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The Optimization of Strength and Ductility in Heat Treated ADC12 Alloys

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It has recently been demonstrated that industrially produced aluminium alloy high pressure diecastings (HPDC's) can be successfully heat treated without encountering problems with surface blistering or dimensional instability. This procedure involves using severely truncated solution treatment times at lower than normal temperatures followed by conventional quenching and T4 or T6 ageing procedures. For the T6 tempers, 0.2% proof stress values may be doubled, whereas for a T4 temper simultaneous increases in 0.2% proof stress and ductility are possible.

The present paper reports recent advances that have been made with the heat treatment of Al-Si-Cu HPDC alloy ADC12 through compositional changes. Special consideration is given to the roles of Cu and Mg and the ways these elements can affect microstructures and mechanical properties in both the as-cast and heat treated conditions. Interrelationships between heat treatment, composition and processing are discussed. It will be shown how some variants of ADC12 may display exceptional tensile yield strengths in a T6 temper (e.g. ~400MPa) or alternately, how other variants may display very high levels of tensile ductility in a T4 temper (e.g. >8%).

Keywords: *Heat Treatment, High Pressure Diecastings, ADC12*

1. Introduction

Successful heat treatment of conventionally produced HPDC's has recently been shown to be possible by the use of severely truncated solution treatment times at lower than normal temperatures (e.g. 15 minutes at 430-490°C) [1-5]. This procedure avoids the well known problems associated with formation of surface blisters and dimensional instability, both of which occur during conventional heat treatment procedures. The new heat treatment schedules have been successfully applied to HPDC components ranging from small complex parts (~50g) up to large castings such as automotive transmission housings (~9kg) and engine blocks (>30kg)[4]).

Following solution treatment and quenching, the HPDC's may be heat treated to a wide variety of tempers (e.g. T4, T6 or T7), and the optimum heat treatment procedure to be used is alloy dependent. As the specifications for many HPDC compositions are broad, it is also important to know what variability in properties is likely to occur within any given specification for any particular heat treatment procedure. In this regard, the compositions of many commercial Al-Si-Cu HPDC alloys are similar, and those of several related alloys relevant to the present study are listed in Table 1. Alloys of these types are popular because of their resistance to hot cracking, superior die filling capacity, corrosion resistance, machinability and strength at elevated temperature [6].

Microstructures of ADC12 type Al-Si-Cu alloys comprise α-aluminium grains in a matrix of Al-Si eutectic. During age hardening, the grains of α-aluminium are strengthened by the formation of dense dispersions of precipitate phases such as θ′ (Al_2Cu) and Q′ ($Al_5Cu_2Mg_8Si_6$). Which precipitate forms, and in what proportions, is primarily related to Cu and Mg contents [3]. A number of precursor phases also exist which often form early during artificial ageing, or at peak properties when the ageing temperatures are reduced (as in the T4 temper). Although up to 3% Zn is permissible in some alloys (e.g. 383, A383, C384 and ADC12Z), this element has been found to display only a negligible effect on age hardening in the absence of higher levels of Mg.

2. Experimental Methods

HPDC alloy specimens for tensile testing were produced using a Toshiba horizontal cold chamber die-casting machine with a 250 tonne locking force, a shot sleeve with an internal diameter of 50mm and a stroke of 280mm. The die provided two cylindrical tensile specimens and one flat tensile specimen from each shot and the metal velocity at the gate was 82 m/s. The cylindrical tensile test bars used in the current work conformed to AS1391 and had a total length of 100 mm with a central parallel gauge section 33 mm long and a diameter of 5.55±0.1mm. Five tensile specimens were tested in each condition.

Table 1 Compositions (wt%) of some HPDC alloys related to the ADC12 specification*

Alloy / w%	Si	Fe	Cu	Mn	Mg	Ni	Zn	Sn	Other total
A383 (US)	9.5-11.5	1.3	2.0-3.0	0.5	0.1-0.3	0.5	3	0.15	0.5
B384 (US)	10.5-12	1.3	3.0-4.5	0.5	0.1-0.3	0.5	1	0.35	0.5
ADC12 (JIS)	9.6-12	1.3	1.5-3.5	0.5	0.3	0.5	1	0.3	
AlSi9Cu3(Fe) (EN-AC-46000)	8-11	1.3	2-4	0.55	0.05-0.55	0.55	1.2	0.25	0.15

* Maximums unless otherwise stated. 383 and A384 alloy have 0.1Mg max. C384 and ADC12Z have 3Zn max. AlSi9Cu3(Fe) has 0.15Cr max, 0.35 Pb max and 0.25 Ti max.

