The T6 Heat Treatment of Semi-Solid Metal Processed Alloy A356

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Abstract: A solution treatment of 1 hour at 540°C provided the best results for rheocast alloy A356-T6. Natural aging has a significant influence on the subsequent artificial aging response of the alloy. Arrhenius-type equations were derived to predict the time-to-peak hardness as a function of artificial aging temperature.

INTRODUCTION

Semi-solid metal (SSM) processing is a unique manufacturing method to produce near-net shape products for various industrial applications [1]. The aim is to obtain a semi-solid structure free of dendrites (which are formed by conventional liquid casting), with the solid present as nearly a spherical form as possible. This semi-solid mixture (like a gel, or toothpaste) flows homogeneously, behaving as a thixotropic fluid with viscosity depending on shear rate and fraction solid [2]. There are two different SSM processes: thixocasting and rheocasting. With thixocasting, a specially prepared billet of solid material with a globular microstructure is reheated into the semi-solid range and formed. Rheocasting involves preparation of a SSM slurry directly from the liquid, followed by a forming process such as high pressure die casting (HPDC). The increased costs associated with thixocasting (recycling of thixocast scrap and the necessity of an outside manufacturer for billet production) have resulted in rheocasting becoming the preferred semi-solid process [2].

The T6 heat treatment produces maximum strength (hardness) in aluminium alloys. Unfortunately it requires a relatively long time to be carried out and therefore has significant financial implications. The heat treatment cycles that are currently applied to semi-solid processed components are mostly those that are in use for dendritic casting alloys. These heat treatments are not necessarily the optimum treatments, as the difference in solidification history and microstructure of rheocast components should be considered. No agreement has been reached on what the optimum heat treatment conditions are for rheocast components. The optimum solution temperature would give the best compromise between energy savings, time savings, lower risk of distortion and maximum dissolution of alloying elements. It appears as if 540°C is the optimum temperature for A356 in terms of the compromise between shortening heat treatment time as well as minimising the risk of blistering and distortion [3,4]. According to Rosso and Actis Grande [4], the shortest possible time for solution treatment of rheocast A356 at 540°C is 1 hour. However, according to Dewhirst [3], the optimum solution treatment time at 540°C is 4 hours. It must also be noted that there exists a fundamental difference between modified and unmodified alloys (where the size and shape of the silicon particles are modified with additions of strontium). Modified alloys undergo fast spheroidisation, while complete spheroidisation is not achieved in unmodified alloys, even after long solution treatment times. Therefore, shorter solution heat treatments can be employed with modified castings [5]. It is well known that aluminium alloy A356 responds to (room temperature) natural aging - the precipitation hardening that results from natural aging alone produces the useful T4 temper [5]. Dewhirst [3] varied the natural aging time of semi-solid processed A356 between 8 and 24 hours. It was found that increasing the natural aging beyond 8 hours had a slight negative effect on the tensile properties of the material. Rosso and Actis Grande [4] also recently studied the optimisation of T6 heat treatment cycles for rheocast A356. In their paper, the natural aging time employed is not mentioned. Popular artificial aging treatments for alloy A356 are either 6 hours at 160°C [4] or 6 hours at 170°C [4]. Both Dewhirst [3] and Rosso and Actis Grande [4], however, have proposed that the optimum artificial aging treatment for rheocast alloy A356 is 4 hours at 180°C. The objective of this study was to determine the influence of solution treatment time (at 540°C), artificial aging temperature and time and prior natural aging time on the T6 heat treatment response of rheocast A356.

EXPERIMENTAL

Semi-solid metal slurries of A356 (chemical composition given in Table **1**) were prepared using the Council for Scientific and Industrial Research (CSIR) rheocasting process [6]. Plates (4 mm × 80 mm × 100 mm) were cast in steel moulds with a 50 ton HPDC machine. Solution treatment was performed at 540°C for times varying from 30 minutes to 6 hours, followed by a water quench (25°C). The samples were then naturally aged for 20 hours, before being artificially aged for varying times at 160, 180 and 190°C. The influence of natural aging time was then investigated by varying the natural aging time prior to artificial aging from 0 to 240 h. Vickers hardness (VHN) was determined (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 used for microscopy were etched in 0.5% HF solution.

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Table 1. Chemical Composition (wt%) of Alloy A356 used in this Study

Si	Mg	Fe	Cu	Ti	Sr	Al
6.91	0.36	0.15	0.01	0.11	0.038	Bal.

RESULTS AND DISCUSSION

Fig. (**1**) 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.

