IMPROVEMENT OF THE T6 HEAT TREATMENT OF RHEOCAST ALLOY A356

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ABSTRACT

The heat treatment cycles that are currently applied to semi-solid processed components are mostly those that are in use for traditional dendritic alloys. These heat treatments are not necessarily the optimum heat treatments for SSM processing. The T6 heat treatment of aluminium alloys is a relatively expensive process and a reduction in treatment times would be advantageous. In order to improve the T6 heat treatment cycle for rheocast alloy A356, the effect of various parameters on the quality index were investigated. These included solution treatment time, natural aging time, artificial aging temperature and artificial aging time.

Keywords: rheocasting, heat treatment, aluminium alloy A356.

1. INTRODUCTION

One of the methods employed by the transportation industry to improve fuel efficiency has been the use of mass production-capable aluminium castings as part of a weight reduction strategy[1]. High pressure die casting (HPDC) has been used widely in the manufacture of light-weight castings to satisfy this need. Unfortunately, the turbulent die-filling in high pressure die casting is responsible for oxide entrapment, porosity and blistering problems during heat treatment. This limits the application of this method to less critical structural applications. Semi-solid metal (SSM) processing has the potential to be a high volume production method that can overcome these deficiencies of conventional HPDC to produce high integrity light-weight aluminium parts.

Semi-solid metal (SSM) processing is a unique manufacturing method used to produce near-net shape products for various industrial applications[2,3]. The aim is to obtain a semi-solid structure free of dendrites with the solid present in a near spherical form. This semi-solid mixture flows homogeneously, behaving as a thixotropic fluid with viscosity depending on the shear rate and fraction of solid[4]. There are two different SSM processing methods: thixocasting and rheocasting. With thixocasting, a specially prepared billet of solid material with a globular microstructure is reheated into the semi-solid range, followed by a forming process such as high pressure die casting. Rheocasting involves preparation of an SSM slurry directly from the liquid, followed by HPDC. The higher costs associated with thixocasting have resulted in rheocasting becoming the preferred semi-solid process[3]. The laminar flow during SSM processing during the die-fill avoids the problems of oxide and gas entrapment and also reduces the shrinkage problems during solidification[1]. Blistering during heat treatment can therefore be prevented.

Large quantities of castings are made annually from aluminium alloy A356 (also known as Al-7Si-0.3Mg). The use of SSM processing to produce automotive components has been described by Winterbottom[1]. The different processing techniques to produce master brake cylinders and fuel rails are compared in Table 1[1].

Table 1: The production of high volume automotive components[1]

Master Brake Cylinders			
Process	**Part mass (kg)**	**Minimum wall thickness (mm)**	**Machining steps**
Permanent mould	0.77	6.3	18
SSM	0.44	3.2	5
Fuel Rails			
Solid forging	0.68	5.1	82
SSM	0.33	3.8	26

SSM processing of alloy A356 has also been used to produce other automotive components, such as a suspension lever arm[5] and an engine mounting bracket[6].

The T6 temper of aluminium alloys consists of a solution heat treatment and quench, then a period of natural aging, followed by artificial aging. The T6 temper produces maximum strength (hardness) in heat treatable aluminium alloys.

The purpose of the solution heat treatment is to[7]:

(a) dissolve solutes (especially Mg, Si), which leads to the formation of a large number of strengthening precipitates during subsequent artificial aging;

(b) cause spheroidisation of the eutectic silicon particles this leads to improved ductility and fracture toughness;

(c) reduce micro-segregation of elements in the aluminium matrix.

The solution treatment time and temperature depend on the casting method, the extent of modification (typically with strontium additions) and the desired level of spheroidisation and coarsening of the silicon particles. For example, the solution treatment time for A356 sand castings is twice as long as for permanent mould castings[7].

The heat treatment cycles that are currently applied to semi-solid processed components are mostly those that are in use for dendritic casting alloys[5,8]. These heat treatments are not necessarily the optimum treatments, as the difference in solidification history and microstructure of rheocast components should be considered. No consensus has been reached on what the optimum heat treatment conditions are for rheocast components. In order for SSM processing to be a competitive processing method, it is imperative that the heat treatment parameters be optimised. It seems as if 540°C is the optimum solution temperature for A356 in terms of the compromise between shortening heat treatment time as well as minimising the risk of blistering and distortion[6-9]. The most popular solution heat treatment employed for SSM processed A356 is 6 hours at 540°C (i.e. similar to that used for permanent mould cast A356)[6,7,9]. Only limited work has been performed on the optimisation of the solution heat treatment of SSM processed A356. According to Rosso and Actis Grande[5], a solution heat treatment of 1 hour at 540°C is sufficient to obtain a high level of properties in the T6 temper (hardness, yield strength, ultimate tensile strength, % elongation). A solution treatment of only 30 minutes caused the presence of brittle intermetallic phases due to an incomplete solution process. According to Dewhirst[8], the optimum solution treatment time at 540°C is 4 hours for SSM processed A356.

