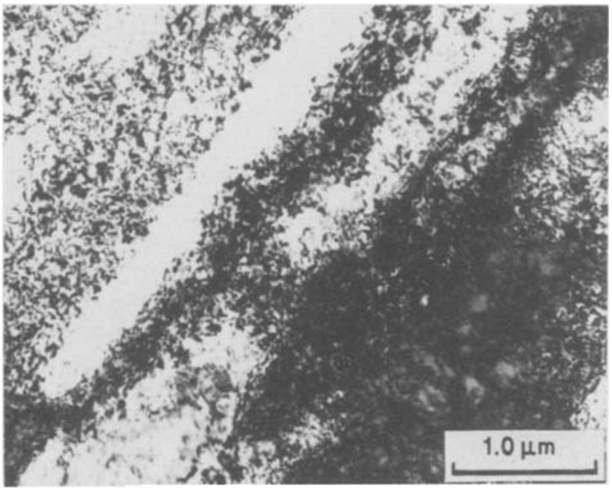

Figure 3 TEM microstructure of TAHA specimen (60%) without final ageing.

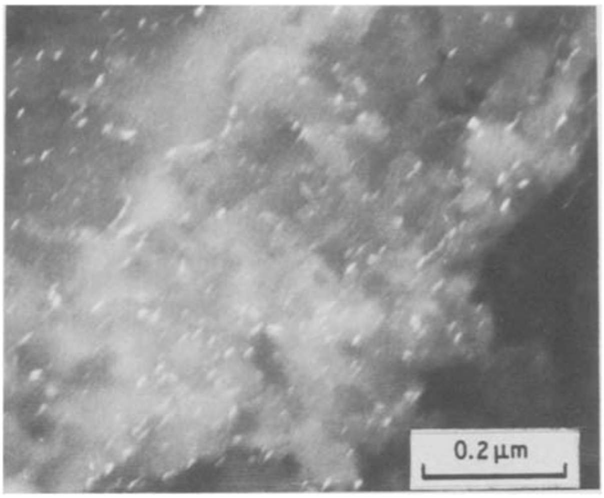

Figure 5 TEM dark-field micrograph of TAHA specimen (60%), final-aged at 140° C for 9 h.

ageing proceeded the precipitates started to appear and grow from clusters to needle-shaped GP zones and finally to the rod-shaped Mg_2Si. For the specimens with 60% cold work and in the vicinity of peak ageing the precipitates in TAHA specimens were finer and more uniformly distributed than in THA specimens. This may result in better tensile properties for TAHA specimens. Fig. 5 shows a TEM dark-field micrograph of a peak-aged TAHA specimen (60%), while Fig. 6 represents the dark-field micrograph of a peak-aged THA specimen (60%). For the specimens of 80% cold work, less fine precipitates were observed in the dislocation-free regions, while nearby or along the subgrain boundaries many coarse precipitates were observed. TEM microscopy demonstrated that in the vicinity of peak-ageing the precipitates in THA specimens were finer and denser than in TAHA specimens, as shown in Figs 7 and 8. This may result in a detrimental effect of the TAHA process.

4. Discussion

The 6201 aluminium alloy investigated contains 0.649% Si, 0.693% Mg and 0.243% Fe which is equivalent to a system of Al–1.09% Mg_2Si–0.208% Si. It has been reported [11] that excess silicon (0.208% in this case) increases the density of GP zones during ageing due to homogeneous nucleation of the solute clusters by pre-ageing. In general the pre-ageing temperature is a little lower than the final ageing temperature, so that a more homogeneous dispersion of solute clusters or precipitates can be produced. However, the pre-ageing temperature should not be too low or the prior solute clusters will reverse during final ageing because the clusters are neither large nor stable enough [12]. From Figs 1 and 2 we see that the strengths of TAHA specimens with 60% cold work are higher than that of THA specimens provided they have the same final-ageing time. Also, from the TEM microstructures as shown in Figs 5 and 6, it is clear that TAHA specimens possess finer, denser and more uniform distribution of precipitates than THA specimens. This proves the beneficial effect of pre-ageing that produces a more homogeneous dispersion of solute clusters which serve as precipitate nucleation sites. However, this is true only when the amount of cold work is controlled such that there is a high density of dislocation tangling and the tanglings are distributed uniformly as shown in Fig. 3. After a long time of final ageing the solutes retained in the matrix are used up and the precipitates will grow at the expense of neighbouring precipitates. Therefore, the size and distribution of precipitates of TAHA specimens will approach