For assessing effects of varying the Cu content, tensile properties were determined for eight alloys corresponding to ADC12 specifications in the as-cast, T4 temper, and two T6 tempers. These eight alloys had the following composition:
Al-(10.4-10.6)Si-(X)Cu-(0.71-0.91)Fe-(0.16-0.2)Mn-(0.2-0.25)Mg-(0.74-0.76)Zn-<0.2 (other); where the Cu contents, (X), were 1.75, 2.01, 2.21, 2.41, 2.61, 2.87, 3.07 and 3.45wt%. The heat treatment schedules used are shown in Table 2. Specimens of these alloys were solution treated in an air-circulating furnace at three temperatures: 450, 470 or 490ºC, water quenched, and then either artificially aged in oil for the T6 tempers, or in air at 25ºC for 14 days for the T4 temper.

Table 2 Heat treatment schedules

Procedure	Solution treatment	Ageing
As Cast	None	None
T4	450/470/490ºC 0.25h	14d 25ºC
T6#1	450/470/490ºC 0.25h	24h 150ºC
T6#2	450/470/490ºC 0.25h	4h 180ºC

For assessing the role of Mg on the development of tensile properties, specimens from a further 11 alloys (designed for high ductility and fracture toughness) were tested in the as-cast, T4 and T6#1 conditions. These alloys were based on the composition Al-(10.2-10.4)Si-(2.1-2.3)Cu-(0.24-0.26)Fe-(0.46-0.49)Mn-(X)Mg-(<0.2 other), where the Mg contents for the 11 alloys were 0.005, 0.028, 0.052, 0.069, 0.095, 0.118, 0.138, 0.159, 0.175, 0.202 and 0.22wt%. The only difference in heat treatment procedures compared to the experiments listed in Table 2 was that the solution treatment temperature was 480ºC. This particular temperature was chosen because it improved the average ductility with little or no detriment to the 0.2% proof stress.

Scanning electron microscopy was conducted using a Leica S440 SEM microscope in backscattered electron mode. The SEM was fitted with a thin-window Oxford Pentafet Si(Li) detector interfaced to a Link ISIS analytical system for conducting energy dispersive spectrometry (EDS). Samples for optical and scanning electron microscopy were sectioned at precisely the same location of each chosen casting using a diamond wafering saw. Multiple representative images were then taken from each polished sample at as close to the same location as was possible. Samples examined using SEM were unetched whereas those for optical microscopy were etched in 0.5% HF solution.

3. Results and Discussion

3.1 The Role of Cu in ADC12.

Representative optical and backscattered SEM images of as-cast alloys containing 1.75, 2.41 and 3.45%Cu are shown in Fig. 1(a-c) and 2(a-c). Corresponding images of the same alloys in the T4 treated conditions at 490 and 450°C are shown in Fig. 1(d-i) and 2(d-i) respectively. Fig. 1(a-c)