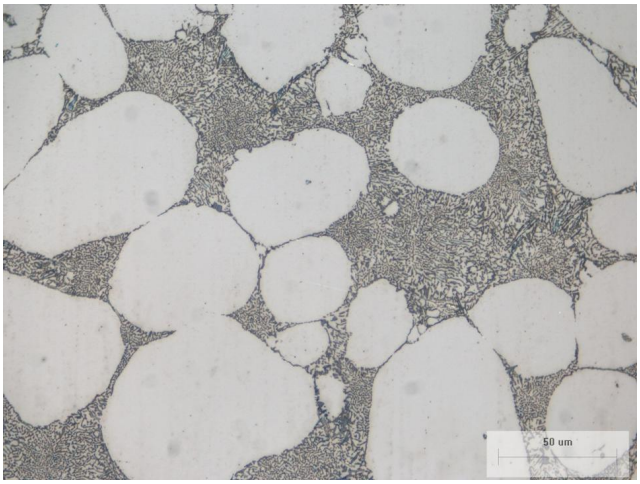

Fig. (1). Optical micrograph of SSM HPDC alloy A356.

Figs. (**2**,**3**) show optical micrographs of A356 after solution treatment at 540°C for 30 minutes and 6 hours respectively. Solution treatment resulted in the eutectic structure changing to a globular type structure. It is seen that the silicon particles of the eutectic are much coarser after solution treatment at 6 hours than after 30 minutes.

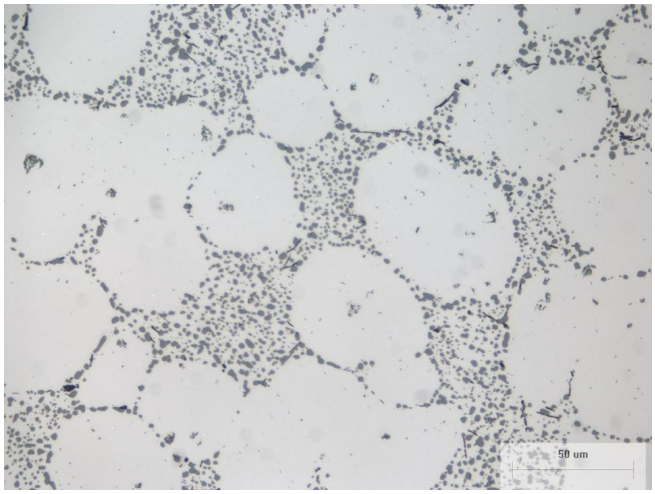

Fig. (2). Optical micrograph of alloy A356 after solution treatment at 540°C for 30 minutes.

Artificial aging curves were determined at artificial aging temperatures of 160, 180 and 190°C. The curves were determined for samples that were solution treated at 540°C (either for 30 minutes, 1 hour, 2 hours, 4 hours or 6 hours), water quenched and naturally aged for 20 hours before artificial aging. Fig. (**4**) shows an example of these aging curves for samples that were solution treated at 540°C for 6 hours. As expected, the maximum hardness is reached in a shorter time as aging temperatures are increased. However, the maximum hardness achieved simultaneously decreases, due to the higher solubility of strengthening phases at higher temperatures.

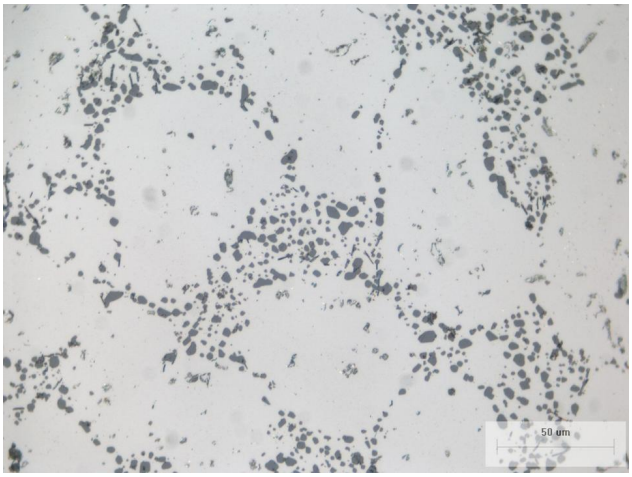

Fig. (3). Optical micrograph of alloy A356 after solution treatment at 540°C for 6 hours.

