HIGH STRENGTH 7XXX ALLOYS FOR ULTRA-THICK AEROSPACE PLATE: OPTIMISATION OF ALLOY COMPOSITION

R. SHAHANI*, T. WARNER*, C. SIGLI*, P. LASSINCE** and P. LEQUEU**

*Pechiney Centre de Recherches de Voreppe, B.P. 27, 38340 Voreppe, France
**Pechiney Rhenalu, ZI des Listes, CP 42, 63502 Issoire, France

ABSTRACT

Improvements in ingot quality and rolling schedules have made possible the production of ultra-thick (150-215 mm) aerospace-quality plate. Until recently the alloy compositions originally defined for thinner products (≈ 100 mm) have simply been transposed for use in these thicker plates. This paper will focus on work performed to optimise alloy composition for 150-215 mm thick plate, which is characterised by low deformation during processing and slow quench rates. The choice of alloy composition is further complicated by the multi-dimensional property balance (high strength, high damage tolerance, corrosion resistance, low residual stresses, ...) required for thick plate in aerospace applications.

The results of lab-scale trials, metallurgical modelling, and industrial production of an optimised product, designated AA7040, are presented. Particular emphasis is placed on the metallurgical implications of slower quench rates on the development of heterogeneous precipitation, and the concomitant damage tolerance properties. The apparent paradox that an alloy with lower solute content can give a higher strength thick plate is demonstrated.

Keywords: *7xxx alloys, plate, strength, damage tolerance, heterogeneous precipitation*

1. INTRODUCTION

Thick-gauge plate for structural aerospace applications requires a balance of high strength, high damage tolerance, good corrosion resistance and low residual stresses. Improvements in casting and rolling practice in recent years have resulted in spectacular improvements in fatigue performance, enabling the development of ultra-thick plate: Pechiney Rhenalu currently produces plate up to 215 mm thick for airframe applications. Ultra-thick plate stretched for stress relief provides a cost-effective alternative to forged components, notably due to the much lower levels of distortion during machining[1]. Alloys AA7050 and AA7010 in overaged tempers are typically used for plate applications. However, these alloys are not necessarily ideal choices for ultra-thick plate, which is characterised by relatively low deformation during processing and slow quench rates.

During slow quenching, heterogeneous precipitation occurs on interfaces such as grain boundaries, subgrain boundaries and incoherent dispersoids. Figure 1 shows typical TEM micrographs. This precipitation reduces the solute available for precipitation hardening, resulting in lower peak strengths after ageing. In addition, the grain boundary precipitates and the relatively wide precipitate-free zone (PFZ) weaken the grain boundaries, favouring low-toughness intergranular fracture (Fig. 2). In very thick gauge products, reduced heterogeneous precipitation should therefore improve the yield strength/toughness compromise.

This paper describes results from Pechiney's ongoing development programme for optimised ultra-thick aerospace plate. Laboratory trials, metallurgical modelling[2] and industrial trials were used to develop a new alloy, AA7040 (see table 1 below), which gives reduced quench sensitivity relative to existing AA7050 and AA7010 alloys. We will focus on the optimisation of the Cu, Mg and Zn levels in the alloy which control the driving force for precipitation during slow quenching. Of the minor elements, Zr is the clear choice for a dispersoid-forming element, since Cr and Mn give incoherent dispersoids and higher quench sensitivity. Impurities such as Fe and Si should be kept to low levels for toughness considerations. Optimisation of processing will be covered briefly but a detailed treatment is outside the scope of this paper.