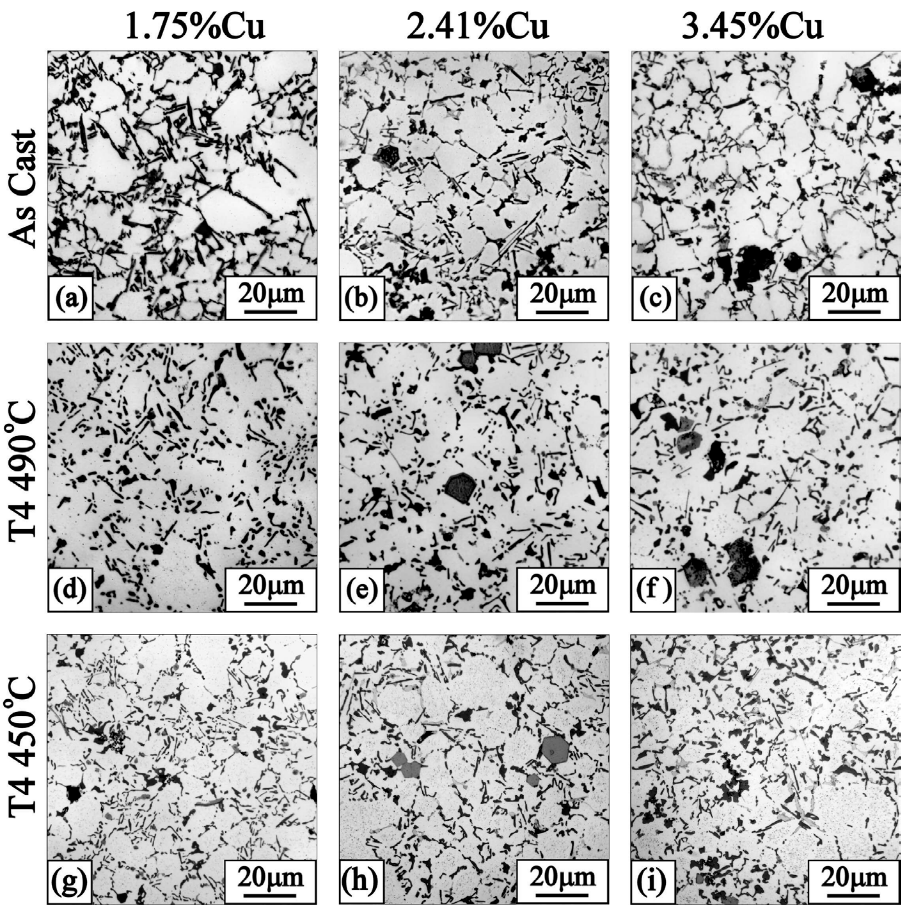

Fig. 1. Optical microstructures of as-cast and heat treated (T4) conditions taken from the same location within alloys containing 1.75, 2.41 and 3.45%Cu. See text for details.

shows the changes to the Si size, distribution and morphology in the alloys as Cu content was increased. Although the Si solidifying in the eutectic was largely spheroidized and fragmented following solution treatment at 490 and 450ºC, some residual blocky Si remained, the amount of which increased as the Cu content was raised. Decreasing the solution treatment temperature from 490º to 450ºC also reduced the levels of fragmentation and spheroidization.

SEM images (Fig. 2) reveal other changes in the as-cast microstructures associated with increases in Cu content, because particles containing the heavier elements Cu or Fe appear with bright atomic number (Z) contrast in the images. Fig. 2(d-e) shows the same alloys treated to a T4 temper at 490°C, and Fig. 2(f-h) shows the results of a T4 temper at 450°C. At both solution treatment temperatures, almost all of the Cu-bearing phases have been dissolved. As a result, the bright particles remaining following solution treatment are almost all polyhedral Fe-bearing phases, despite the low Mn content. This result is interesting because the high Fe contents present normally result in a greater proportion of the needle shaped β-Al_5FeSi phase. As Cu was increased from 1.75% to 2.41%, the total amounts of the polyhedral α-phase were similar, but much of it was present as larger particles, meaning the size distribution had changed. As the Cu level was further increased to 3.45%, another Fe-bearing phase was observed within the microstructures, which was residual from the solidified eutectic. This phase was always found to contain transition metal elements such as Fe and Ni, as well as some Si and approximately 30% Cu. Because this phase was not dissolved during solution treatment and always contains transition metal elements, it would appear to be a hard, residual intermetallic phase formed when Cu contents are high.