The natural aging time (the time at room temperature after solution treatment and quenching, before artificial aging) has not received much attention for rheocast alloy A356. For example, Dewhirst[8] varied the natural aging time of semi-solid processed A356 between 8 and 24 hours. He found that increasing the natural aging beyond 8 hours had a slightly negative effect on the tensile properties of the material. However, it was concluded that artificial aging temperature and time were of greater importance. Rosso and Actis Grande[5] did not even document the natural aging time that was employed in their study. Finally, the most popular artificial aging treatment for alloy A356 seems to be 170°C for 6 hours[8,9]. However, the optimum artificial aging treatment for rheocast A356 was determined to be 4 hours at 180°C by both Dewhirst[8] and Rosso and Actis Grande[5].

The aim of this study was to investigate the effect of various heat treatment parameters on the T6 properties of SSM processed alloy A356. These parameters included solution treatment time, natural aging time, artificial aging temperature and artificial aging time.

The quality index (QI) was used in this work to allow comparison of different heat treatment cycles. The quality index relates the ductility and strength (ultimate tensile strength or UTS) into a single term[8]. It was developed by Drouzy et al,[10] based on the observation of trends in empirical data. Caceres et al[11] have done further work to show the fundamental basis of the quality index. The quality index (specifically for alloy A356) is given by equation 1[8,10,11]:

$$QI\ (MPa) = UTS\ (MPa) + 150\log(\%\ elongation) \qquad [1]$$

2. EXPERIMENTAL

Semi-solid metal slurries of A356 (chemical composition given in Table 2) were prepared using the CSIR rheocasting process[12]. Plates (4 mm × 80 mm × 100 mm) were cast in steel moulds with a 50 ton HPDC machine.

Table 2: Chemical composition (wt%) of alloy A356 used in this study

Si	Mg	Fe	Cu	Mn	Zn	Ti	Sr	Al
7.14	0.34	0.14	0.01	0.01	0.01	0.08	0.03	Balance

Solution treatment was performed at 540°C for either 1 hour or 6 hours, followed by a water quench (20°C). Samples were then naturally aged for either 0 or 20 hours, before being artificially aged for varying times at 180°C. Vickers hardness numbers (VHN) were determined (using a 20 kg load) from the average of at least four readings per sample. The average hardness values were found to be reproducible within ± 3 VHN for all heat treatment conditions tested. All samples were etched with 0.5 % HF solution for optical microscopy. The tensile properties of T6 heat treated samples were also determined and different heat treatment cycles were compared by using the quality index (equation 1). The tensile samples (sub-standard size) were machined from the plates (see Figure 1 for the dimensions of the samples). A total of 5 tensile tests were used for each heat treatment condition.

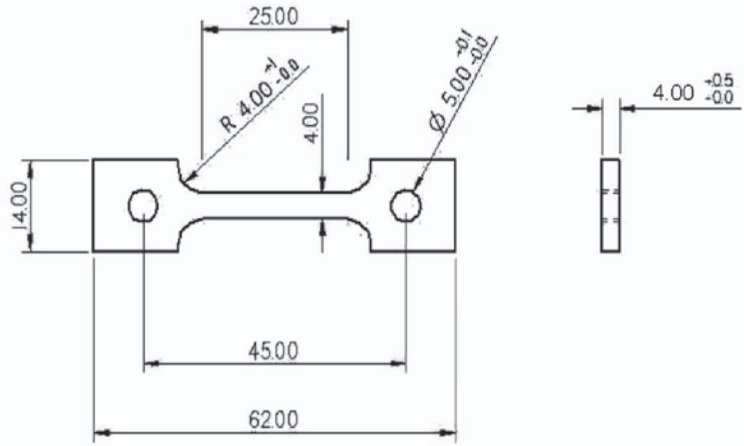

Figure 1: The dimensions of the samples (in millimetres) used for tensile testing

3. RESULTS AND DISCUSSION

Figure 2 shows an optical micrograph of the A356 after SSM HPDC. It is seen that the material has a globular primary grain structure and a fine eutectic.

