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The Effect of Ti Content on Mechanical Properties of an Al7Si0.35Mg Alloy

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Abstract

The effect of titanium additions on the age hardening response and mechanical properties of an Al7Si0.35Mg alloy has been studied. It is found that titanium additions have little effect on the grain size of the as-cast microstructure, particularly when TiB_2 is also added to the alloy. While the titanium-containing alloys have yield strengths higher than those of Ti-free alloys in the as-quenched condition, they exhibit a reduced age hardening response, during isothermal ageing at 160°C, and lower yield strengths in the T6 condition (4 hours at 160°C). This reduction in the increment in strength appears to be associated with preferential interactions between titanium and solute atoms.

1. Introduction

Aluminium alloy A356 (Al-7wt%Si-0.35wt%Mg modified with 0.02wt%Sr) is widely used because of its good castability and mechanical properties in the T6 condition. Titanium has conventionally been added up to 0.2wt%, reputedly as a grain refiner for aluminium under the assumption that Al_3Ti particles act as nucleating sites. However, addition of a titanium/boron master alloy has been found to be much more effective in grain refinement than titanium alone, and sub-stoichiometric ratio[1] grain refiners have been developed, eg. Al3Ti3B [1] or boron-based grain refiners such as SiBloy® [2], with reputedly improved grain refinement capabilities over conventional Al5Ti1B grain refiners [1]. A number of researchers have found that solute titanium additions have little grain refining effect [3-5], especially when TiB_2 particles are also present. This is because titanium additions have little effect on the development of constitutional undercooling and thus have virtually no effect on the grain size, and that effective nucleant particles are required for effective grain refinement of foundry alloys [6]. Despite this, titanium additions are regularly added to Al-Si foundry alloys. From an industrial point of view, it would be beneficial to determine the optimum titanium content for this alloy, which could then be used to establish a standard composition to achieve the most favourable mechanical properties. The aim of this investigation is thus to examine what effects titanium has on the precipitation hardening response of alloy A356.

[1] The weight ratio of Ti:B to form TiB_2 is 2.2.

2. Experimental Methods

Inverted low pressure gravity casting (90kg capacity) was used to produce plates of six alloys. The melt was degassed with argon gas using rotary impeller degassing for 10 minutes prior to casting. Casting temperature was 720°C and a copper chill was used at one end of the sand mould. Compositions were determined using Optical Emission Spectroscopy (OES). A residual titanium content of 0.005wt% was present in the melt, and TiB_2 was added as an Al-5Ti-1B master alloy (0.005wt% Ti). The compositions of the plates are shown in Table 1.

Table 1: Alloy composition in weight per cent as measured by OES.

Alloy	Si	Mg	Ti	B	Sr	Fe
0Ti	6.90	0.34	0.004	0.002	0.019	0.066
0.05Ti	6.91	0.35	0.056	0.001	0.020	0.066
0.12Ti	6.82	0.35	0.122	0.001	0.018	0.056
0Ti + TiB_2	6.95	0.36	0.009	0.003	0.020	0.066
0.05Ti + TiB_2	7.15	0.36	0.055	0.002	0.018	0.068
0.12Ti + TiB_2	6.70	0.35	0.127	0.002	0.023	0.058

Two 10mm strips were cut from each plate with a face at a distance of 35mm from the chill, where the cooling rate is similar to that obtained in a typical permanent mould cast wheel. Samples for the experimental work performed here were obtained from these strips. To determine grain size, the as-cast samples were electropolished using a solution of water (244ml), ethanol (144ml), hydrofluoric (6ml) and fluoroboric (6ml) acids. Micrographs were then taken of each sample using polarised light. Grain size was measured in accordance with ASTM Designation E112-96 (Standard Method for Determining Grain Size).

Solution treatment was carried out at 540°C for 6 hours, followed by a quench of 1 minute in water at 80°C. There was a 20 minute changeover time from the solution treatment furnace to the aging furnace. The samples were placed in the ageing furnace at 160°C. Samples were aged as follows: 0.5, 1, 1.5, 2, 3, 4, 6, 8, 12 and 24 hours. A thermocouple was used to determine when the samples reached ageing temperature. This time was taken as 0 hours ageing. Upon removal, the samples were quenched for 2 minutes in water at room temperature and given a light grinding on 600grit paper to remove the oxide layer. Hardness testing was carried out using the Rockwell F scale.