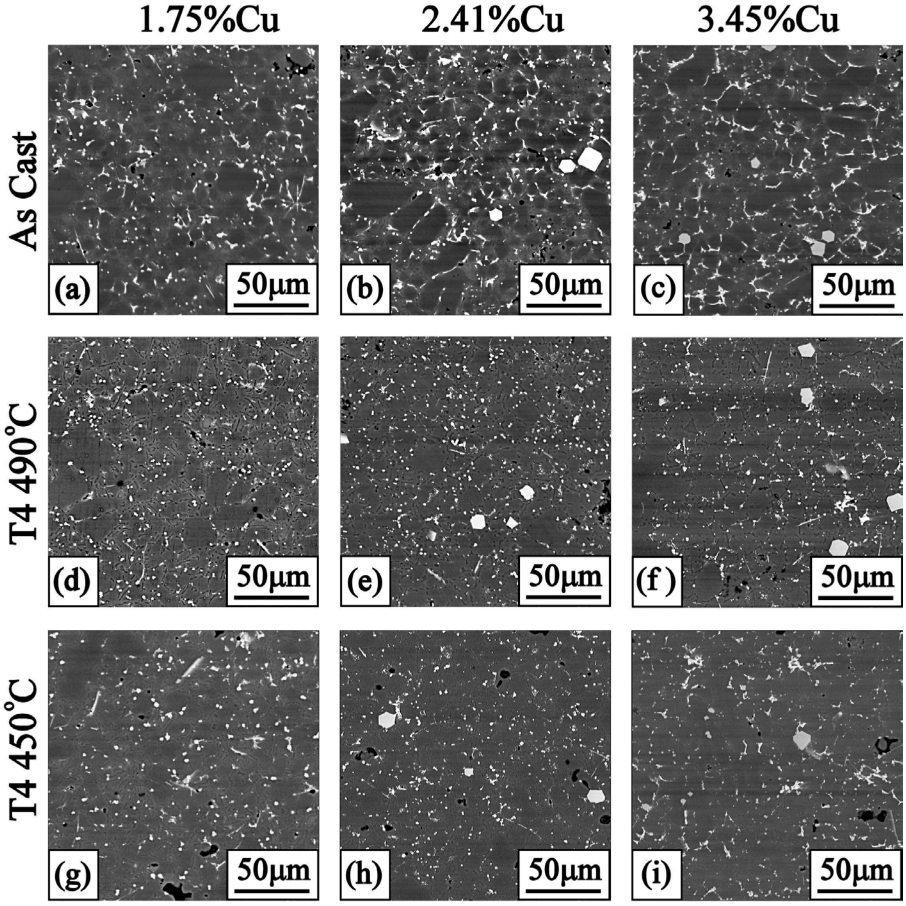

Fig. 2. Backscattered SEM images of as-cast and heat treated (T4) conditions taken from the same location of alloys containing 1.75, 2.41 and 3.45%Cu. See text for details.

Fig. 3 summarizes the tensile properties for each of the eight alloys in the 10 conditions tested. Each data point in the plot represents the average of five individual tensile tests, for a specific alloy, in its nominated temper. In all cases, mechanical properties rose progressively with Cu content within each heat treatment group. In the as-cast condition, the changes across the eight alloys were less significant than in heat treated conditions. For example, for the alloy containing 1.75% Cu, the 0.2% proof stress was 162 MPa in the as-cast condition, whereas for the alloy containing 3.45%Cu, the 0.2% proof stress was 181 MPa. After ageing to a T6#1 temper, the 0.2% proof stress of the alloy containing 1.75%Cu was 259 MPa when solution treated at 450ºC and 279 MPa when solution treated at 490ºC. If the Cu content was increased to 3.45%, these values of 0.2% proof stress were 317 and 395 MPa respectively following solution treatment at 450 and 490ºC. These values represent increases of 75 and 118% above the as-cast values. Tensile strengths also rose with increasing Cu contents, whereas elongation at failure decreased. For the T4 tempers, the tensile results followed the same general trends as the Cu content was raised. However, the levels of 0.2% proof stress and tensile strength were lower, whereas the elongations were higher.