Table 1. AA registered composition of 7040

Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr
0.10	0.13	1.5-2.3	0.04	1.4-2.4	0.04	5.7-6.7	0.05-0.12

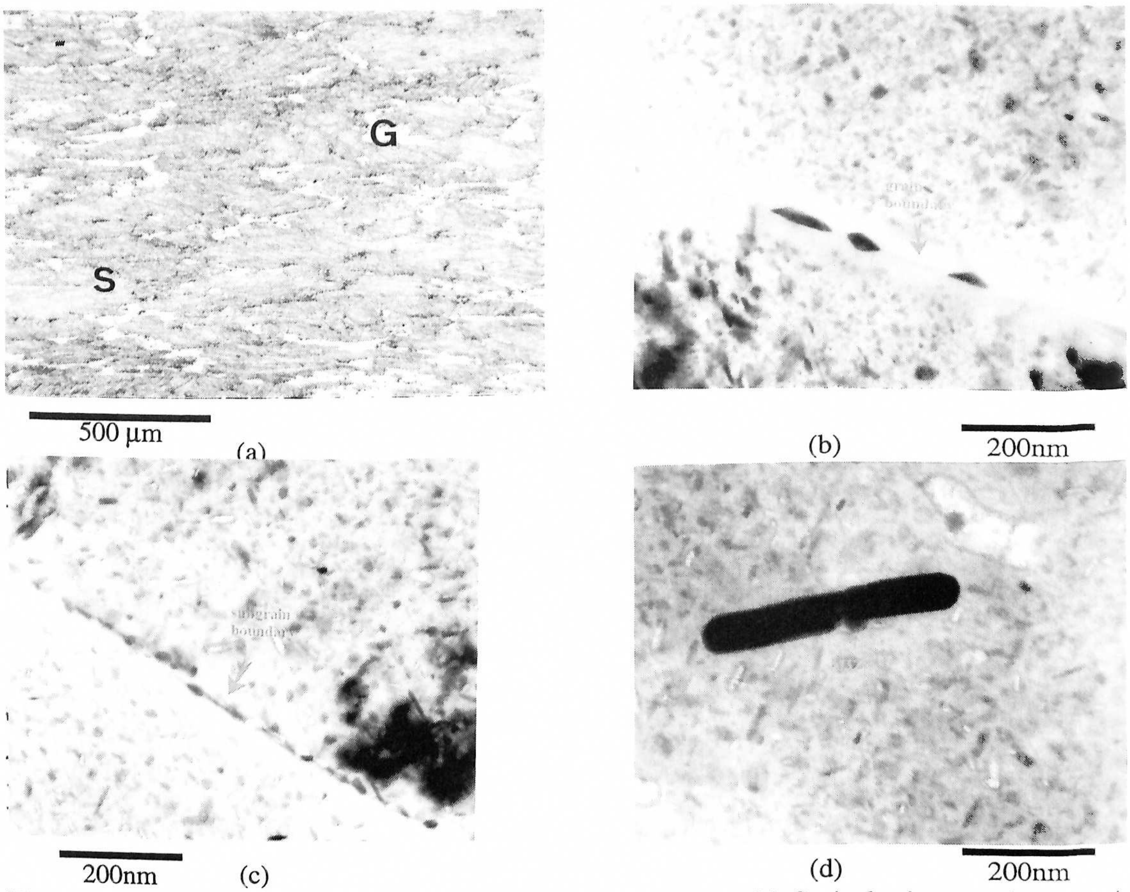


Figure 1 : Microstructure of 150 mm-thick AA7050 T7451 plate. (a) Optical micrograph (chromic acid etch) showing recrystallised grains (G) and recovered subgrains (S). (b-d) Bright field transmission electron micrographs of heterogeneous precipitation at (b) a high angle grain boundary, (c) a subgrain boundary and (d) an incoherent Al_3Zr dispersoid in a recrystallized grain.