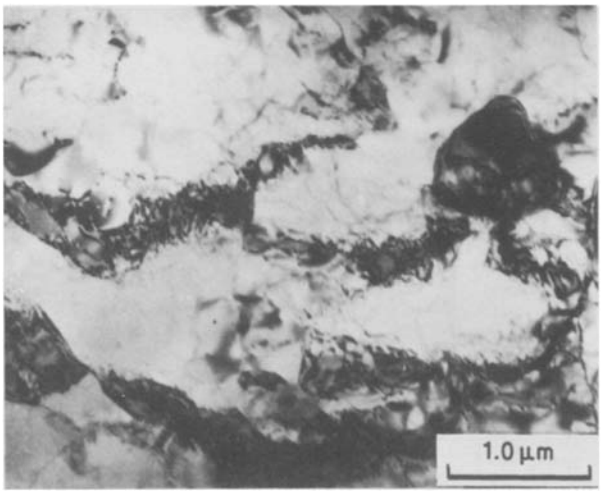

Figure 4 TEM microstructure of TAHA specimen (80%) without final ageing.

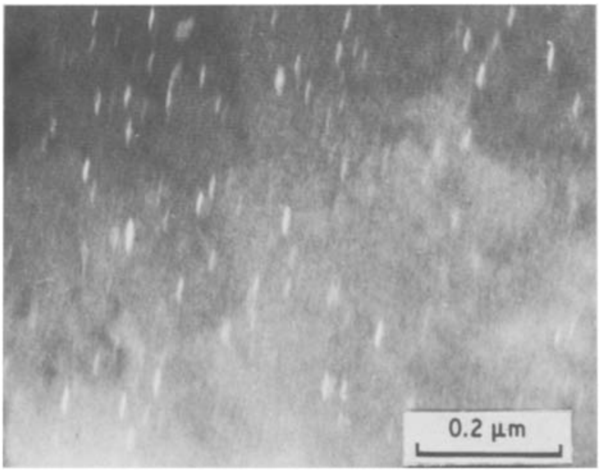

Figure 6 TEM dark-field micrograph of THA specimen (60%), final-aged at 140° C for 9 h.

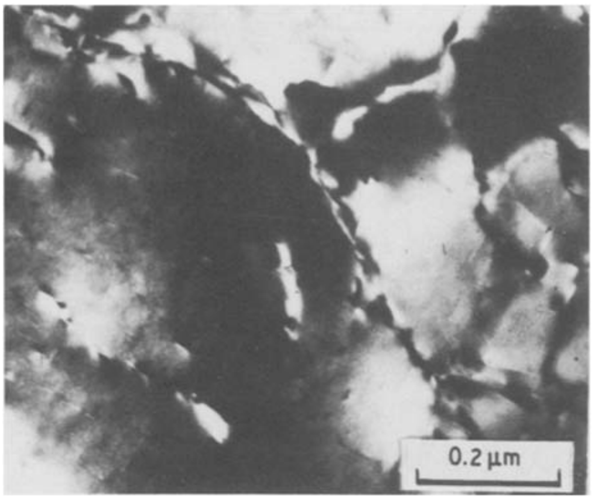

Figure 7 TEM micrograph of peak-aged TAHA specimen (80%).

that of THA specimens such that the strengths of TAHA and THA specimens approach each other after many hours of final ageing.

