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The influence of solution heat-treatment temperature on the mechanical properties of a recrystallized aluminium alloy 2020

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The effect of solution heat-treatment temperature on the undissolved phases was determined for a recrystallized aluminium alloy 2020. The lower solution heat-treatment temperatures retained a greater volume fraction of undissolved T_B, T_1 and T_2 phases, however, these phases did not significantly affect ductility of the alloy. The optimum solution heat-treatment condition (for 10 mm thick plate) in a salt bath was within a temperature range between 505 and 520° C for 30 min. The fracture mode of tensile samples was a form of brittle intergranular fracture regardless of solution heat-treatment temperature.

1. Introduction

Recently, considerable research has been undertaken to improve the ductility of aluminium alloy 2020 through modifying grain structure and alloy composition [1, 2]. Starke and Lin [1] used a thermomechanical process to vary grain structures and found that ductility of this alloy was improved 200% with respect to the as-received T651 plate. An optimum grain structure for this improvement in ductility was a fully unrecrystallized grain structure. However, in order to retain this structure the alloy had to be solution heat-treated at a lower temperature of 490° C instead of 515° C. It was suggested that the improvement in ductility was partly due to the lower solution heat-treatment temperature since the sample quenched from 490° C contains a much greater volume fraction of T_B ($Al_{15}Cu_8Li$), T_1 (Al_2CuLi) and T_2 (Al_6CuLi_3) phases than that quenched from 515° C. These incoherent phases may homogenize plastic deformation of the alloy and thereby increase ductility. Therefore, this work is the result of continuing research to investigate the effect of these phases on ductility of this alloy.

In order to make this investigation, the alloy had to be initially processed to obtain a fully recrystallized grain structure and grain size which would be unaffected by subsequent solution heat-treatment. As a result, the solution heat-treatment temperature would be the sole parameter for this study. The effect of solution heat-treatment temperature and time on the volume fraction of undissolved T_B, T_1 and T_2 phases were determined and thus the effect of these phases on ductility could be evaluated.

2. Experimental procedure

The chemical composition (wt %) of the aluminium alloy 2020 used in this study was copper 4.45%, lithium 1.21%, manganese 0.51%, cadmium 0.21%, silicon 0.08%, iron 0.16% and aluminium balance. The material was received from Air Force Materials Laboratory as a 25 mm thick plate in the T651 temper. In order to produce a fully recrystallized

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grain structure, the plate was solution heat-treated at 515° C in a salt bath for 30 min, quenched in cold water and then rolled at room temperature with a reduction of 40%. The rolled plate was annealed at 515° C for 30 min, slowly cooled in a salt bath to 300° C and then air cooled. The slow cooling rate was designed to precipitate all T_B, T_1 and T_2 phases out of the solid solution.

The samples were solution heat-treated at different temperatures from 475 to 540° C for 30 min and 2 h, and then quenched in cold water. The experimental schedules are given in Table I. All samples were aged at 160° C for 18 h to reach the peak hardness. The volume fraction of the undissolved T_B, T_1, and T_2 phases as a function of solution heat-treatment temperature was determined by X-ray diffraction pattern, obtained with a Nonius Guinier–de Wolff quadruple focusing camera. The samples used for this analysis were prepared by a chemical solution with 400 ml HCl, 400 ml H_2O, 20 g NaCl and 4 g $NiSO_4$.

Round tensile samples with gauge dimensions of 4 mm diameter and 20 mm length were machined with the loading axis parallel to the longitudinal direction. Tensile tests were carried out in laboratory air on a servohydraulic testing machine (MTS) with a strain rate of 1×10^{-3} sec^{-1}. The optical microscope and transmission electron microscope (TEM) were used to examine grain structure and precipitates of the alloy. Fracture surfaces of tensile samples were examined by scanning electron microscopy (SEM).

3. Results and discussion

3.1. Grain structure

In order to study the effect of solution heat-treatment temperature and thereby the undissolved phases on the mechanical properties, the grain structure must be retained constant regardless of solution heat-treatment temperature. The cold-rolled plate was annealed at 515° C for 30 min and then furnace cooled before solution heat-treatment at different temperatures. The annealed treatment already produced a fully recrystallized structure. Consequently, the sample which was solutionized at 475° C still had the same grain structure as the annealed condition. On the other hand, the grain structure for solution heat-treatment at 540° C was also similar to that of the annealed condition since the manganese dispersoids impeded grain-boundary migration and inhibited grain growth. The grain structure for solution heat-treatment at 475° C and 540° C is shown in Fig. 1 in which grain size is nearly identical for both conditions. Eutectic melting along grain boundaries was not observed even after solution heat-treatment at 540° C although it was reported by other workers [3, 4].

