

Effect of Solution Treatment on Microstructure and Mechanical Properties of Thick Plate Aluminium Alloy 7150

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Approaches to the optimisation of solution treatment, and the effects on the microstructure and mechanical properties of a high strength aluminium alloy 7150 plate with a thickness of 78 mm have been investigated. By exploring the stability of individual constituent phases, measuring the volume fraction of remaining constituent particles and investigating the grain structure variation after different stages of multi-step solution treatments, a solution treatment sequence optimised with respect to tensile properties has been defined. The results indicate that such a solution treatment can give a good balance between a reduced volume fraction of remaining constituents and a partially-recrystallised grain structure. By allowing a final stage of solution treatment to be conducted at an increased temperature of 495°C, the volume fraction of remaining constituents decreases from $4.3 \pm 0.5\%$ (as-received condition) to $0.8 \pm 0.05\%$, whereas the recrystallised fraction increases from $3 \pm 1\%$ (as-received condition) to $45 \pm 5\%$. Moreover, it is observed that, the 495°C optimised process improves the artificial ageing response of the alloy at 120°C, with resulting maximum hardness values of up to 195 ± 3 HV₅. To understand the effects of such optimised solution treatments on mechanical properties, tensile testing in the short transverse direction has been carried out both before and after retrogression and re-ageing (RRA) treatments. Samples subjected to final-stage solution treatment at 495°C have higher tensile strengths, both before and after the RRA treatments.

Keywords: *Solution treatment; dissolution; recrystallisation; 7150; strength*

1. Introduction

Alloys of the Al-Zn-Mg-(Cu) system (7xxx series) are widely used as structural materials in the aeronautical fields because they can possess attractive combinations of properties such as high specific strength, ductility, toughness and fatigue strength, depending on how they are processed [1, 2]. Below the solidus temperature, four major constituent phases, i.e. η (MgZn₂), T (Al₂Mg₃Zn₃), S (Al₂CuMg) and θ (Al₂Cu) can typically exist in Al-Zn-Mg-Cu 7xxx series Al alloys of current commercial interest [3, 4]. It has been reported that the melting temperatures of η -, T- and S-phase particles are about 475°C [5], 482°C [6] and 490-501°C [6, 7], respectively. However, the widely used industrial solution treatment temperature range for alloy 7150 is 471-482°C [8]. This temperature range normally allows for sufficient dissolution of constituent particle while minimising the risk of incipient melting that may occur at higher temperatures. However, since this temperature range is not high enough to dissolve all S-phase particles, a high density of coarse S-phase particles still commonly exists in Al alloy 7150 after commercial solution treatments.

Generally, the fracture resistance of Al-Zn-Mg-(Cu) alloys is very sensitive to the existence of any coarse constituent particles that may act as void/crack initiation sites or provide preferential crack propagation paths and thus greatly degrade the fracture resistance [9]. Therefore, reducing the volume fraction of these particles becomes an important means for improving the fracture toughness of aged 7xxx alloys [10-12]. Since coarse Fe- and Si-containing phases do not dissolve at solution treatment temperatures, these have been controlled in recent alloys by reducing the alloy Fe and Si contents [13]. By dissolving the S-phase, however, the additional released solute from the S-phase particles

also aids in the formation of a higher density of strengthening precipitates in the matrix and thereby enhances the strength of the alloy. Recently, Chen *et al* have reported that by using a stepped solution treatment, the dissolution of constituent particles was improved in as-extruded 7075 and 7055 Al alloys [14-16]. However, their work mainly focused on the dissolution of constituent particles. Generally, to dissolve S-phase particles, higher solution temperatures must be employed at the final stage [16]. While holding at higher temperatures, the recrystallisation process will be accelerated. Dorward *et al* [17] reported that a higher recrystallised fraction can ultimately decrease the tensile properties and fracture toughness of 7xxx Al alloys.