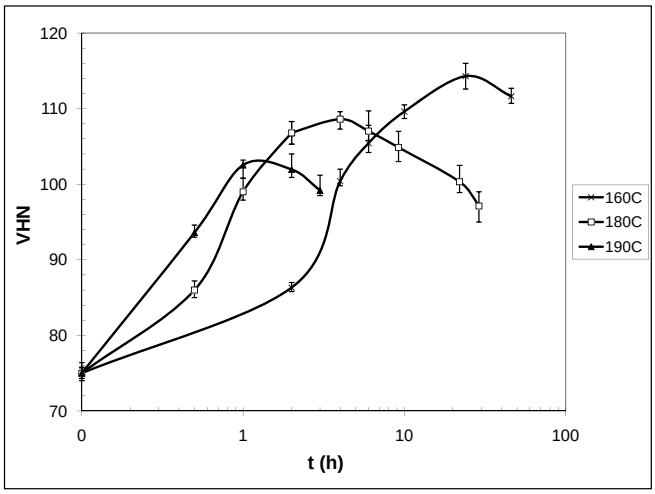

Fig. (4). Artificial aging curves for alloy A356 after solution treatment at 540°C for 6 hours, water quenching, natural aging for 20 hours and artificial aging at different temperatures.

The maximum hardness obtained as a function of the artificial aging temperature is shown in Fig. (**5**). It is seen that a solution treatment time at 540°C of 1 to 2 hours results in the highest hardness values after artificial aging. This implies that the shorter solution treatment time of 30 minutes was probably too short to get all the alloying elements into solution. This conclusion is supported by Rosso and Actis Grande [4]. The longer solution treatment times of 4 and 6 hours were long enough to get complete dissolution of alloying elements, but the relatively coarse microstructure obtained (Fig. **3**) probably resulted in the lower maximum hardness values. Solution treatment for 1-2 hours gives optimum conditions in terms of obtaining a relatively fine microstructure in combination with complete dissolution of

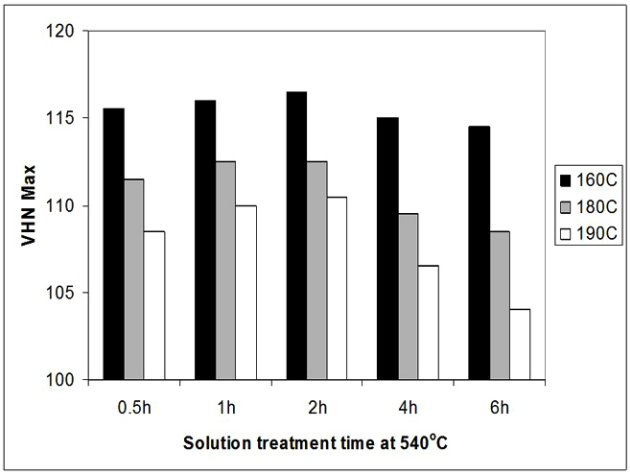

Fig. (5). Maximum hardness values obtained after solution treatment for different times at 540°C, 20 h natural aging and artificial aging at 160, 180 and 190°C.

alloying elements. The optimum artificial aging parameters depend on the properties required. If a high hardness is required, a low aging temperature is required (such as 160°C). It unfortunately takes relatively long times to obtain this high hardness at these low temperatures. The best combination of relatively short aging treatments resulting in acceptably high hardness values is obtained by aging at 170-180°C. If a short aging time is, however, a more important factor than maximum hardness, then 185-190°C will give optimum results.

The results presented thus far have all been obtained using 20 hours natural aging prior to artificial aging. To study the influence of natural aging, solution treatment was performed at 540°C for 1 hour, followed by a water quench (25°C). The samples were then naturally aged for times ranging from 0 to 240 hours, before being artificially aged. Fig. (**6**) shows the natural aging curve for SSM HPDC alloy A356 after solution treatment for 1 hour at 540°C, followed by a water quench.

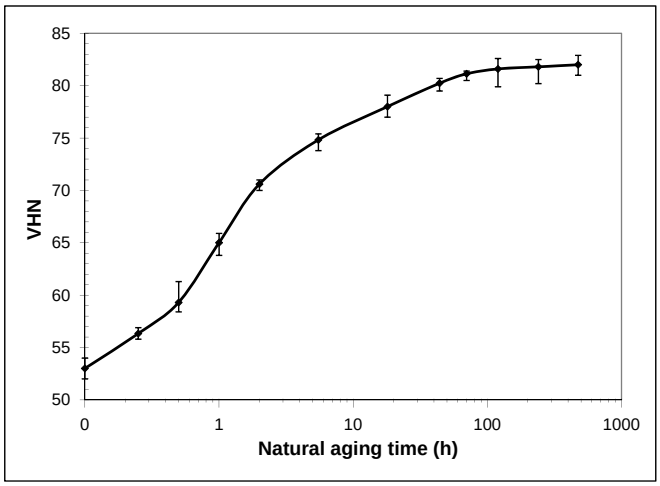

Fig. (6). Natural aging curve for SSM HPDC A356 following solution treatment at 540°C for 1 h and a water quench.