3.2. Effect of solution heat-treatment temperature on the undissolved phases

The volume fraction of undissolved phases as a function of solution heat-treatment temperature was determined qualitatively by X-ray diffraction

TABLE I The undissolved phases and precipitates detected in guinier patterns of the 2020 alloy at different solution heat-treatment temperatures

	T_B	T_1	T_2	δ'	θ
As Furnace Cooling (FC)	D-S	D-M	D-W	D-VW	D-VVW
FC + 475° C 30 min CWQ	D-W	D-W	D-VW	D-VW	D-VVW
FC + 490° C 30 min CWQ	D-VW	D-VW	D-VW	D-VW	D-VVW
FC + 505° C 30 min CWQ	D-VW	D-VW	D-VW	D-VW	D-VVW
FC + 515° C 30 min CWQ	D-VW	D-VW	D-VW	D-VW	D-VVW
FC + 525° C 30 min CWQ	D-VVW	D-VVW	D-VVW	D-VW	D-VVW
FC + 540° C 30 min CWQ	D-VVW	D-VVW	D-VVW	D-VW	D-VVW
FC + 475° C 2 h CWQ	D-W	D-W	D-VW	D-VW	D-VVW
FC + 490° C 2 h CWQ	D-VW	D-VW	D-VW	D-VW	D-VVW
FC + 505° C 2 h CWQ	D-VW	D-VW	D-VW	D-VW	D-VVW
FC + 515° C 2 h CWQ	D-VW	D-VW	D-VW	D-VW	D-VVW
FC + 525° C 2 h CWQ	D-VVW	D-VVW	D-VVW	D-VW	D-VVW
FC + 540° C 2 h CWQ	D-VVW	D-VVW	D-VVW	D-VW	D-VVW

D-S: detected strong. D-VW: detected very weak.
D-M: detected medium. D-VVW: detected very, very weak.
D-W: detected weak. CWQ: cold-water quenched.
All aluminium matrix lines were very strong.

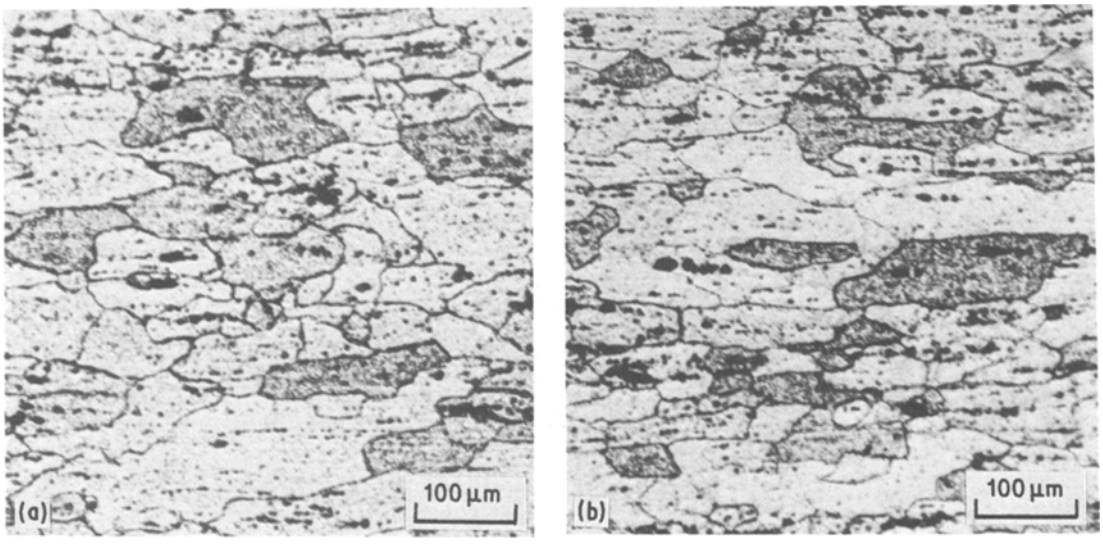


Figure 1 Recrystallized grain structure of an aluminium alloy 2020 solution heat-treated at (a) 475° C, and (b) 540° C.