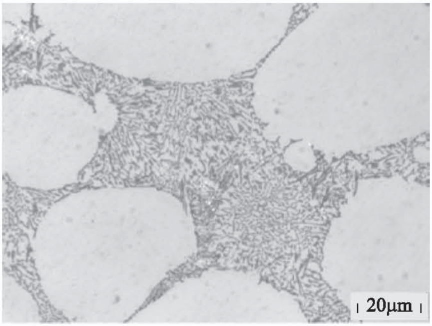

Figure 2: Optical micrograph of alloy A356 after SSM HPDC

Figures 3 and 4 show optical micrographs of A356 after a solution heat treatment at 540°C for 1 hour and 6 hours respectively. It is seen that solution treatment resulted in the eutectic structure changing to a globular type structure. Strontium-modified alloys undergo fast spheroidisation, while it is known that complete spheroidisation is not achieved in unmodified alloys, even after long solution *treatment* times[13].

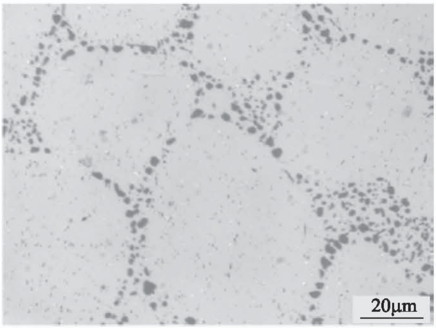

Figure 3: Optical micrograph of alloy A356 after solution treatment at 540°C for 1 hour

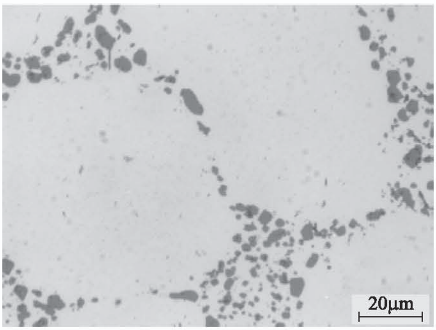

Figure 4: Optical micrograph of alloy A356after solution treatment at 540°C for6 hours

It is also clear from Figures 3 and 4 that the silicon particles of the eutectic are much coarser after 6 hours of solution treatment at 540°C than after 1 hour, and that the inter-particle spacing is increased by longer solution treatment.

Natural aging curves for alloy A356 after solution treatment at 540°C for 1 hour and 6 hours are shown in Figure 5. The T4 hardness of the alloy (at natural aging times > 120 h) is reasonably similar for both solution treatment times.

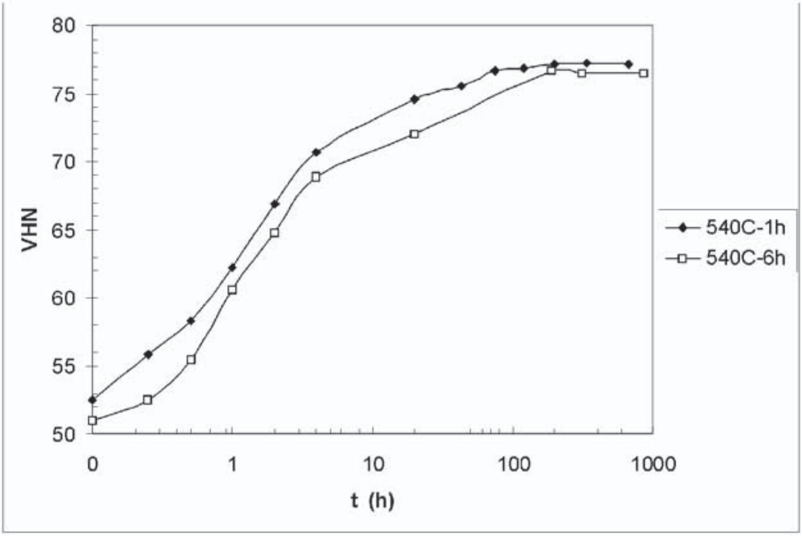

Figure 5: Natural aging curves for SSM processed A356 after solution treatment at 540oC

In Al-Mg-Si alloys containing an excess of silicon, the decomposition of the supersaturated solid solution (SSS) is believed to occur in the following way[14]:

$$\begin{aligned} &SSS \rightarrow (Mg + Si)_{clusters} / GP(I)_{spherical} \\ &\rightarrow \beta'' / GP\,(II)_{needles} \rightarrow \beta'_{\;rods} + Si + \text{others} \\ &\rightarrow \beta_{plates} + Si \end{aligned} \qquad [2]$$

where GP = Guinier-Preston Zones

β = equilibrium Mg_2Si

β' and β'' = metastable precursors of β

It is believed that the hardness increase in freshly solution-treated A356 during natural aging occurs due to the precipitation of solute clusters and GP zones[14,16].

