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Research Article

The Influence of Prior Natural Aging on the Subsequent Artificial Aging Response of Aluminium Alloy A356 with Respective Globular and Dendritic Microstructures

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Alloy A356 is one of the most popular alloys used for semisolid metal forming. The heat treatment cycles that are currently applied to semisolid processed components are mostly those that are in use for dendritic casting alloys. The assumption has been made that these heat treatments are not necessarily the optimum treatments, as the difference in solidification history and microstructure of SSM processed components should be considered. The objective of this study is to determine whether dendritic A356 behaves in a similar way to globular A356 in terms of its response to artificial aging with or without prior natural aging. The results indicate that the differences in microstructures (globular or dendritic) do not have a noteworthy effect on the heat treatment response. It is also shown that strong linear correlations are found between T4 and T6 hardness and wt% Mg of A356, regardless of the casting technique used.

1. Introduction

Semisolid metal (SSM) processing is a unique manufacturing technique to fabricate near-net shape products for a variety of industrial applications [1]. The objective is to achieve a semisolid structure which is free of dendrites and with the solid present in a near spherical form. This semisolid mixture flows homogeneously, behaving as a thixotropic fluid with viscosity depending on the shear rate and fraction of solid [2]. There are two different SSM processing methods, namely thixocasting and rheocasting. With thixocasting, a specially prepared billet of solid material with a globular microstructure is reheated into the semisolid range, followed by a forming process such as high pressure die casting (HPDC). Rheocasting on the other hand involves preparation of an SSM slurry directly from the liquid, followed by HPDC. Rheocasting has become the preferred semisolid process due to the higher costs of thixocasting [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 [4]. Blistering during heat treatment can therefore be prevented.

Large quantities of castings are made annually from aluminium alloy A356 (also known as Al-7Si-0.3 Mg). This alloy is one of the most popular alloys used for semisolid metal forming due to its good "castability" [5]. The chemical composition limits of this alloy are shown in Table 1 [6]. The heat treatment cycles that are currently applied to semisolid processed components are mostly those that are in use for dendritic casting alloys [7, 8]. The assumption is that these heat treatments are not necessarily the optimum treatments, as the difference in solidification history and microstructure of SSM processed components should be considered [7–11]. However, a recent paper by the authors has shown that the heat treatment response and tensile mechanical properties of A356 automotive brake calipers are in fact not influenced by having a globular or dendritic microstructure [12]. The same conclusion was also reached by Birol [13, 14].

In addition, the authors have shown before that natural aging (room temperature aging after the solution treatment and quench) prior to artificial aging has an adverse influence on the subsequent artificial aging response of SSM-HPDC A356 [9, 10]. An artificial aging treatment at 180°C for 4 h can, however, negate the effects of any prior natural aging [10]. A recent review paper [15] on the heat treatment of Al-Si-Cu-Mg alloys (which included alloy A356) has concluded that the influence of natural aging on subsequent artificial aging needs to be studied further in these alloys. Finally, it has also been shown previously by the authors [9, 11] that strong correlations exist between strength and Mg-content of SSM-HPDC A356 (with other element contents kept constant). The objective of this study is to determine whether dendritic A356 behaves in a similar way to globular A356 in terms of its response to artificial aging with or without prior natural aging. Also, the influence of microstructure on the maximum hardness in the T4 and T6 temper conditions is compared that can be achieved with A356 cast using different techniques (with similar Mg contents).

Figure 1: Wax pattern assembly used for IC of alloy A356.

2. Experimental

Semisolid metal (SSM) slurries of alloy A356 (chemical composition, as well as the chemical composition limits for the alloy are given in Table 1) were prepared using the Council for Scientific and Industrial Research (CSIR) rheocasting process [16]. Automotive brake calipers were cast in steel moulds with an LK DCC630 HPDC machine, resulting in a globular microstructure. For comparison, automotive brake calipers of similar composition and exact design (shape, size, mass) were cast by a local manufacturer using gravity die casting (GDC), resulting in a dendritic microstructure (see [12, 17] for more details of the casting parameters, size, heat treatments, and tensile mechanical properties of these brake calipers).

In addition, rectangular plates ($95 \times 30 \times 4\,mm^3$) with composition given in Table 1 were cast using investment casting (IC) to obtain a coarser dendritic microstructure than achieved in the brake caliper cast using GDC. Wax pattern assemblies consisted of 6 of the plates assembled with 3 plates per opposite side, spaced 40 mm apart. A vertical 25 mm × 20 mm rectangular runner bar was used (250 mm long) as shown in Figure 1. The plates were assembled at an angle of 75 degrees inclined to the runner bar. The runner bar extended below the lowest plates tip to form a dross trap. A pouring cup was attached to the top of the runner bar. The wax used was Remet 289B green wax. The preferred bottom pouring method for aluminium was not used to simplify the assembly and to ensure symmetry in the mould. Wax assemblies were prepared by washing with Pattern Wash 6 from Remet and rinsed with de-ionised water. The wax assemblies were left for 24 hrs to dry and to stabilise at the dipping room temperature of 21°C. The primary slurry consisted of Ransom & Randolph Primecote, colloidal silica 30% binder and Zircon flour (Zircon silicate) −325 mesh as refractory filler. The secondary slurry consisted of Ransom and Randolph Customcote colloidal silica 25% binder with fused silica (−325 mesh) as the refractory filler. The face coat stucco used was Zircon sand P109 (mean 109 μm) and the back-up coat stucco was Chamotte (Alumino silicate). The shell making facility was temperature controlled to 21°C ± 1°C and the humidity was monitored—the relative humidity was measured as ±60%. The dipping procedure is given in Table 2.