Tensile testing was carried out for the 0, 2 and 4 hours aged conditions on the following samples: 0Ti, 0.12Ti, 0Ti + TiB_2 and 0.12Ti + TiB_2. Tensile testing was performed on an Instron 4505 tensile tester. Each sample was tested at a strain rate of 1mm/min using a 100kN load cell. A pre-load of approximately 20N was applied prior to each test to ensure the sample was held in the correct position for testing. Six tests were performed for each condition.

Transmission electron microscopy (TEM) was also carried out on selected samples. The discs were electropolished using a solution of 33 vol.% nitric acid and 67 vol.% methanol at –20°C. TEM examination was carried out using a Philips CM20.

3. Results and Discussion

Examination of the as-cast microstructure of TiB_2-free alloys indicated that titanium had a small effect on grain refinement, with an average grain size of approximately 800 μm in the 0Ti alloy and approximately 600 μm in the 0.12Ti alloy, Figure 1. This was in contrast to TiB_2-containing alloys, in which a significantly smaller grain size (~400 μm) was achieved. There was no effect of titanium on grain refinement when titanium was added together with TiB_2. These observations were consistent with the expectation that the grain size is independent of titanium content when TiB_2 is added and that TiB_2 is a much more effective grain refiner than titanium [4, 6].

During isothermal ageing at 160°C, the level of titanium additions does not seem to affect the hardness of alloys with and without TiB_2 (Figure 2). It is to be noted that the alloys investigated in this study contained large volume fractions of eutectic Si and intermetallic phases and that any slight variations in strength may not be detected by the hardness tests. The effect of titanium additions on mechanical properties of the alloys is better reflected in tensile testing, as shown in Figure 3. In the 0 hours aged condition, the tensile yield strengths of Ti-containing alloys were higher than those of Ti-free alloys. The strength of the 0.12Ti containing alloy was approximately 8 MPa higher than the 0Ti alloy, and the 0.2% yield strength of the 0.12Ti+TiB_2 alloy was approximately 8 MPa higher than that of the 0Ti+TiB_2 alloy. It is to be noted that, while the 0Ti+TiB_2 alloy had a significantly smaller grain size than the 0Ti and 0.12Ti alloys, the 0.2% yield strength of the 0Ti+TiB_2 alloy was only 5 MPa higher than that of the 0Ti alloy and was lower than that of the 0.12Ti alloy.

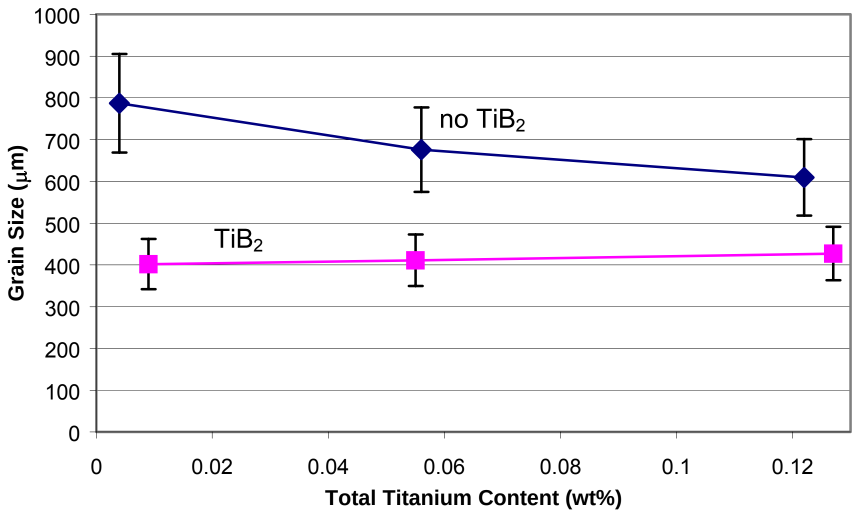


Figure 1: Variation in grain size as a function of titanium content.

While the Ti-containing alloys had higher tensile yield strength in the 0 hours ageing condition, these alloys exhibited a reduced age hardening response during isothermal ageing at 160°C and lower tensile yield strengths than the Ti-free alloys in the peak-aged condition, Figure 3(a). After ageing for 4 hours at 160°C, the 0.12Ti alloy had a 0.2% yield strength of 214 MPa, which was about 8 MPa lower than that of the 0Ti alloy, and the 0.12Ti+TiB_2 alloy had a yield strength (212 MPa) that was about 9 MPa lower than that (221 MPa) of the 0Ti+TiB_2 alloy. The increments in strength in Ti-containing alloys were thus about 16 MPa lower than those achieved in the Ti-free alloys.