During natural aging of Al-Si-Mg alloys, hardening is believed to occur due to the precipitation of solute clusters and Guinier-Preston (GP) zones [7,8]. During artificial aging, these clusters and GP zones transform to the strengthening β'' phase (needles), followed by β' (rods). These phases are the precursors of the equilibrium β phase (plates) [7,8]. In summary, considering the Al-Mg-Si phase diagram [8,9], decomposition of the supersaturated solid solution (SSS) of these alloys (containing an excess of Si) is believed to occur in the following way [7]:

$$SSS \rightarrow (Mg + Si)_{clusters} / GP(I)_{spherical}$$

$$\rightarrow \beta'' / GP\ (II)_{needles} \rightarrow \beta'_{rods} + Si + others$$

$$\rightarrow \beta_{plates} + Si$$

where GP = Guinier-Preston Zones

β = Equilibrium Mg_2Si

β' and β'' = Metastable precursors of β

Fig. (**7**) shows artificial aging curves that were determined for alloy A356 at an artificial aging temperature of 180°C (after solution treatment at 540°C for 1 hour, water quenching and natural aging for different times). It is interesting to note that when no natural aging was applied, the artificial aging response was very rapid. The converse is also true - when natural aging was employed, the artificial aging response was sluggish. Natural aging of only 1 hour decreased the artificial aging response of the alloy significantly. This phenomenon can be explained by two different mechanisms. Firstly, it has been shown that the precipitates which grow during artificial aging from the clusters are coarser than those that develop in certain 6000 series alloys aged immediately after quenching. This results in a reduction of up to 10% in tensile properties for certain alloys [8]. Secondly, it has been shown that natural aging following the solution treatment reduced the age hardenability of Al-Mg-Si wrought alloy AA6016 [7], especially in the under-aged condition. This was attributed to solute clustering during natural aging, and the subsequent dissolution of these clusters during artificial aging. The extent of the loss was, however, recovered by precipitation of β'' particles upon further aging [7]. Considering Fig. (**7**), it is seen that for alloy A356, the hardness values of naturally aged samples are also recovered with further artificial aging. The mechanism proposed in Polmear [8] (the formation of coarser precipitates that leads to a decrease in tensile properties), does not allow for a full recovery in hardness. It is therefore concluded that reversion of the solute clusters is probably also responsible for the initial slow artificial aging response in naturally aged alloy A356.

To verify this hypothesis, the initial artificial aging response (after 5 minutes at 180°C) for two samples (naturally aged for 0 h and 240 h respectively) at 180°C was also studied (Fig. **8**). It is seen that the hardness of the sample that did not age naturally increases immediately during artificial aging. However, the sample that was naturally aged for 240 hours softens during the first 10 minutes at 180°C, before the hardness increases again. As before, the initial hardness loss is recovered with further artificial aging. The sluggish artificial aging response of all the naturally aged samples (Figs. **7**,**8**) is therefore due to an initial decrease in hardness when the solute clusters dissolve.

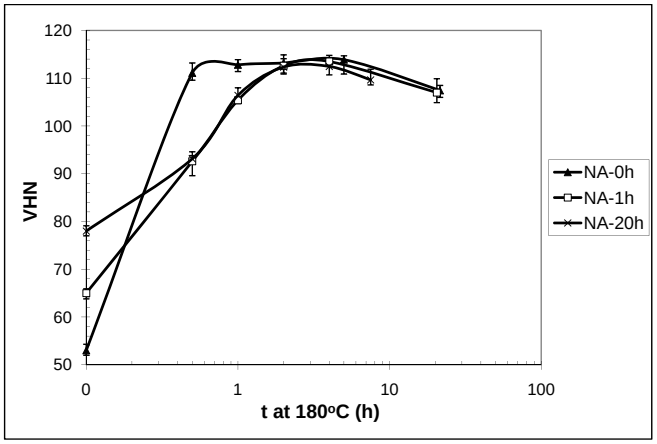

Fig. (7). Artificial aging curves at 180°C for alloy A356 as a function of natural aging (NA) time.