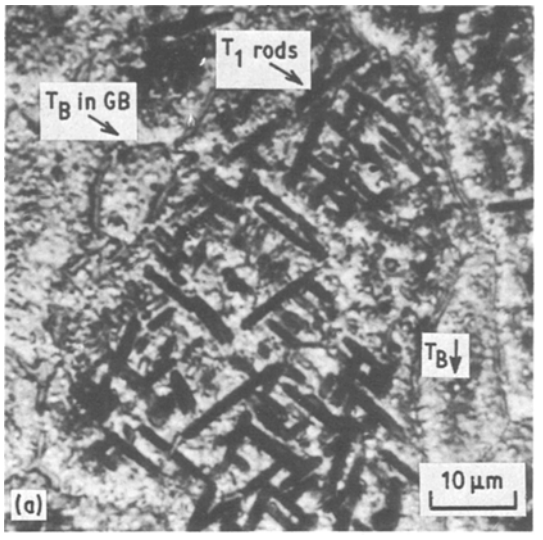
patterns and the results are listed in Table I. For the furnace-cooled condition, T_B phase showed the strongest intensity in the X-ray diffraction lines, and intensity of the diffraction line decreased in the order T_1, T_2, δ and θ phases. This implies that a high volume fraction of T_B, T_1 and T_2 phases precipitates during this treatment. For samples solution heat-treated at different temperatures, most of the T_B, T_1 and T_2 phases were dissolved into the solid solution as indicated by a sharp decrease in intensity. The amount of T_B, T_1 and T_2 phases dissolved increases as the solution heat-treatment temperature increases since intensity of these lines decreases. It is important to note that the increased holding time from 30 min to 2 h at a given temperature does not change the amount of these phases dissolved. The equilibrium phase θ (Al_2Cu) does not change its line intensity, regardless of solution heat-treatment temperature. $\delta'(Al_3Li)$ exhibits a very weak line for each heat-treatment condition, probably resulting from δ' precipitation which occurs immediately after quenching or during room temperature ageing [1, 5]. The low lithium content in the alloy limited the increase of volume fraction of δ' even if it was subsequently aged at 160° C for 18 h.

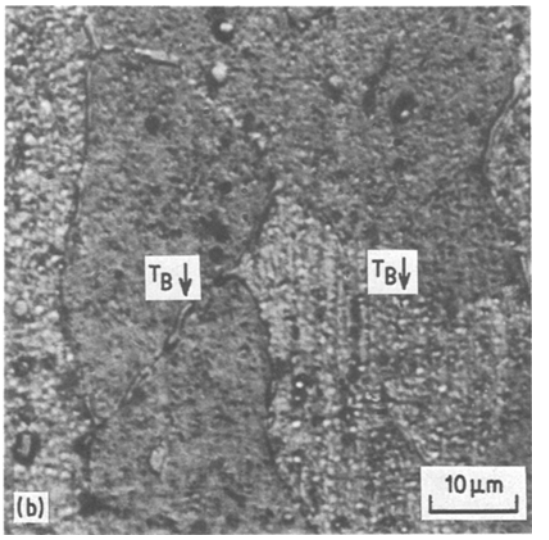
In addition to these phases identified by X-ray diffraction, the intermetallic particles such as Al_7Cu_2Fe, $Al_{12}(Fe,Mn)_3Si$, $Al_{20}Cu_2Mn_3$, Al_9Mn_3Si and Al_6Mn were also detected (Table II). The X-ray diffraction intensity of these constituent and dispersoid particles does not change with solution heat-treatment temperature, indicating that they are stable over the range of temperatures studied.

The optical microscope and SEM attached, with an energy dispersive X-ray analysis (EDXA) unit, were also used to observe and identify these undissolved phases. Fig. 2 shows the change of the undissolved phases as a function of heat-treatment. For the furnace-cooled condition the rod-shaped precipitates were identified as T_1 phase; the precipitates along grain boundaries and small round particles in the matrix were T_B phase (Fig. 2a). After solution heat-treatment at 475° C, the T_1 phase was dissolved in the solution and disappeared from the microstructure; however, a significant amount of T_B phase could still be observed (Fig. 2b). Fig. 2c shows that the T_B and T_1 phases had been dissolved after solution heat-treatment at 515° C. The dark spots shown in this micrograph are associated with the etched pits. These results are consistent with those of the X-ray diffraction study (Table I).

