ANALYSIS OF STRENGTHENING MECHANISMS OF THE ALCU5MGTI ALLOY REINFORCED WITH TiB_2 PARTICULATES

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Abstract
The present study was devised to analyse the strengthening mechanisms of a reinforced AlCu5MgTi alloy. TiB_2 particulates were created into the aluminium alloy in an in situ process were titanium and boron containing salts added into melt aluminium reacted and formed TiB_2 particulates following long known reactions. The obtained material was subsequently cast in order to obtain samples and characterise them. The metallurgical analysis showed that, as foreseen, TiB_2 particulates play an important role in the precipitation of the different phases of the alloys as well as in the reduction of grain size and porosity. It was clearly shown that the elongation values got increased (46% in the as cast condition and 63% in theT6 thermally treated specimens). The observed microshrinkages were also much less abundant in the case of the reinforced materials. This latter effect is related to the shortening of the solidification interval.

1. Introduction

Pure aluminium is a soft material with low mechanical properties and it cannot be used in structural applications unless it is alloyed with other chemical elements such as Copper, Silicon and Magnesium. Alloying is one of the most common methods used to strengthen aluminium and other metals but there is quite a large additional range of possibilities that are also employed with the same objective, (thermal treatments, dispersion of small sized particles, use of grain refiners, increase of the solidification rate, addition of ceramic reinforcements or cold working). The strengthening scheme of all these methods is common, though. They are all based on reducing the mobility of dislocations and increasing the stress levels needed to move dislocations through an appreciable distance within the material. [1-5].

The most relevant mechanisms that may play an important role in the case of cast aluminium based casting alloys and composites are the load transfer between matrix and reinforcement, the Orowan strengthening or dispersion strengthening, precipitation strengthening or age hardening, the grain and subgrain size decrease, the CTE mismatch between the matrix and reinforcements and solute hardening.

The relevance of each of these mechanisms has been studied in the AlCu5MgTi reinforced with 6 wt. % of TiB_2 particles.

2. Experimental procedure

2.1. Material

The reinforced alloy was produced by the company London & Scandinavian Co. Ltd. in the United Kingdom. The composition is based on the Al-Cu5MgTi alloys modified by the incorporation of TiB_2 particulates produced through a proprietary in situ process. The final alloy presented 6wt. % of TiB_2 particulates. Around 20% of the particles were created into the alloy through an in situ reaction. The Flux Assisted Synthesis (FAS) was used by mixing the required K_2TiF_6 and KBF_4 salts with the melt alloy. The rest of the particulates were exogenously added as powders of around 5 µm up to complete the desired reinforcement concentration of around 6 wt.%.

The following tables present the composition of the AlCu5MgTi alloy and the reinforced material.

Al-Cu5MgTi + TiB_2 6 wt. %									
	Al%	Si%	Fe%	Cu%	Mg%	Zn%	Ti%	B%	Others%
wt. %	Balance	0.08	0.11	5,05	<0.01	<0.01	3.4	1.7	0.14

Table 1: Composition of the reinforced AlCu5MgTi alloy

Al-Cu5MgTi									
	Al%	Si%	Fe%	Cu%	Mg%	Zn%	Ti%	B%	Others%
wt. %	Balance	0.18	0.10	5	0	0.01	0.01	0	0

Table 2: Composition of the unreinforced AlCu5MgTi alloy

2.2. Production of samples

The two alloys were melt using an induction furnace into Silicon Carbide (SiC) crucibles. All the alloys were cast in the same conditions, mould temperature 200ºC and casting temperature 710ºC. The casting step has been controlled so that there were no differences in the casting parameters and procedure. Two castings of each material were carried out to check that repetitive data were obtained.

The samples were produced through the plaster casting process. This is a variant of the lost wax process in which wax patterns are cladded with plaster. The assembly is subsequently heated into electrical furnaces that eliminate the wax and sinter the plaster where the melt alloys are finally cast into The wax is heated by an electrical heating plate up to around 70-80ºC and cast into silicone moulds with cylindrical cavities. The raisers, feeding channels and rest of the elements that will form the filling and feeding system are produced similarly. Eventually and once all the components that will form the final wax assembly have been produced they are joined together manually through the use of hot sticky waxes.

Half of the samples were submitted to a conventional T6 treatment consisting of a solution treatment at 530ºC during 6 hours followed by quenching in water and artificial ageing at 130ºC for 2 hours.

Tensile specimens were subsequently machined. The tensile tests were carried out with a universal testing equipment following the standard ASTM A-370 with cylindrical threaded specimens. Elongation was measured with an extensometer in the tests at room temperature. The dimensions of the cylindrical specimens were as follows:
Diameter = 6.25 ± 0.12 mm, L_0 = 25 ± 1, L_c > 32 mm, R = >5 and L =80 mm.

The study was completed by the measurement of porosity, grain size and the analysis of the microstructure with Scanning Electronic Microscopy (SEM) and optical microscopy.