Based on the description mentioned above, two competing factors, i.e. a higher density of strengthening precipitates and an increased fraction of recrystallised grains should be considered in researching the effects of a higher solution temperature on the mechanical properties of aged 7xxx Al alloys. However, the effect of solution treatment time and temperature on the volume fraction of remaining particles and on the recrystallised fraction is still unknown. In this work, the volume fraction of remaining constituent particles and the grain structure variation at different solution treatment stages (from 475°C to 505°C) have been investigated to obtain optimised solution treatment procedures for hot-rolled 7150 Al alloy in terms of mechanical properties after ageing treatments.

2. Experimental Procedures

The material used in this study was commercial hot-rolled high strength 7150 Al alloy thick plate (6.22 Zn, 2.11 Mg, 2.39 Cu, 0.11 Zr, 0.09 Fe, 0.06 Si and balance Al, in wt%), provided by CHALCO's Southwest Aluminium (Group) Co. Ltd.

To have a comprehensive understanding of the effect of different solution procedures on the dissolution of the remaining constituent particles, multi-step solution treatments starting from 475°C and progressing to 505°C have been carried out on as-received 7150 Al alloy which had been hot-rolled to 78mm thick plate. The goals mainly included: 1) determining the shortest solution time corresponding to the lowest volume fraction of remaining constituents at 475°C and defining the corresponding samples as 475°C-optimised samples; 2) carrying out solution treatment on these 475°C-optimised samples at 485°C to determine the shortest solution time corresponding to the lowest volume fraction of remaining constituents and defining the corresponding samples as 485°C-optimised samples; and 3) in the same way, determining the shortest solution times for 495°C- and 505°C-optimised samples. During the solution process, the samples were firstly put into the 475°C salt bath and the temperature subsequently increased as needed at a ramp rate of ~1°C/min. After the solution treatments, all the samples were quenched into room-temperature oil. To measure the volume fraction of the remaining constituents in differently solution treated samples, optical images were taken at a magnification of ×100 at three random sites for each polished sample. By using Image J software, the volume fractions of the remaining constituent particles in the as-received and differently solution treated samples were measured. Finally, the selected samples subjected to multi-step solution treatments were etched with Keller's reagent to investigate the grain structure variation. By using a point counting method [17], the recrystallised fractions of solution treated samples were measured.

After quenching, the 475°C-, 485°C-, 495°C- and 505°C-optimised samples were exposed to a one step ageing treatment at 120°C. Then, these aged samples were Vickers hardness tested with a load of 5 kg (HV₅), and electrical conductivities were tested using a Foerster Sigmatest 2.068 instrument. Tensile tests on the aged 475°C-, 485°C- and 495°C-optimised samples were carried out. Specimens were tested in the short transverse direction (STD). The final plate tensile specimen geometry had a gauge length of 20 mm, a cross-section of 5 mm × 4 mm and a radius between the gauge length and the grip ends of 6 mm. To ensure the reliability of the tensile data, three repeated tensile tests were carried out. After testing, the tensile fracture surfaces were observed using backscattered electron imaging (BEI).

3. Results and Discussion

3.1 Volume fractions of constituent particles

Figure 1 shows that during the first stage of solution treatment at 475°C, the volume fraction of constituent particles decreases rapidly from $4.3 \pm 0.5\%$ to $2.3 \pm 0.1\%$ at holding times of 0-8h and then stabilises at longer holding times. When adding a second stage at 485°C to the 475°C/8h sample, the volume fraction of constituent particles decreases from $2.3 \pm 0.1\%$ to $1.2 \pm 0.1\%$ when the holding time is 0-4h and then becomes stable with increasing holding time. When adding a third stage at 495°C to the 475°C/8h + 485°C/4h sample, the volume fraction of constituent particles decreases from $1.2 \pm 0.1\%$ to $0.8 \pm 0.05\%$ when the holding time is 0-4h and then becomes stable with increasing holding time. However, when adding a fourth stage at 505°C to the 475°C/8h + 485°C/4h + 495°C/2h sample, the volume fraction of constituent particles changes very slightly with increasing time. This suggests that by using multi-step solution treatments, the highest reasonable solution temperature should be 495°C and it is unnecessary to increase it further for the purpose of constituent particle dissolution.