TABLE II Intermetallic particles detected in Guinier patterns in 2020 alloy

Al_7Cu_2Fe	$Al_{12}(Fe, Mn)_3Si$	$Al_{20}Cu_2Mn_3$	Al_9Mn_3Si	Al_6Mn
D-W	D-VW	D-VW	D-VVW	D-VVW





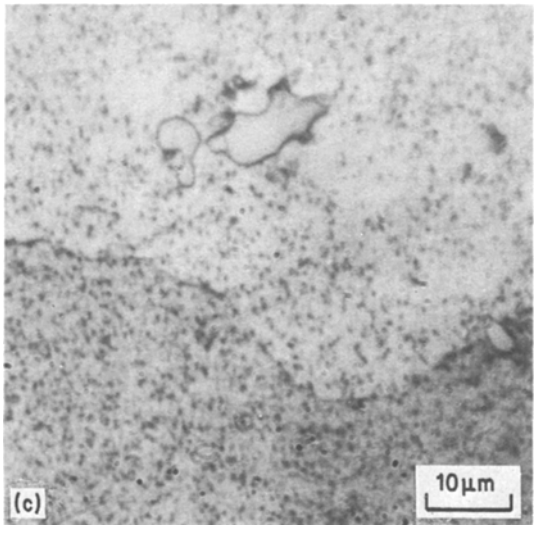


Figure 2 Optical micrographs showing the undissolved phases in an aluminium alloy 2020. (a) Furnace-cooled condition, (b) and (c) solution heat-treated at 475 and 515° C, respectively, and then quenched in water.

with TEM are θ' and T_1 phases, with θ' being the principal precipitate, as illustrated in Fig. 4. Ductility was not significantly affected by solution heat-treatment temperature. In addition, the trend of tensile properties for a longer soaking time (2 h) was identical to that for a shorter soaking time (30 min). These results combined with those in the previous section indicate that the volume fraction of the undissolved phases (T_B, T_1 and T_2) cannot significantly influence ductility of the alloy 2020. This result also indicates that the optimum solution

3.3. Mechanical properties

As described in the introduction, the purpose of this study was to retain a constant grain structure regardless of solution heat-treatment temperature and thereby allow the evaluation of the undissolved phases on ductility. These results are shown in Fig. 3. Both yield and tensile strength considerably increase with increase in temperature from 475 to 505° C; however, no significant change in these parameters was observed for solution heat-treatment temperatures higher than 505° C. Higher solution heat-treatment temperatures reduce the amount of T_B, T_1 and T_2 phases and thus increase the amount of solute that can form strengthening precipitates during subsequent ageing. The strengthening precipitates observed

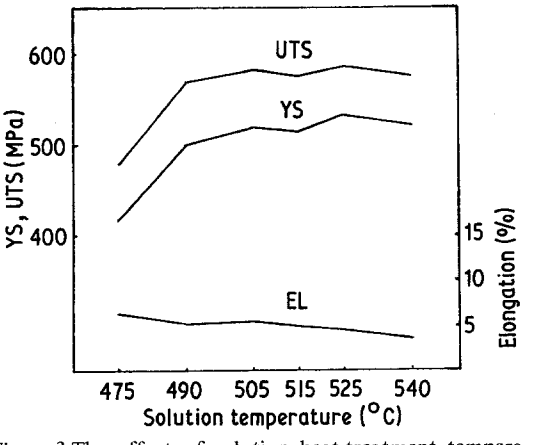


Figure 3 The effect of solution heat-treatment temperature on tensile properties. The alloy was aged at 160° C for 18 h. The solution heat-treatment time was 30 min.

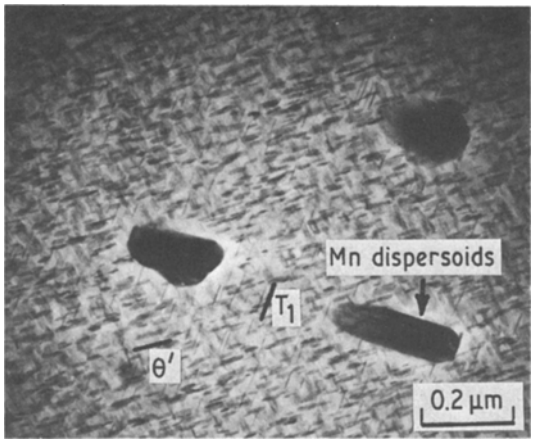
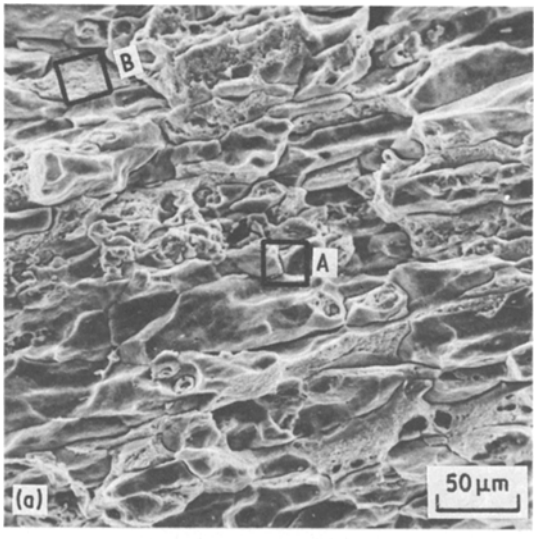