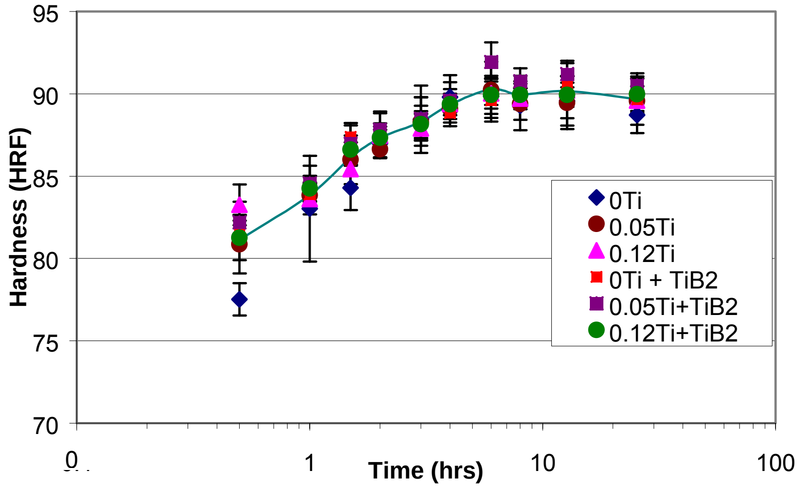


Figure 2: Age hardening response during isothermal ageing at 160°C.

It appeared that the 0.12Ti alloys had a higher tensile strength at the 0 hours aged condition compared to the Ti free alloys (Figure 3(b)), which is due to a slightly increased work hardening rate. Grain size also appears to have a significant effect on the tensile strength after solution treatment. However, like the yield stress, the variations in the tensile strength with titanium content and grain refinement decreases with ageing.

The effect of ageing on the elongation to fracture is shown in Figure 3(c). It shows that grain refinement by TiB_2 has the greatest effect on the ductility. The increase in ductility due to TiB_2 additions is particularly significant for shorter ageing times (~3-4%), although is still significant after four hours of ageing (~2%). It also shows that addition of 0.12Ti titanium may reduce ductility up to 1%, particularly at shorter ageing times.