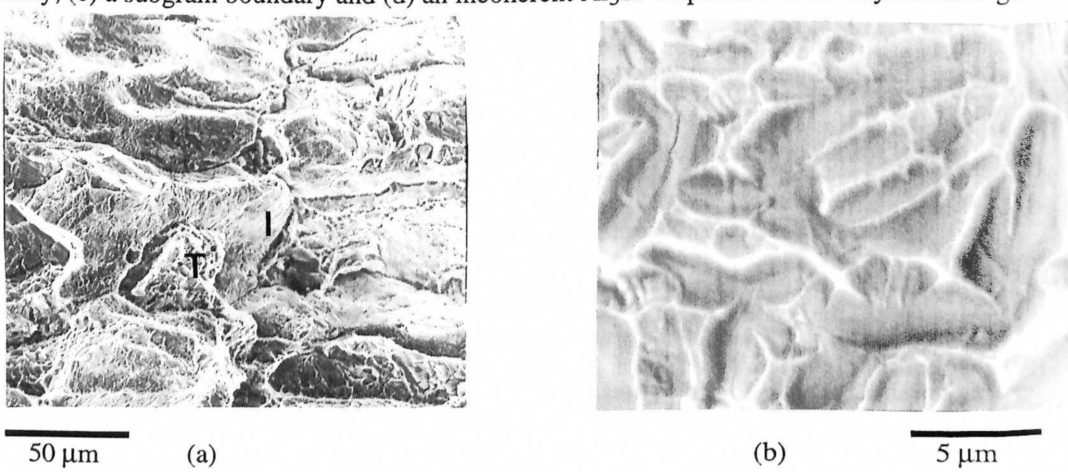


Figure 2 : Scanning electron fractographs of short bar toughness test samples. AA7050 T7451 tested in the T-L direction; industrially cast material processed in the laboratory to simulate the deformation and slow quench of 170 mm-thick plate. (a) Fracture surface showing regions of intergranular (I) and transgranular (T) failure. (b) Region of intergranular failure at higher magnification showing dimples formed around grain boundary precipitates.

2. LABORATORY TRIALS

2.1 Optimisation of alloy composition

Ten alloy compositions were selected as indicated in Figure 3. Variants of the existing AA7050 and AA7010 alloys were chosen. In addition, low-magnesium and low-copper alloys were considered. Alloys with higher zinc contents were evaluated in a parallel programme aimed primarily at upper wing skin applications[3]. The alloys were cast as 30 mm-thick ingots, homogenised at 472°C, scalped to 25 mm and hot rolled at around 400°C to 18 mm thick plate and solution treated using a simulated commercial practice#. After solution treatment, samples were quenched either slowly (in air) or rapidly (in a commercial quenching medium) as indicated in Figure 4. Three ageing treatments were used:

- 24h 120°C (near peak strength)
- 12h 120°C + 8h 170°C (overage)
- 12h 120°C + 10h 170°C (longer overage)

The microstructures were similar to the structure shown in Figure (1a), although the unrecrystallised grains were only weakly elongated due to the low rolling reduction; the alloys were approximately 20% recrystallized.

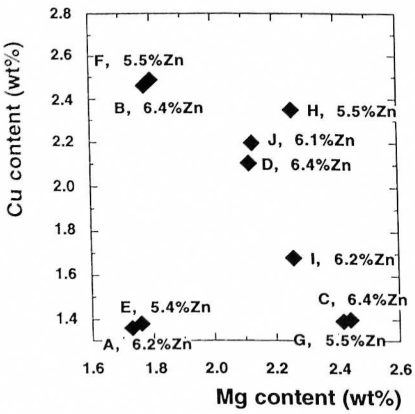


Figure 3: Compositions of alloys selected for the laboratory-scale trials. All alloys contained 0.09% Zr and low impurity levels.

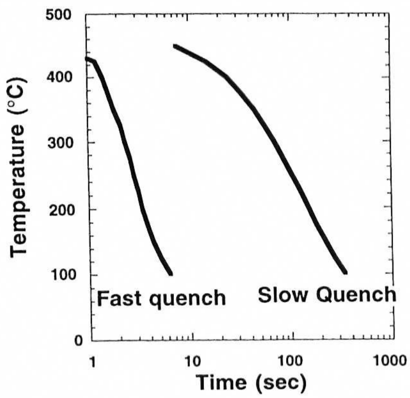


Figure 4: Quench paths for fast- and slow-quenched samples. The slow quench simulates 215 mm plate at mid-thickness.