Figure 4 TEM micrograph showing θ′, T_1 and manganese dispersoids for the alloy aged at 160° C for 18 h. (1 1 2) foil plane.

heat-treatment temperature is between 505 and 520° C.

The fracture features of tensile samples were characterized. For any case regardless of solution heat-treatment temperature, the fracture feature was a type of brittle intergranular fracture. The representative features are shown in Fig. 5. Fig. 5a shows that intergranular fracture is dominant and controls the fracture process. Fig. 5b shows brittle intergranular fracture facets with small particles decorated on the boundary. Fig. 5c shows that some local grains exhibit transgranular dimple fracture. The mechanisms for this type of fracture have been discussed previously [1, 6]. It is indicated that numerous constituent and dispersoid particles would lie on grain boundaries during grain growth since these particles impeded grain-boundary migration. The particles along grain boundaries would decrease the bonding strength of the boundary, resulting in a form of brittle intergranular fracture. Consequently, the solution heat-treatment temperature which determines the amount of undissolved phases cannot change the fracture mode of the alloy, and thus, it cannot affect the ductility either.



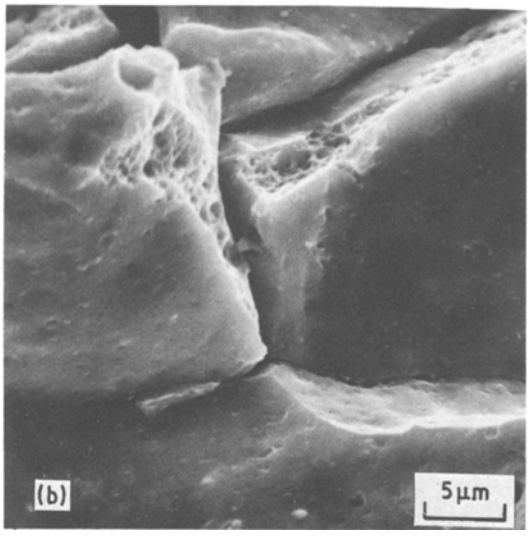
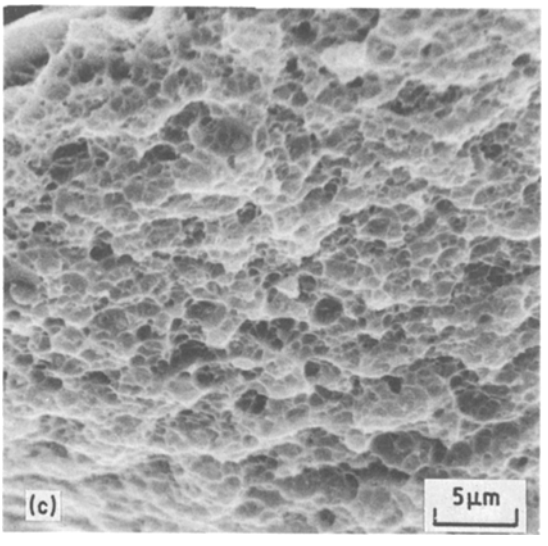


Figure 5 SEM micrographs showing fracture features of tensile samples which were solution heat-treated at 515° C and then aged at 160° C for 18 h. (a) Intergranular fracture feature, (b) enlarged area A of (a), showing brittle grain-boundary facets and small dispersoids, and (c) enlarged area B of (a), showing dimples.



4. Conclusions

1. The solution heat-treatment temperature which determines the amount of undissolved phases in an aluminium alloy 2020 does not significantly affect ductility of the alloy.

2. An increase in soaking time from 30 min to 2 h during solution heat-treatment does not increase the amount of T_B, T_1 and T_2 phases dissolved in the solid solution.

3. The optimum solution heat-treatment temperature for the alloy is between 505 and 520° C for 30 min.

4. The fracture mode of tensile samples for any solution heat-treatment temperature is a form of brittle intergranular fracture.

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