Artificial aging curves for alloy A356 at 180°C are shown in Figure 6 (after 0 h natural aging) and Figure 7 (after 20 h natural aging). The artificial aging response of alloy A356 is influenced significantly by prior natural aging[15]. This phenomenon can be explained by considering the sequence of decomposition of the supersaturated solid solution (SSS) in Al-Mg-Si alloys (equation 2). The initial softening of the naturally aged samples during artificial aging is attributed to the dissolution of the clusters and GP zones during artificial aging. It is seen that the extent of the loss is recovered, presumably by the precipitation of β particles upon further aging[14]. The dissolution of the clusters and GP zones causes the time-to-peak-hardness (T6) to be longer compared to when no natural aging is used.

It is also seen from Figure 5 (for natural aging) and Figures 6 and 7 (for artificial aging) that solution treatment at 540°C for 1 hour tends to result in slightly higher hardness values being obtained compared to when 6 hours solution treatment is used. The longer solution treatment time of 6 hours produced a relatively coarse microstructure (Figure 4) which probably resulted in the lower maximum hardness values being obtained. Solution treatment for 1 hour gives optimum conditions in terms of attaining a relatively fine microstructure (Figure 3) in combination with complete dissolution of the strengthening alloying elements[15].

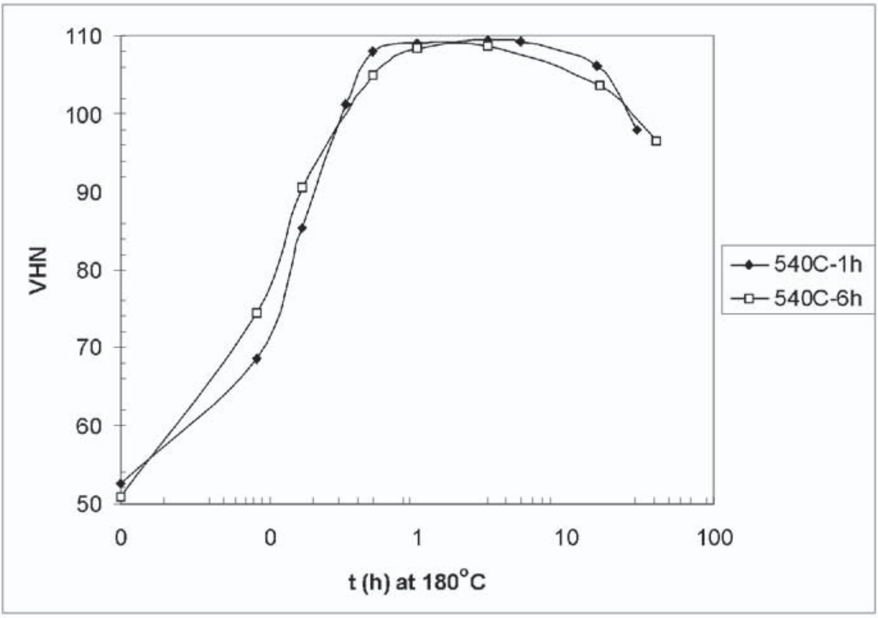

Figure 6: Artificial aging curves for SSM processed A356 after 0 hours natural aging

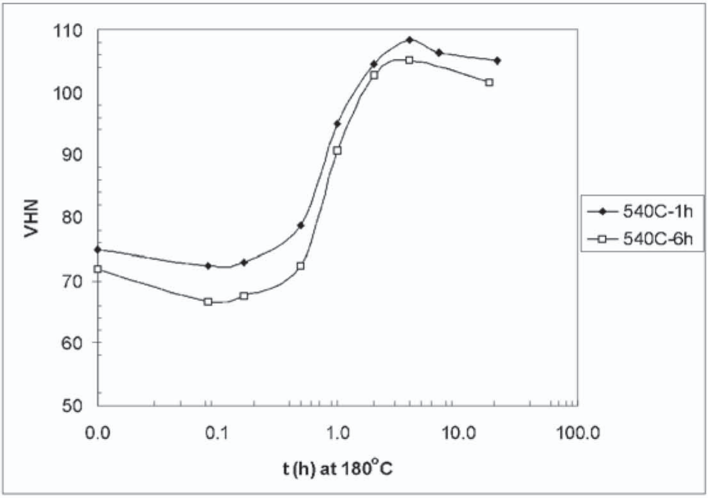

Figure 7: Artificial aging curves for SSM processed A356 after 20 hours natural aging

Based on the artificial aging curves presented in Figures 6 and 7, T6 heat treatments were performed on samples for tensile tests. The "traditional" T6 heat treatment[6,9] of solution treatment for 6 hours at 540°C, water quenching, natural aging for 20 hours and artificial aging for 6 hours at 170°C was also used for comparison. Details of the T6 heat treatment cycles used for tensile testing are shown in Table 3 while the results of the tensile tests are shown in Table 4.