Tensile properties are shown in Figure 5. The less concentrated alloys, and particularly the low copper variants, were found to show lower quench sensitivity. The yield strength difference between the slow- and fast-quenched samples is directly related to the volume fraction of heterogeneous precipitation during quenching, and indirectly related to the area fraction of grain boundary precipitation. We would therefore expect the lower copper alloys to give improved toughness at equivalent yield strength in the case of thick gauge material. Moreover, our results show that reducing alloy solute content can increase yield strength at constant ageing treatment in the case of a slow quench (figure 5b).

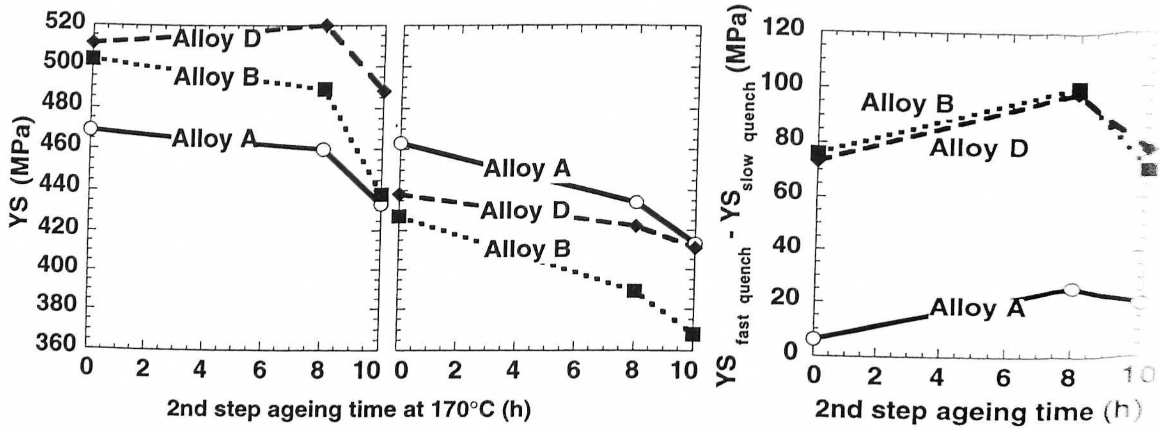
Quantification of the effects of alloy composition and quench rate on heterogeneous precipitation, particularly at grain boundaries, would assist interpretation and modelling of these effects. In rapidly-quenched material, grain boundary coverage can be studied using TEM[4], but in these slowly-quenched samples the grain boundary precipitates become longer than typical TEM foil thicknesses, so SEM observations would be more appropriate, either using fractography[5], or based on polished sections (Figure 6).

Metallurgical modelling[2] was also used to predict the volume fraction of heterogeneous precipitation during quenching for concentrated (AA7050) and more dilute (AA7040) alloys. The

Alloy H was not fully solutionised since although phase diagram calculations show that incipient melting should not occur below 511°C, in practice dissolution of the Al_2CuMg phase occurs extremely slowly, resulting in incipient melting below the solvus at 492°C and thus limiting the temperature of commercial heat treatment practices.

model calculates yield strength using physically-based models and the following principal inp
parameters:
- alloy composition
- solution treatment temperature
- temperature profile during quenching
- degree of stretching for stress relief
- ageing cycle

As shown in Figure 7, the total predicted loss of solute due to heterogeneous precipitation durin quenching is significantly higher for 7050 than for the more dilute 7040 alloy.



(a) Fast quench (b) Slow quench (c) Quench sensitivity

Figure 5 : Selected results from the laboratory-scale programme showing effects of alloy composition and quench rate on yield strength for three ageing cycles. (a) The 7050 variant D gives highest strength in the case of a fast quench. (b) The more dilute alloy A gives highest strength following the slow quench. (c) Alloy A has low quench sensitivity, and therefore reduced heterogeneous precipitation during slow quenching.