3.2 The Effect of Mg content in ADC12

Even small amounts of Mg can have a profound effect on the mechanical properties of Cu-containing HPDC's. For example, there are significant differences in the response to age hardening between alloys containing 0.1%Mg, and those containing higher levels such as 0.2-0.3wt% [1-3]. However, no beneficial changes occur if the Mg content is raised further to 0.7% [1]. The major differences between alloys containing ~0.1%Mg and those containing higher levels have been found to be a function of the precipitate type that forms during artificial ageing [3]. At the lower concentrations, the dominant precipitate type is θ′, whereas at the higher Mg contents a high

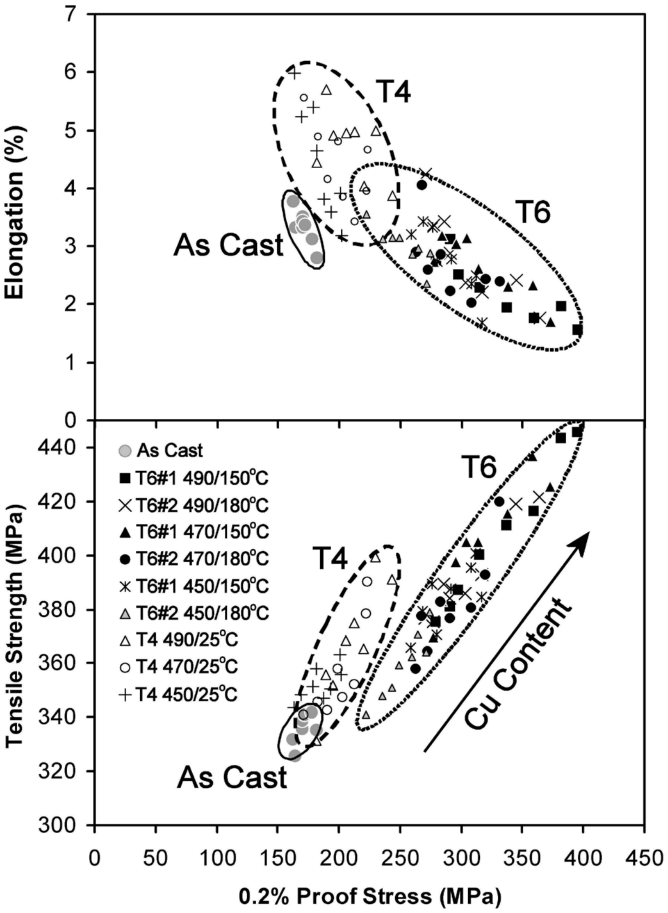

Fig. 3. Tensile properties for each of the eight ADC12 Alloys tested where Cu was varied, in each of the 10 different conditions. Each point represents the average of five tensile tests.

proportion of Q′ phase (or its precursor L) become dominant. At Cu contents below 3%, Al-Si-Cu alloys containing >0.2%Mg form only Q′ or L precipitates and occasional particles of the θ′ phase that are present at the sites of prior dislocations.

The primary goal of this experiment was to identify the optimal Mg concentrations for improved ductility and fracture resistance in HPDC's [5], both as-cast and heat treated. These alloys contained no Zn, the presence of which may have complicated the effect Mg has upon heat treatment processes. Small amounts of Mg were progressively added to the molten aluminium alloy at predetermined intervals during casting, and samples were produced at each composition.

Fig. 4 shows the tensile properties for the 11 compositions in as-cast, T4 or T6#1 tempers. What is particularly noticeable is that Mg has a disproportionate effect on tensile properties of the alloys. At 0.028% Mg and below, there is little or no age hardening response for either T4 or T6 tempers, and in both conditions the alloys display very high tensile ductility. As the Mg content was raised, the 0.2% proof stress and tensile strength rose rapidly. For example, increasing the Mg content from 0.028% to 0.052% increases the 0.2% proof stress from 145 MPa to 245 MPa in the T6 temper. This result would suggest that Mg stimulates precipitation strengthening. In T4 tempers, tensile ductility of these alloys is excellent, and does not drop below 7% for any composition. In the T6 temper, tensile ductility was inversely related to 0.2% proof stress and decreases from 9.3% to 6.5% when Mg was raised from 0.028% to 0.052%. In difference to the other properties, the tensile strength rises consistently with Mg content. What is most interesting from these results is the extraordinary effect that Mg has. Between 0.005% and 0.22%Mg, the 0.2% proof stress increases from only 132 MPa at the lower concentration, up to 317 MPa at the higher concentration.