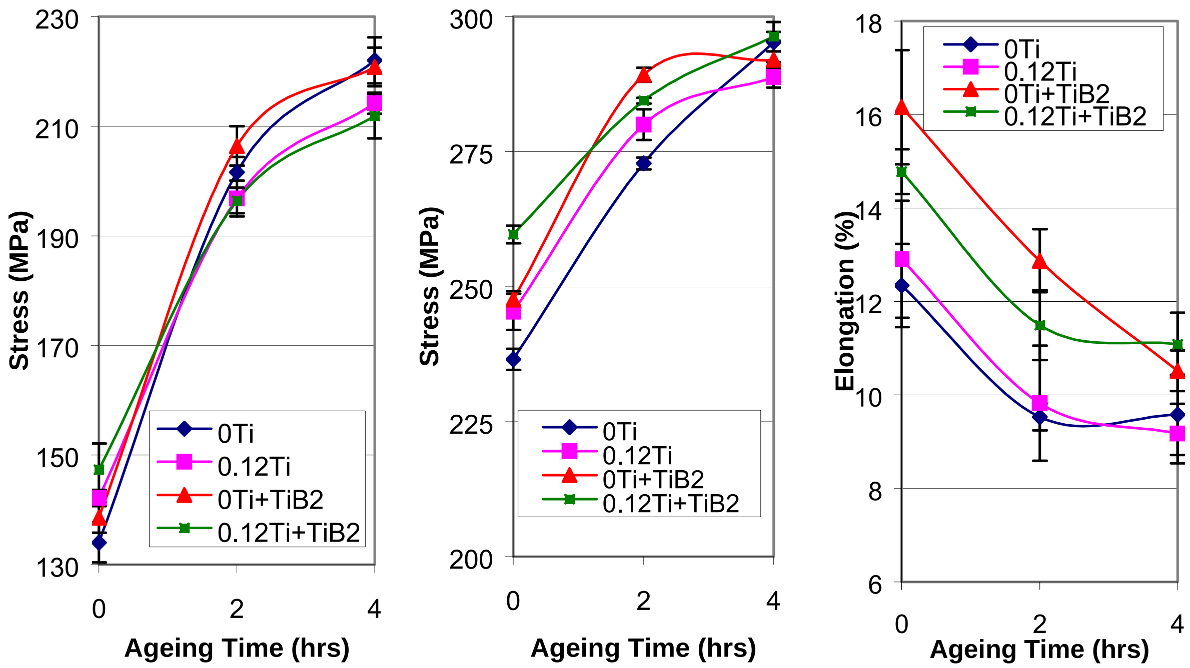
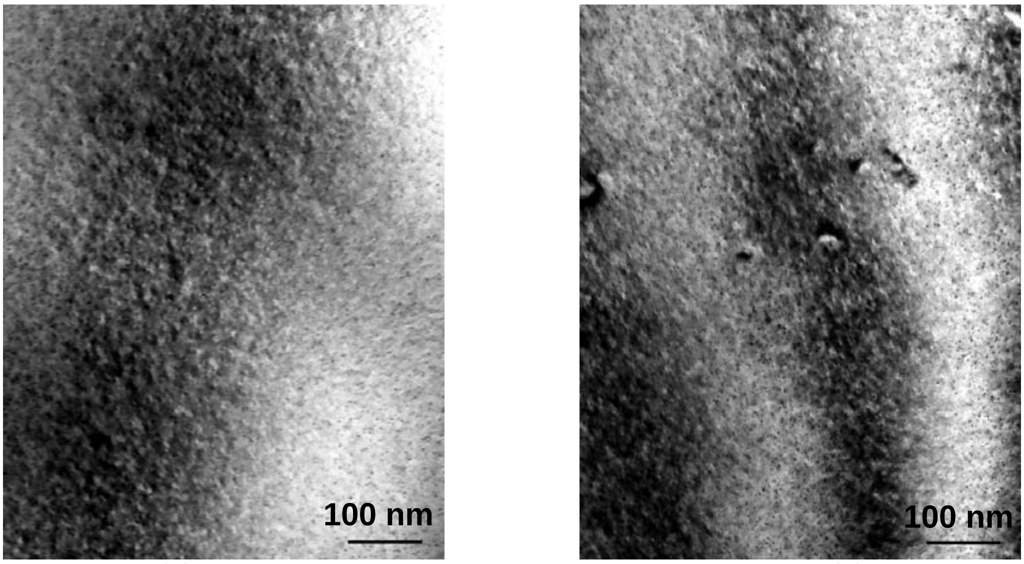


Figure 3: Variation in (a) 0.2% yield strength, (b) ultimate tensile strength, and (c) elongation to fracture as a function of ageing time at 160°C.

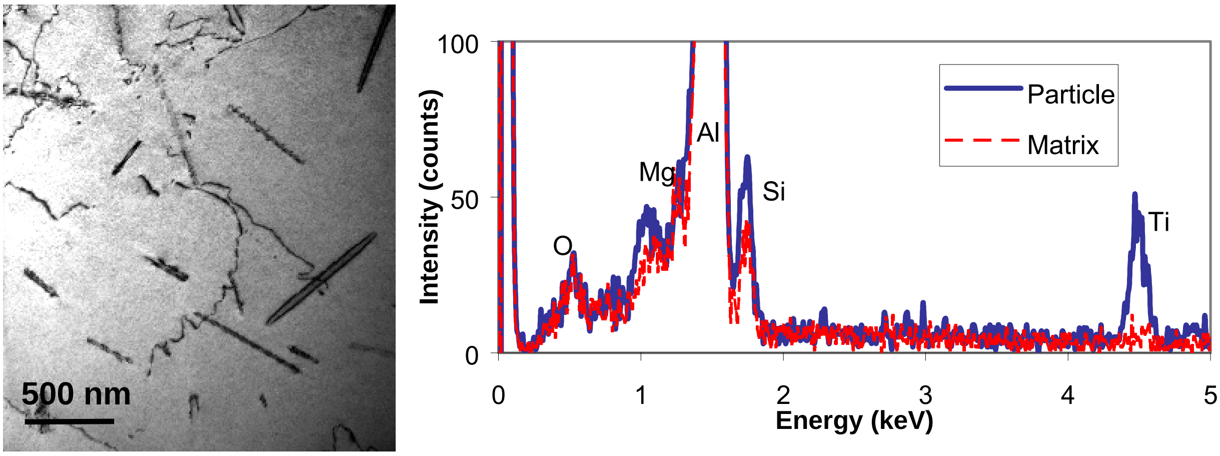
A dense distribution of nano-scale precipitates, presumably magnesium silicide, were visible in the microstructures of both the 0Ti and 0.12Ti alloys (Figure 4). Given the size of precipitates in the peak-aged condition, it was difficult to assess quantitatively the size, number density and identity of precipitates in the two alloys. It was thus difficult to assess whether there were any differences in the distribution of precipitates between microstructures of the 0Ti and 0.12Ti alloys and whether the variation in strength increments was attributable to such differences.