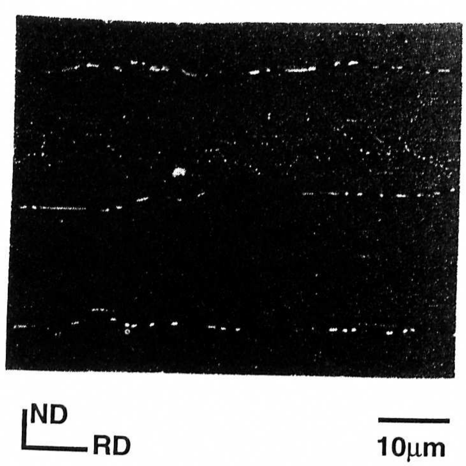


Figure 6: SEM micrograph showing intergranular precipitation in AA7010 T7451 quenched at around 2°C/sec.

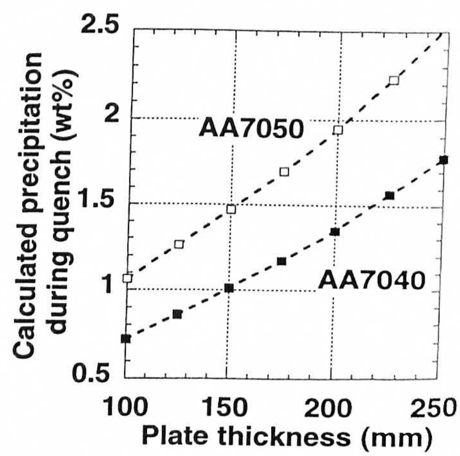
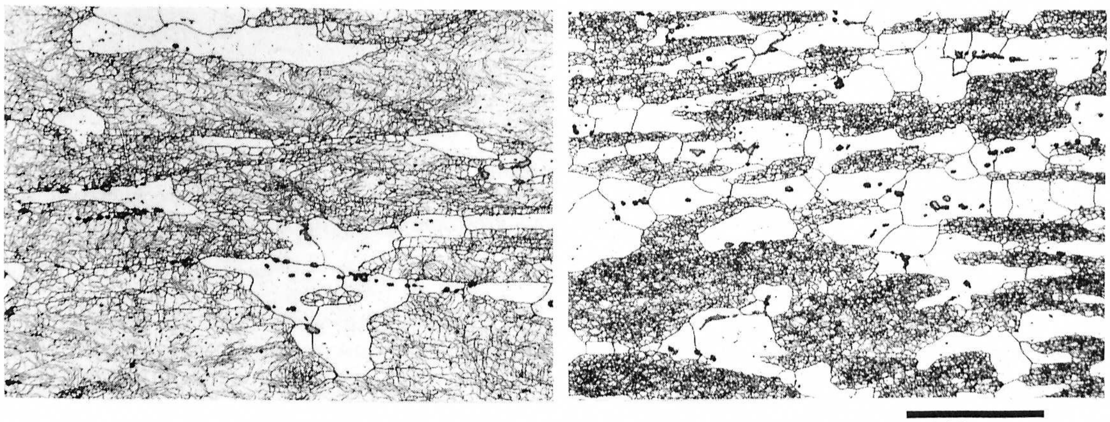


Figure 7 : Predictions for precipitation (essentially of $MgZn_2$) during quenching of AA7050 and of the more dilute alloy AA7040 as a function of plate thickness.

2.2 Optimisation of processing conditions

In order to reduce the strength loss due to heterogeneous precipitation, it is desirable to minimise the surface area of nucleation sites - grain boundaries, subgrain boundaries and incoherent dispersoids. In addition, it is well known that parameters such as grain shape and degree of recrystallization also have direct effects on properties such as fracture toughness (e.g. [6,7]). Optimised processing conditions for microstructural control in ultra-thick plate have therefore been studied with an emphasis on the effects of composition, casting practice, homogenisation, hot rolling and solution treatment parameters on recovery and recrystallization. As in previous studies [8,9] hot plane strain compression testing has been used to give controlled simulations of hot rolling. Details of this study are outside the scope of this paper, but as shown in Figure 8 a wide range of microstructures can be obtained, with corresponding changes in quench sensitivity and final properties. Low levels of recrystallization were found to be preferable for high plane strain and plane stress fracture toughness, particularly in the L-T direction.