Table 3: T6 Heat treatment cycles used for tensile testing

Heat treatment	Solution treatment	Natural aging	Artificial aging	Total furnace time (h)	Total time (h)
540-6, 20NA, 170-6	540°C for 6 h	20 h	170°C for 6 h	12 h	32 h
540-1, 0NA, 180-1	540°C for 1 h	0 h	180°C for 1 h	2 h	2 h
540-6, 0NA, 180-1	540°C for 6 h	0 h	180°C for 1 h	7 h	7 h
540-1, 20NA, 180-4	540°C for 1 h	20 h	180°C for 4 h	5 h	25 h

From Table 4 it is seen that the "traditional" heat treatment results in the worst quality index. The best quality index is achieved using the "540-1, 0-NA, 180-1" heat treatment, which is also the shortest heat treatment (Table 3). These results show that it is not only possible to decrease the heat treatment time of SSM processed alloy A356, but that the tensile properties (or quality index) can actually be improved simultaneously.

Table 4: Yield strength, UTS, % elongation and QI of heat treated samples. The standard deviation for tensile properties is also indicated in brackets

Heat treatment	Yield strength (MPa)	UTS (MPa)	% Elongation	QI (MPa)
540-6, 20NA, 170-6	261 (4.5)	316 (5.9)	8.3 (2.1)	454
540-1, 0NA, 180-1	251 (3.8)	324 (7.3)	10.1 (1.5)	475
540-6, 0NA, 180-1	256 (1.3)	325 (4.6)	8.2 (1.1)	462
540-1, 20NA, 180-4	259 (5.2)	317 (7.1)	8.8 (1.4)	459

In summary, this study corroborates some of the results obtained by Dewhirst[8] and Rosso and Actis Grande[5]. In addition, valuable new information is also presented. The possibility of using a shorter solution heat treatment time of 1 hour at 540°C confirms the results presented by Rosso and Actis Grande[5].

However, the influence of natural aging time on the artificial aging response was not adequately studied by either Dewhirst[8] or Rosso and Actis Grande[5]. The optimum artificial aging heat treatment proposed in both papers[5,8] is 180°C for 4 hours. This was also confirmed in this work, but importantly, this applies only when natural aging is used before artificial aging. When no natural aging is applied, then 1 hour at 180°C is the preferred artificial aging heat treatment. This heat treatment is not only the shortest of all the studied treatments (Table 3), but it also resulted in the best quality index (Table 4).

If it is not possible to artificially age the A356 immediately after solution treatment, the 180°C for 4 hours treatment is still shorter than the "traditional" T6 heat treatment, with the added benefit of resulting in a similar quality index (Table 4). The quality indices of the last two heat treatments in Table 4 fall within the standard deviation and their differences compared to the "traditional" heat treatment may not be significant. Also note that previous work[15] has indicated that natural aging of only 1 hour decreased the artificial aging response of this alloy significantly.

4. CONCLUSIONS

The conclusions of this study are:

- The most favourable solution treatment time at 540°C to give optimum mechanical properties after artificial aging for SSM HPDC A356 is 1 hour. This represents the shortest possible solution treatment time to obtain complete dissolution of strengthening alloying elements, while still retaining a relatively fine microstructure.
- The dissolution of solute clusters and GP zones (which are formed during natural aging) during the initial stages of artificial aging causes softening of the alloy. This in turn causes the time-to-peak-hardness (T6) to be longer compared to the time when no natural aging is used.
- The quality index constitutes a useful tool to gauge the effect of changes to the heat treatment cycles of SSM HPDC A356. The best quality index in this study was obtained using a short solution heat treatment of only 1 hour at 540°C, no natural aging and artificial aging at 180°C for 1 hour. The much longer "traditional" T6 heat treatment cycle of solution treatment at 540°C for 6 hours, 20 hours natural aging, followed by artificial aging at 170°C for 6 hours gave the worst quality index of all the studied heat treatment cycles.

5. ACKNOWLEDGEMENTS

The contributions of L. Ivanchev, D. Wilkins, G. Kunene (SSM HPDC), C. McDuling, A. Grobler (tensile testing) are gratefully acknowledged.

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