3. Results and discussion

3.1. Tensile properties

Table 3 shows a comparison of the values obtained in tensile tests for the reinforced and unreinforced Al-Cu alloys with improvements obtained by the addition of the particulates signalled in brackets.

TENSILE PROPERTIES AT 20ºC		AlCu5MgTi	AlCu5MgTi + 6 wt.% TiB_2
UTS (20ºC) (MPa)	As Cast	124	172 (+39%)
	Thermally treated T6	176	191 (+8%)
YS (20ºC) (MPa)	As Cast	78	93 (+19%)
	Thermally treated T6	126	91 (-28%)
Elongation % (20ºC)	As Cast	3,2	4,7 (+46%)
	Thermally treated T6	4	6,5 (+63%)
E (20ºC) (GPa)	As Cast	75	82 (+9%)
	Thermally treated T6	79	75 (-5%)
TENSILE PROPERTIES AT 200ºC			
UTS (200ºC) (MPa)	As Cast	123	149 (+21%)
	Thermally treated T6	159	166 (+4%)
YS (200ºC) (MPa)	As Cast	70	98 (+40%)
	Thermally treated T6	103	99 (-4%)

Table 3: Tensile properties of the alloys at room temperature and 200ºC at as cast and thermally treated conditions.

Physical properties of the materials have a direct influence in their eventual mechanical properties. Therefore the measurement of the grain size, density and porosity was carried out in order to draw data to complete the analysis of the mechanical properties obtained.

3.2. Grain size

The grain size of each of the materials (see table 4 below) was measured from samples obtained from tensile specimens in regions far from the fractured area. The Al-Cu based alloys were attacked with the Keller reactive. The images obtained with an optical microscope were compared to a series of standard macrographies (x10) to determine their grain size range (SG). The latter parameter can be directly converted into grain size ranges.

The obtained results are presented in the following table:

Grain size /Material	AlCu5MgTi		AlCu5MgTi + 6 wt.% TiB_2	
As cast /T6	As cast	T6	As cast	T6
Grain size range	SG 2 -3	SG 3-4	SG 1-2	S-G 3-4
ASTM grain size (µm)	200-315	315-500	125-200	315-500

Table 4: Grain sizes of the alloys in both as cast and T6 conditions

Plaster casting is a low cooling process due to the poor heat conductive nature of the plaster moulds. Therefore the grain sizes that are usually obtained in this process are much larger than gravity casting or other processes using metallic moulds. The Optical microscopy micrographs show that it is very difficult to obtain a refined condition of the alloys. It is generally accepted that to consider that an alloy is refined it should present grain size values lower than <200 µm and these values are only obtained in the case of some of the Al-Cu The presence of TiB_2 reduces the grain size in the reinforced alloy samples in the as cast condition from 200-315 µm down to 125-200 µm. This effect is annulled by the applied thermal treatment.

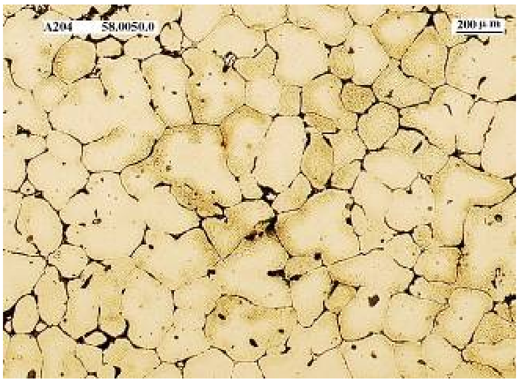

Fig.1: AlCu5MgTi (as cast). Grain size 200-315 µm

Figure 2: AlCu5MgTi (T6). Grain size 315-500 µm

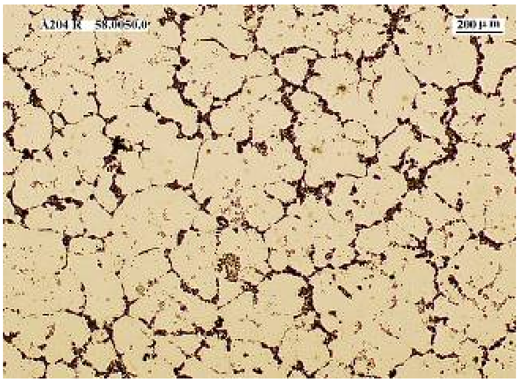

Fig.3: AlCu5MgTi (as cast). Grain size 125-200 µm

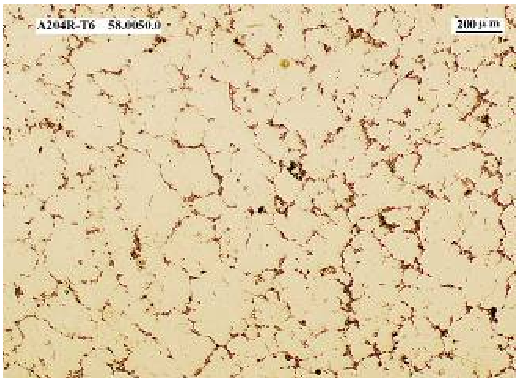

Figure 4: AlCuMgTi + TiB2 6 wt. % (T6) Grain size 315-500 µm

3.3. Porosity level

The density of the samples was measured through the method based on the determination of the density in air compared to its displacement in water or "Archimedes´ principle". Comparison with bibliography data was used to calculate the porosity of the samples.