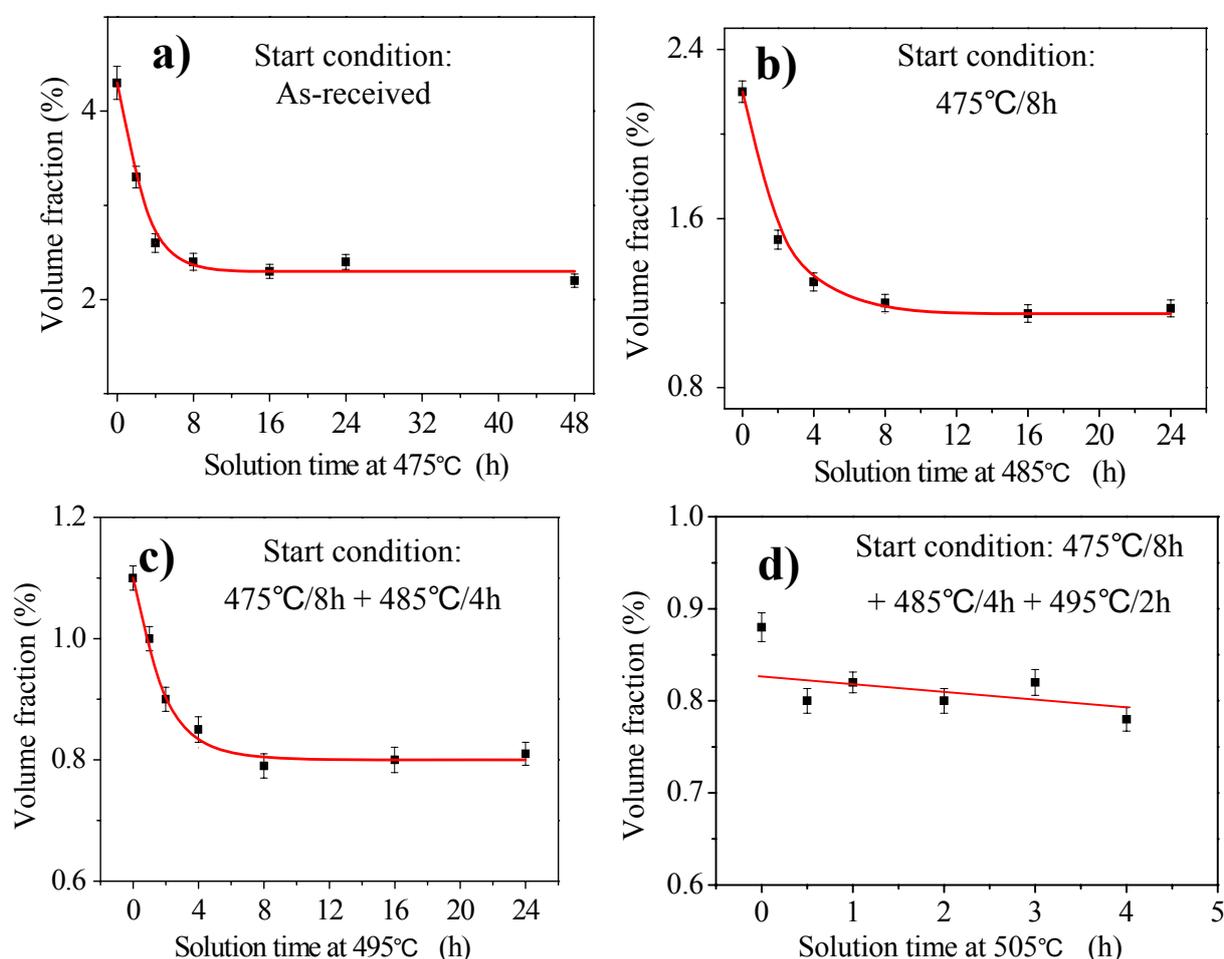


Fig. 1. Volume fraction changes of remaining constituent particles in differently solution treated samples: a) 475°C for different times, b) 475°C/8h + 485°C for different times, c) 475°C/8h + 485°C/4h + 495°C for different times and d) 475°C/8h + 485°C/4h + 495°C/2h + 505°C for different times.