Comparison of precipitate microstructures of the 0Ti and 0.12Ti alloys revealed that the microstructure of the 0.12Ti alloy also contained a sparse distribution of rod-shaped precipitates, Figure 5, that were absent in the 0Ti alloy. These precipitate rods were considerably larger than the precipitates shown in Figure 4. They were typically 25 nm in diameter and 900 nm in length, which is similar to the size of the particles observed by Misra and Oswalt [7] in the same alloy system. The orientation of the long axes of these precipitate rods was such that they did not appear to have a well-defined orientation relationship with the matrix phase. The energy dispersive x-ray spectrum recorded from one such particle is compared with the spectrum from the matrix in Figure 5(b). Comparison of the two spectra indicated that the rod-shaped particles contained an appreciable amount of Ti and possibly a higher level of silicon. In the absence of electron diffraction patterns, the identity of such precipitate rods remained unclear in the present study. Nevertheless, the size and the distribution of such precipitate rods were such that it was unlikely that they form during solidification or isothermal ageing at 160°C. It was speculated that they form during post-solidification cooling and/or solution treatment. Misra and Oswalt [7] claimed that these particles dissolve on ageing. However, no evidence of this was observed in this work. It is also difficult to understand why an ageing process would re-solutionise these particles when the higher temperature solution treatment did not, as the solubility of Ti in the matrix phase increases with increasing temperature [8].



(a) (b)

Figure 4: Transmission electron micrographs showing precipitate microstructures in (a) 0Ti, and (b) 0.12Ti alloys aged 4 hours at 160°C.



(a) (b)

Figure 5: (a) Transmission electron micrograph showing rod-shaped particles in 0.12Ti alloy aged 4 h at 160°C, and (b) energy dispersive x-ray spectra recorded from a rod-shaped particle and the adjacent matrix phase.

The presence of a marginally higher yield stress, tensile strength and work hardening rate in the 0.12Ti containing alloys may be due to the Ti-containing rods. The coarseness and the low density of these particles mean that they could only have a minimal effect on the yield stress. It is possible the presence of Ti may also lead to some solid solution strengthening. The Ti-containing rods may also be the reason for the marginally lower ductility at shorter heat treatment times; however, once again the effect can only be small because of their sparse distribution. The effect of the titanium additions decreases at longer ageing times as the magnesium silicide precipitates become the dominant strengthening mechanism.

The reduced age hardening response in Ti-containing alloys may be due to interactions between titanium atoms and other solute atoms during the ageing process. Another possibility is if the rod-shaped particles are numerous enough, form during solution treatment and contain silicon, then the formation of these particles may influence the local precipitation of magnesium silicide. Further investigations are required to determine the mechanism by which titanium reduces the ageing response.

4. Conclusions

Titanium additions have been found to have little effect on the as-cast grain size of alloy Al7Si0.35Mg, especially when TiB_2 particles are also present. An addition of 0.12Ti to the alloy decreases the age hardening response by about 16 MPa over four hours ageing at 160 °C. It is speculated that this is due to interactions between the titanium atoms and the solute atoms during the ageing process, although changes in the size or distribution of the precipitates were not obvious. Grain refinement by TiB_2 was found to increase the ductility of the alloy, by up to 4% at shorter ageing times although this decreased after ageing for 4 hours to about 1%. Titanium-containing, rod-shaped precipitates were found in the solid phase in the higher titanium content alloys. It is speculated that these precipitates may be the cause of the marginally increased yield and tensile strengths and reduced ductility at shorter ageing times for the titanium-containing alloys.

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