(a) (b)

Figure 8 : Microstructures of laboratory-processed AA7040 T7451 showing (a) plane strain compression sample deformed at high temperature giving very low levels of recrystallization and a poorly-defined subgrain structure (b) sample deformed at lower temperature giving significant recrystallization and a well-developed substructure. Zr-content, homogenisation practice and solution treatment practice also have significant effects on the final microstructures.

3. INDUSTRIAL TRIALS AND COMMERCIAL PRODUCTION

As a result of the laboratory trials, combined with statistical analysis of plant data on properties of existing 7050 and 7010 variants, several compositions were selected for industrial trials. These trials were used to tune the composition and processing of the new alloy[10], now designated AA7040. The alloy shows an improved strength/toughness compromise over existing AA7050/7010 thick plate products (Figure 9). Moreover it has very good fatigue resistance, low levels of residual stress, and excellent stress corrosion resistance. No failures have been observed during extensive SCC testing to ASTM G44 of 7040 T7451 ultra-thick plate at stress levels of 242 MPa and even 310 MPa. In DCB testing of 7040-T7451, no crack propagation was observed with an initial stress intensity of 25 MPa$\sqrt{m}$. This excellent performance is principally the rolling schedule for this material which results in a relatively isotropic grain structure and properties. Other parameters, in particular the increased PFZ widths and intergranular precipitation resulting from the slower quench [11], copper level [12], and recrystallisation, clearly have secondary roles.

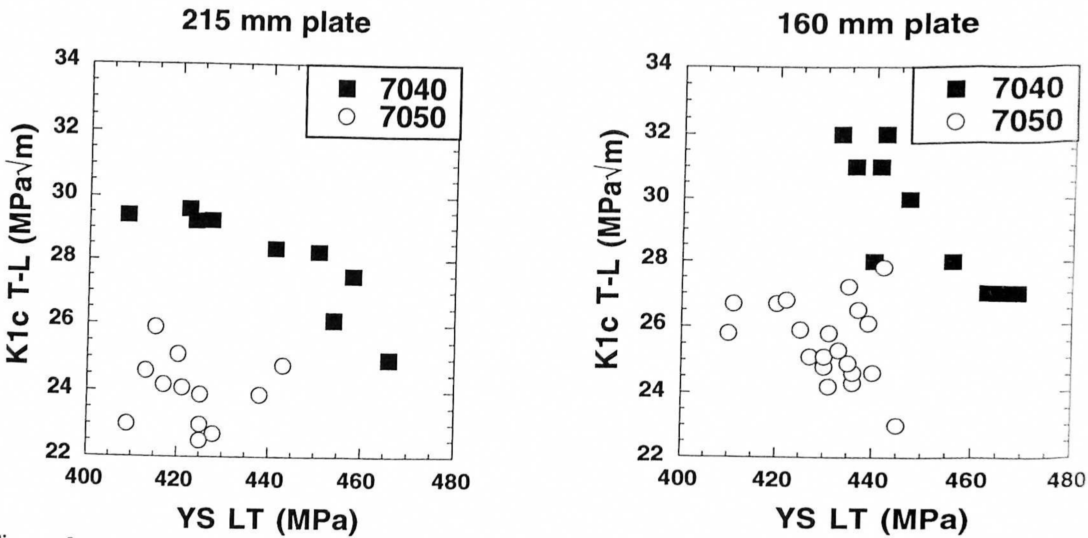


Figure 9 : Comparison of conventional 7050-T7451 and 7040-T7451 strength-toughness balances for plate of thicknesses 160 mm and 215 mm. At given strength, K_{IC}(T-L) values are improved for 7040-T7451. Several heats and processing conditions are represented for the 7040-T7451 plate.

4. CONCLUSIONS

Laboratory-scale experiments and metallurgical modelling were used to optimise the composition of a high strength 7xxx alloy for thick gauge aerospace plate, leading to the development of a new alloy designated AA7040. Relatively low levels of magnesium and copper were found to reduce levels of heterogeneous precipitation during quenching, resulting in an improved yield strength/toughness compromise. Hence for a given toughness, AA7040 gives higher levels of strength than more concentrated alloys such as AA7050 or AA7010.

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