3.2 Grain structure variations

Figure 2 shows typical etched microstructures of the differently solution-treated samples. Based on the point counting method, the measured recrystallised fractions of the 475°C-, 485°C- and 495°C-optimised samples are $10 \pm 5\%$, $25 \pm 5\%$ and $45 \pm 5\%$, respectively. However, for the 505°C

stage, the recrystallisation process can be rapidly completed after holding for 0.5h, resulting in a recrystallised fraction of $90 \pm 5\%$. In addition, the recrystallised fraction of the as-received sample was measured to be about $3 \pm 1\%$.

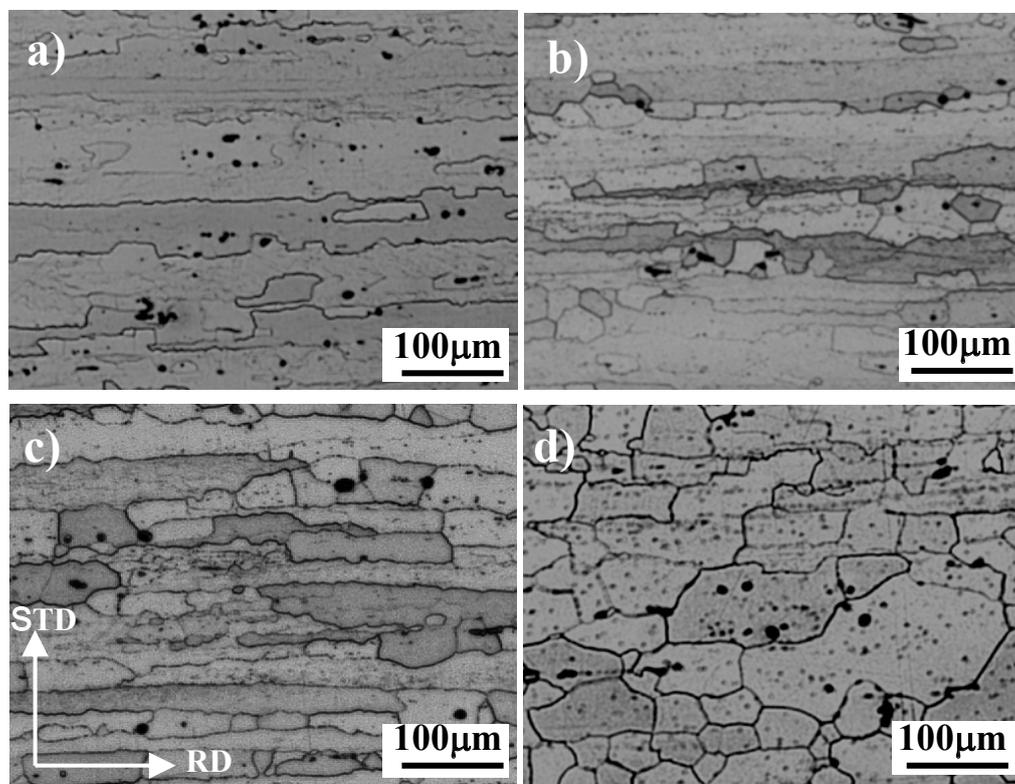


Fig. 2. Optical micrographs of typical grain structures from differently solution-treated samples: a) $475^{\circ}\text{C}/8\text{h}$, b) $475^{\circ}\text{C}/8\text{h} + 485^{\circ}\text{C}/4\text{h}$, c) $475^{\circ}\text{C}/8\text{h} + 485^{\circ}\text{C}/4\text{h} + 495^{\circ}\text{C}/2\text{h}$ and d) $475^{\circ}\text{C}/8\text{h} + 485^{\circ}\text{C}/4\text{h} + 495^{\circ}\text{C}/2\text{h} + 505^{\circ}\text{C}/0.5\text{h}$.