4. Conclusions

1. Low-Cu HPDC alloys may be readily heat treated to achieve high strengths, and respond well to a variety of tempers in the same manner as higher-Cu containing alloys.
2. Despite the relatively high levels of Fe present (0.71-0.91%) and low levels of Mn (0.16-0.2%) within the alloys tested to examine the role of Cu, the Fe-bearing particles were mostly identified as the α-phase, $Al_{15}(Fe,Mn)_3Si_2$.
3. Increasing Cu content from 1.75% to 3.45% has three effects on the microstructures of ADC12 alloys. These were: a), the proportion of what appears to be blocky Si particles is increased; b), the relative size distribution of the hard particles of the α-phase, $Al_{15}(Fe,Mn)_3Si_2$, is changed, favoring fewer small particles and more larger ones; and c), the highest levels of Cu gave rise to a

hard intermetallic phase residual from the solidified eutectic which was not dissolved during solution treatment.

4. In the as-cast condition, increasing Cu from 1.75% to 3.45% improves the mechanical properties only moderately.

5. Increasing Cu content significantly raised the levels of mechanical properties achievable through heat treatment. Following a T6#1 treatment of 24h at 150ºC, for example, an alloy containing 1.75%Cu displayed a 0.2% proof stress of 279 MPa (72% above the as-cast value), whereas an alloy containing 3.45% Cu displayed a 0.2% proof stress of 395 MPa (118% above the as-cast value). Similar differences were also observed for the other tempers examined.

6. Increasing Mg content from 0.005% to 0.22% in the as-cast condition had a greater relative effect than Cu on mechanical properties.

7. In heat treated conditions, the mechanical properties that develop are particularly sensitive to Mg content. When Mg is below 0.04%, no age hardening response was recorded, and above this amount, the mechanical properties increased significantly. The transition in behavior occurs between 0.03%Mg and 0.05% Mg, and was especially pronounced for the T6 treated material.

8. The optimum range for good combinations of strength and ductility in the ADC12 alloys are achieved at between ~0.05%Mg and 0.17%Mg.

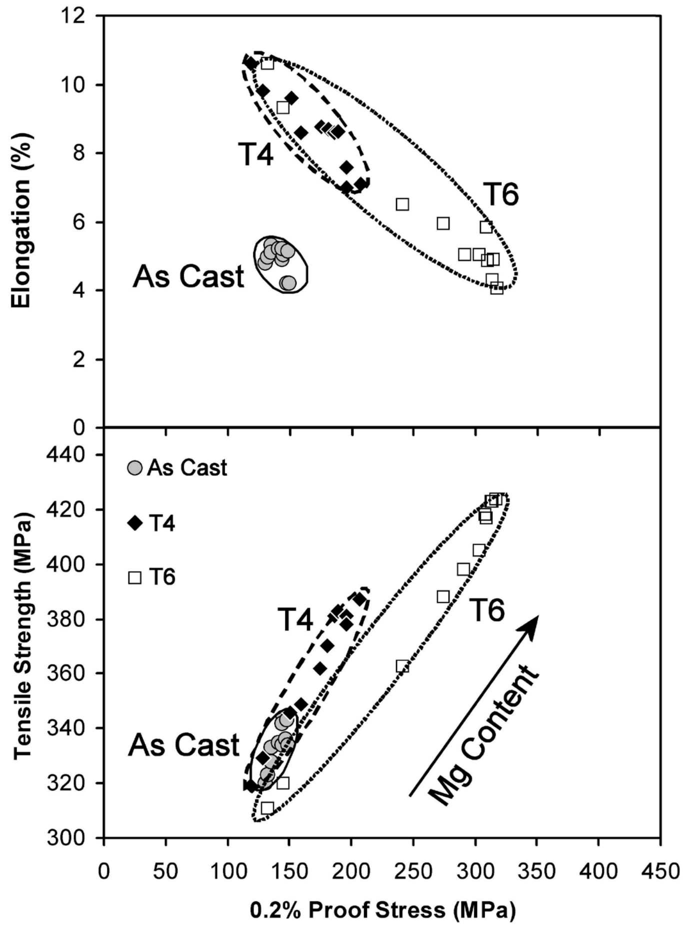

Fig. 4. Tensile properties for each of the 11 ADC12 alloys tested for the effect of Mg content, in As Cast, T4 and T6 tempers. Each point represents the average of five tensile tests. See text for details.

5. References

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