As the amount of cold work is increased, the deformation is large enough for dynamic recovery to occur such that the rather uniform distribution of high dislocation density is destroyed. The solute clusters due to pre-ageing are mostly reversed under this high energy state by dislocation shearing, and the solute atoms are trapped at or near dislocations. During final ageing it is easier for solute atoms to recluster at the dislocations so that the precipitates will nucleate and grow faster. In other words, the combination of pre-ageing and a high amount of cold work enhances the ageing effect. As the deformation ratio is increased to 80%, the high amount of cold work not only reverses the solute clusters nucleated by pre-ageing but also carries the solute atoms to the vicinity of the dynamic recovered subgrain boundaries; the precipitates are thereby easier to nucleate and grow along the sub-boundaries, resulting in a coarser and non-uniform distribution of precipitates. Our experimental results are in agreement with this effect as shown in Figs 7 and 8. This is the interpretation of the detrimental effect of pre-ageing if the amount of cold work is too high (e.g. 80% in this case).

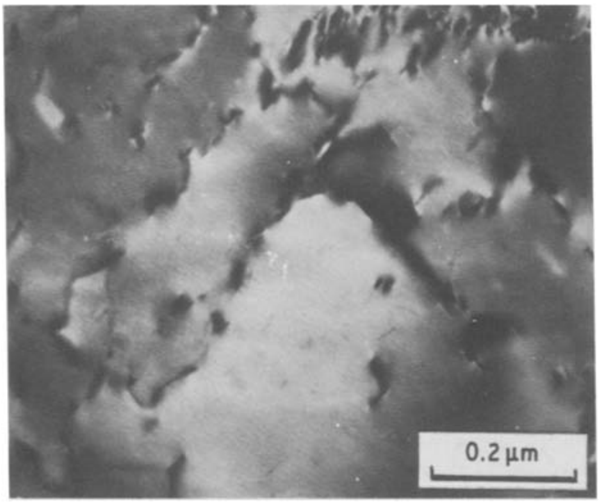

Figure 8 TEM micrograph of peak-aged THA specimen (80%).

5. Conclusions

The TAHA process has a beneficial effect on the strengths of 6201 aluminium alloy, and good ductility may still be maintained if proper TMT conditions are performed. The mechanisms are explained in terms of TEM microscopy.

1. The TAHA process with 60% cold work leads to an improvement of the strengths of 6201 alloy. The strengthening results from the refinement of precipitates by pre-ageing and because of the numerous nucleation sites developed by a uniform distribution of high-density dislocation tanglings owing to 60% cold work.
2. The increases of strengths by the TAHA process are about 5% compared to the THA process. The maximum increment in strengths occurred in the peak-aged condition.
3. The TAHA process with 80% cold work leads to a detrimental effect on the strength of 6201 alloy. This phenomenon is due to the inclination to localized nucleation of solute clusters near or along the dynamic recovered sub-boundaries, which results in a coarser and non-uniform distribution of precipitates.
4. The solute clusters nucleated by pre-ageing are reversed and the solute atoms are carried to sub-boundaries by dislocation shearing when the amount of cold work is high enough (80% in this case).

References

1. M. T. JAHN and M. JEN, *J. Mater. Sci.* **21** (1986) 799.
2. E. Di RUSSO, M. CONSERVA, F. GATTO and H. MARKUS, *Met. Trans.* **4** (1973) 1133.
3. E. Di RUSSO, M. CONSERVA, M. BURATI and F. GATTO, *Met. Sci. Eng.* **14** (1974) 23.
4. J. WALDMAN, H. SULINSKI and H. MARKUS, *Met. Trans.* **5** (1974) 573.
5. F. OSTERMANN, *ibid.* **2** (1971) 2897.
6. J. C. BENEDYK, *Light Met. Age* **26** (1968) 10.
7. A. A. TAVASSOLI, *Met. Sci.* **8** (1974) 424.
8. H. J. RACK and R. W. KRENZER, *Met. Trans.* **8A** (1973) 335.
9. S. IKENO, S. KAKUCHI, T. MAE and S. TADA, *Keikinzoku* **33**(1) (1983) 3.
10. S. IKENO, Y. YAMAMOTO, Y. UETANI and S. TADA, *ibid.* **35**(3) (1985) 154.
11. S. CERESARA, *Met. Sci. Eng.* **5** (1969/70) 220.
12. R. C. DORNARD, *Met. Trans.* **4** (1973) 507.

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