3.3 Properties of aged samples

Figure 3 shows the hardness and electrical conductivity curves of differently solution-treated samples during 120°C ageing treatments. Apart from the 505°C -treated sample, the hardness increases with increasing solution temperature, whereas the electrical conductivity response exhibits the opposite trend. In particular, the 495°C -optimised sample has the strongest hardness response with a peak-aged Vickers hardness value of up to $195 \pm 3 \text{ HV}_5$. On the other hand, the 475°C -optimised sample has the weakest hardness response with a peak-aged Vickers hardness value of $180 \pm 3 \text{ HV}_5$. For the 505°C -optimised sample, the hardness and conductivity responses are basically the same as those of the 485°C -optimised sample.

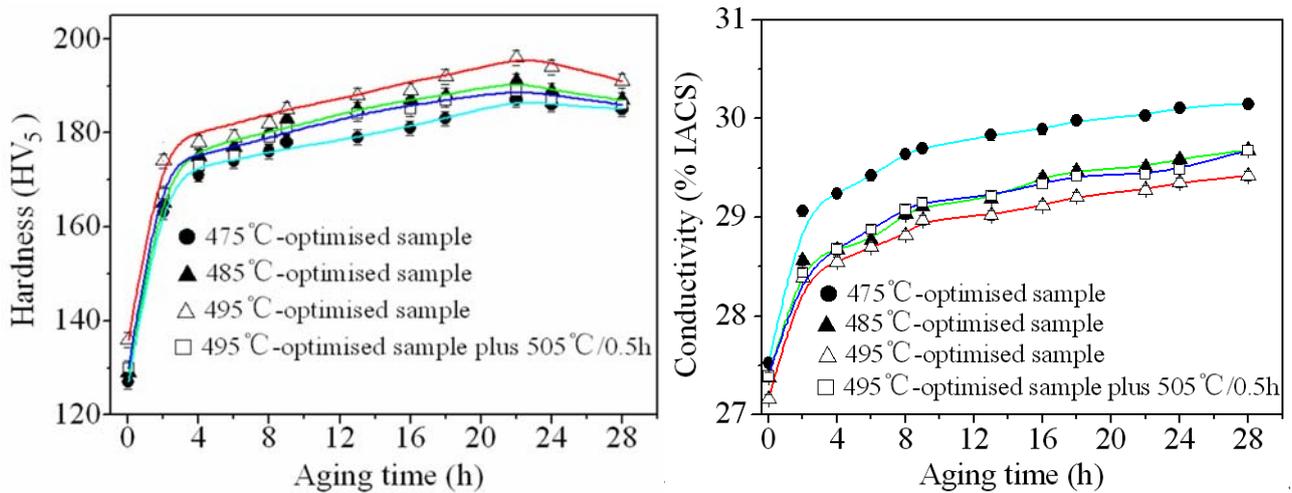


Fig. 3. Hardness and electrical conductivity responses of the differently solution-treated samples during artificial ageing at 120°C.