Material	AlCu5MgTi	AlCu5MgTi + 6 wt.% TiB_2
Porosity (%)	2.55	0.71

Table 5: Porosity of the cast materials.

It can be seen that the presence of the TiB2 particles has a direct positive effect on the porosity level of the alloy. The resulting reinforced materials present very low percentages of internal porosity, 0.71% compared to 2.55% of the unreinforced alloy.

3.4. analysis of the experimental results

The presence of the TiB_2 particles tends to increase the tensile properties of the alloys at the two temperatures tested of TiB_2 particles on the ductility of the Al-Cu5MgTi is this influence is more marked in ductility values with an increase of 47% and 63% in the as cast and T6 conditions respectively.

TiB2 particles decrease the grain size of the alloy and the porosity of the reinforced samples is lower. The microstructural analysis shows that in the case of the reinforced alloys, the brittle phases are few and are more homogeneously distributed, there are almost no microshrinkages or porosity related defects and furthermore the TiB2 particles are small and the interface with the matrix is clean. Moreover there has not been observed any TiB2 particle fracture, probably due to the small size of the particles. The fracture initiation is therefore mainly due to microvoid coalescence and growth as can be deduced from the much dimpled surface of the reinforced materials, the microvoids may have created in the grain boundaries where the TiB2 particles cluster together to reduce the interfacial energy. These areas are sites where strain discontinuities may be created and cluster cracking may take place. When the strain gets increased the microvoids grow, coalesce and form the dimpled fracture surface.

The analysis of the results obtained with the Al-Cu based materials shows the elongation values obtained in the tensile tests get increased (46% in the as cast condition and 63% in the thermally treated specimens). This is attributed to the effective refining action and the reduction of defects provided by the TiB_2 particles. The analysis of the fracture shows that the material becomes ductile when 6% of TB_2 particles are present. The reinforced material presents a refined state in the as cast condition, grain size is <200 µm. On the other hand the effect of the TiB_2 particles on the porosity of the samples is large. The porosity decreases from 2.55% down to 0.71%. The microshrinkages are also much less abundant in the case of the reinforced materials. This latter effect may be related to the shortening of the solidification interval of the alloys. The additional strengthening mechanisms proposed are those linked to the generation of dislocations in the vicinity of the TiB_2 particles during solidification due to the different CTE of the matrix and particles and the interaction of the Al_2Cu phase with TiB_2 particles that has been observed in the microstructure of the reinforced samples where it seems that the latter may be acting as precipitation sites for the former [6-7].

Nevertheless the improvement of properties that should entail all the previous details are not seen in the thermally treated condition. The as cast material presents a clear improvement of both Yield Stress and Ultimate Tensile Strength and Modulus at both room temperature and 200ºC. (Improvements in the range of 20-35% for the YS and UTS and around 8% for the rigidity at room T) but even though the U.T.S values get improved (+5-10%) in the thermally treated condition, a decrease can be appreciated in the Young Modulus at room T (-5%) and in the Yield Stress (-30% at room T and -45% at 200ºC). The analysis of the data (grain size, internal defects, fracture, etc.) does not provide a clear clue for this effect but one possibility may be pointed out to be related to the thermal treatment itself. It is known that the thermal treatment applied to the Al-Cu5MgTi alloy is a very delicate operation. Temperatures of 530ºC are needed to get the phase in solution and this temperature is very near to the start of the melting of the alloy and local meltings can easily take place if the operation is not perfectly controlled. The difference in the composition due to the addition of the TiB_2 particles affects the response of the alloy to thermal treatment.

4. Conclusions

The main conclusions of the analysis of the mechanical properties of these materials are as follows:

1) The presence of 6%wt. of TiB_2 particles in the Al-Cu alloy has a positive effect on the tensile properties. The improvement of mechanical properties takes place in both room temperature and high temperatures.

2) The porosity and microshrinkages are clearly lower due to the presence of TiB_2 particles.

3) The main strengthening mechanisms involved are related to the lower grain sizes of the reinforced alloys and lower degree of defects. Other additional effects such as interactions of particles with different phases that precipitate during solidification may also influence the final result.

4) The TiB_2 particles increase the ductility of the Al-Cu based alloy mainly due to the decrease in the grain size and defects.

5) The grain refining capability of the TiB_2 particles incorporated as reinforcements get impaired by the very low cooling rates of the plaster casting process and the actual grain refined condition (considered to exist when grain sizes lower than 200 µm are obtained) is only obtained in the as cast state. Even so grain refining effects can be appreciated in all the conditions.

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