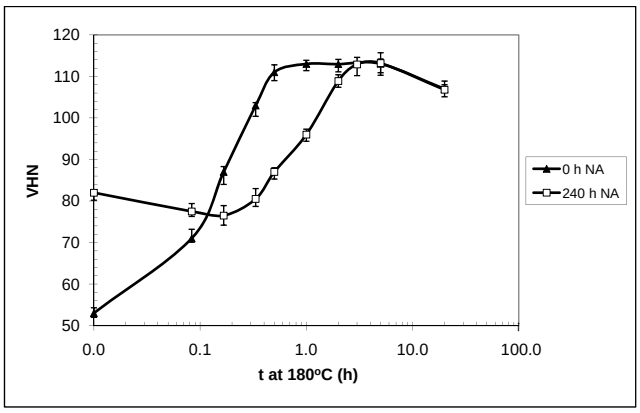

Fig. (8). Artificial aging response of A356 samples that were naturally aged for 0 h and 240 h prior to artificial aging.

When no natural aging is employed, a plateau is maintained once the maximum hardness is reached (Figs. **7**,**8**). This differs from when a natural aging period is used, when a hardness peak is observed (Figs. **7**,**8**). The onset of this hardness plateau (no natural aging) and hardness peak (with natural aging) as a function of artificial aging temperature follow an Arrhenius-type response (t_{T6} = C EXP (Q/RT) with C the pre-exponential factor, Q the apparent activation energy in J/mol and R the universal gas constant = 8.314 J/mol K). The equations that describe the time to reach maximum hardness (t_{T6}) are given by equation 1 (with prior natural aging time) and equation 2 (for no natural aging time):

$$\mathbf{t_{T6} = 2.3 \times 10^{-15}\ EXP\ (163000/8.314T)} \quad (1)$$

$$\mathbf{t_{T6} = 4.9 \times 10^{-16}\ EXP\ (163000/8.314T)} \quad (2)$$

with t_{T6} the time in seconds and T the artificial aging temperature in K.

Arrhenius-type plots are shown in Fig. (**9**) for the artificial aging of rheocast A356 with prior natural aging (Equation 1, Experimental 1) and without prior natural aging (Equation 2, Experimental 2). Comparing the equations and plots, it is seen that an instantaneous transfer from quench to artificial aging does not have an influence on the apparent activation energy (Q). It does, however, decrease the pre-exponential factor C, thereby resulting in a much faster artificial aging response. The apparent activation energies in Equations 1 and 2 are representative of the overall artificial aging process and can be considered as a combination of the separate activation energies of individual nucleation and growth steps during the precipitation processes.

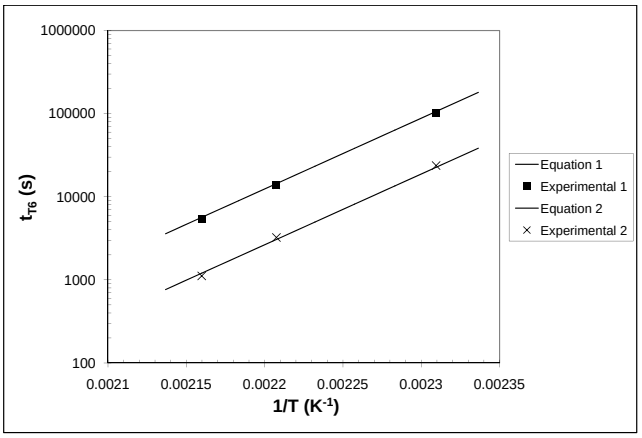

Fig. (9). Arrhenius-type plots for the artificial aging of rheocast A356. Prior natural aging (Equation 1 and Experimental 1). No prior natural aging (Equation 2 and Experimental 2).

These equations are useful for determining how long an A356 component must be artificially aged at a specific temperature to get maximum hardness (i.e. the T6 temper).

Tensile properties of rheocast A356-T6 were determined by the authors using the heat treatment cycles developed in this study. These tensile properties were determined as a function of solution treatment time [10], prior natural aging time [10,11,12], artificial aging parameters [10,11,12] and the wt% Mg of the alloy [11].

CONCLUSIONS

The optimum solution treatment time at 540°C to give maximum hardness after artificial aging 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. SSM HPDC A356 hardens significantly at room temperature (natural aging) after solution treatment at 540°C, followed by a water quench. The time required to obtain maximum hardness at artificial aging temperatures of 160 to 190°C can be predicted using Arrhenius-type equations. The artificial aging response of the alloy can be increased by an instant transfer from quench to artificial aging.

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