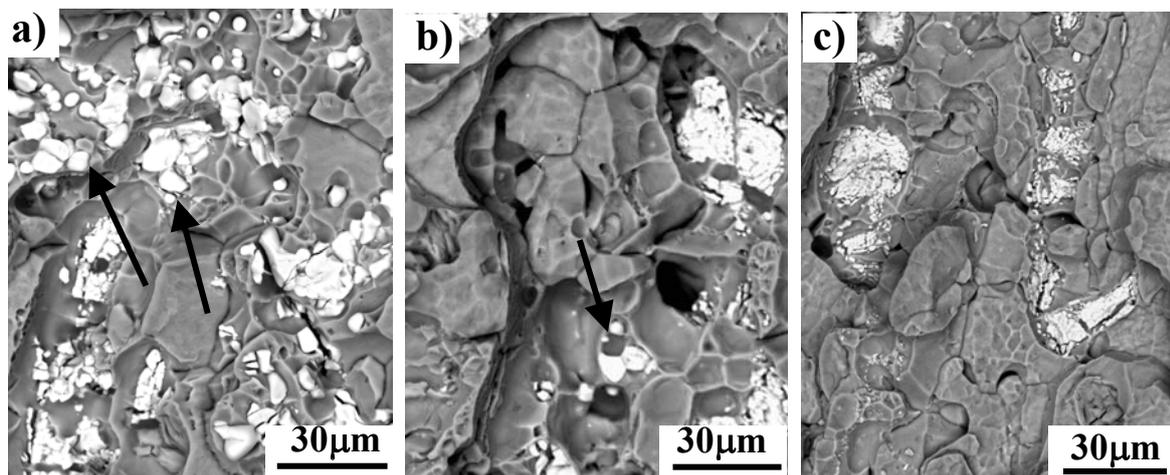


Fig. 4. Fractographs of: a) 475°C-, b) 485°C- and c) 495°C-optimised samples after RRA treatment as indicated in Table 1. Images were taken using backscattered electron imaging and particles were identified by EDS. Arrows point to S-phase particles, none of which could be found in image (c). Other bright particles are Al_7Cu_2Fe .

Table 1. Tensile properties of the 475°C-, 485°C- and 495°C-optimised samples after T6 (120°C for 24h) and RRA (120°C for 24h + 185°C for 1.5h + 120°C for 24h) treatments.

Conditions	$\sigma_{0.2}$ (MPa)	Tensile strength (MPa)	Elongation (%)
475°C-optimised (T6)	474 ± 5	545 ± 5	6.1 ± 0.8
485°C-optimised (T6)	482 ± 3	551 ± 6	5.6 ± 0.5
495°C-optimised (T6)	489 ± 4	560 ± 3	5.3 ± 0.5
475°C-optimised (RRA)	524 ± 3	554 ± 3	2.4 ± 0.4
485°C-optimised (RRA)	530 ± 4	564 ± 4	2.3 ± 0.3
495°C-optimised (RRA)	546 ± 3	573 ± 3	1.7 ± 0.3

Tensile results of the 475°C-, 485°C and 495°C-optimised samples after T6 and retrogression and re-ageing (RRA) treatments are summarised in Table 1. It firmly indicates that samples subjected to final-stage solution treatment at 495°C have higher tensile strengths, both after T6 and RRA treatments. The fractographs in Fig. 4 demonstrate that a higher stress concentration occurs around

Al₇Cu₂Fe and S-phase particles and that crack nucleation is caused by the cracking of these coarse constituent particles or decohesion at the particle/matrix interfaces. In addition, Fig. 4 also reveals that the S-phase particles can be fully dissolved by using 495°C-optimised solution procedures. For the 495°C-optimised samples, more solute can be released from the dissolved S-phase particles for the formation of fine precipitates during ageing while still controlling the recrystallised fraction. Therefore, the 495°C-optimised solution treatment results in the highest tensile strengths in all ageing conditions.

4. Conclusion

By allowing a final stage of solution treatment to be conducted at an increased temperature of 495°C, the volume fraction of remaining constituents decreases from $4.3 \pm 0.5\%$ (as-received condition) to $0.8 \pm 0.05\%$, whereas the recrystallised fraction increases from less than $3 \pm 1\%$ (as-received condition) to $45 \pm 5\%$. The yield strengths of T6- and RRA-treated 495°C-optimised samples are higher than those of the 485°C- and 475°C-optimised samples by about 6-7 MPa and 12-15 MPa, respectively. It is expected that similar improvements could be seen on an industrial scale, provided that the ramping up from 475 to 495°C is sufficiently slow (~12h) and the temperature control is sufficiently good (within about $\pm 5^\circ\text{C}$) to avoid overheating.

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