Dewaxing (wax removal) was performed using a standard LBBC steam boilerclave with 200°C steam at 8 bar pressure for 15 min. The moulds was prefired in a gas fired furnace with a 5% oxidising atmosphere to a temperature of 800°C, kept for 2 hrs, and furnace cooled. The mould was inspected and vacuumed to ensure that the mould was clean and preheated to the required casting temperature and soaked for 1 hr in an electric kiln furnace. The metal and mould temperature during casting was 720°C to ensure a relatively coarse microstructure. Aluminium alloy A356, from the same master melt as was used for the SSM-HPDC plates, was melted in a SiC crucible in an electric furnace. Melting was timed to reach 720°C as the mould reached the 1 hr soaking time. This was to reduce metal time at temperature to reduce hydrogen pick-up as no de-gassing was done due to the small volume of the melt. The mould and metal were removed from the furnace at the same time. The mould was suspended in still air on a mould stand and the metal surface was skimmed to remove dross and slowly poured into the mould. The mould was left to cool to room temperature and mould removal was done by hand.

Solution heat treatment of all castings was performed at 540°C for 1 hour, followed by a water quench (20°C) (see [7, 9–12] that shows that 1 hour at 540°C is sufficient for alloy A356). The time necessary to place magnesium in solid solution by dissolution of the Mg_2Si in the alloy is rapid at 540°C. It has been suggested that it takes less than 5 minutes in alloy A356 [18]. Homogenisation occurs in approximately 8–15 minutes at 540°C. The samples were then naturally aged (NA) for either zero hours (artificial aging only) or 120 h (stable T4 temper), before being artificially aged at 180°C to determine artificial aging curves. Vickers hardness

Table 1: Chemical composition limits for alloy A356 [6], as well as the compositions of the alloys used in this study.

	Si	Mg	Fe	Cu	Mn	Zn	Ti	Other (Each)	Other (Total)
Min	6.5	0.25	—	—	—	—	—	—	—
Max	7.5	0.45	0.2	0.2	0.1	0.1	0.2	0.05	0.15
SSM-HPDC	7.0	0.35	0.14	0.01	0.01	0.01	0.14	Sr = 0.020	
GDC	6.6	0.36	0.27	0.03	0.01	0.02	0.06	Sr = 0.024	
IC	6.7	0.25	0.10	0.01	0.01	0.01	0.06	Sr = 0.026	

Table 2: The dipping procedure for investment casting of alloy A356.

Coate no.	Slurry	Stucco	Drying time	Drying method
Primary 1	Zircon Primary	Zircon Sand	8 hours	Air dry
Primary 2	Zircon Primary	Zircon Sand	8 hours	Air dry
Secondary 1	Customcote	Chamotte 0.25–0.7 mm	45 Min	Fan
Secondary 2	Customcote	Chamotte 0.25–0.7 mm	45 Min	Fan
Back-up 1	Customcote	Chamotte 0.7–1.2 mm	45 Min	Fan
Back-up 2	Customcote	Chamotte 0.7–1.2 mm	45 Min	Fan
Back-up 3	Customcote	Chamotte 0.7–1.2 mm	45 Min	Fan
Back-up 4	Customcote	Chamotte 0.7–1.2 mm	45 Min	Fan
Seal coate	Customcote	—	24 Hours	Air

numbers (VHN) were determined (using a 10 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.

3. Results and Discussion

The globular microstructure produced with SSM-HPDC is shown in Figure 2(a). In contrast, the dendritic microstructures obtained with GDC and IC are shown in Figures 2(b) and 2(c). Modification of the eutectic from a plate-like to a fine fibrous silicon structure has been achieved by the addition of strontium (Table 1) [19]. It is evident from Figure 2 that GDC produced a finer microstructure than SSM-HPDC and IC. Image analysis revealed a secondary dendrite arm spacing (SDAS) of approximately 20 μm in the GDC calipers, whereas the SDAS of the IC plates was 32 μm. The average globule size in CSIR SSM-HPDC calipers was approximately 60 μm.

Solution treatment at 540°C for 1 h results in the spheroidisation of the eutectic silicon particles in all the A356 castings (Figure 3).

Figure 4 shows artificial aging curves that were determined for alloy A356 after solution treatment at 540°C for 1 hour, water quenching, and no natural aging. The artificial aging response is very rapid when no natural aging is applied whether the microstructure is globular or dendritic [9, 10]. Note that the hardness values are significantly lower for the IC plates than for the brake calipers. This is due to the low Mg-content of the IC plates (Table 1), resulting in a lower volume fraction of strengthening precipitates during artificial aging [9, 11, 20]. Artificial aging curves were also determined for alloy A356 after solution treatment at 540°C for 1 hour, water quenching and 120 hours natural aging (Figure 5) followed by artificial aging. The artificial aging response is slow when prior natural aging has occurred, regardless of the microstructure of the A356. This slow artificial aging response can be explained by two different mechanisms. Firstly, it has been shown that the precipitates which grow during artificial aging from the clusters (formed during natural aging) are coarser than those that develop in certain 6000 series alloys aged immediately after quenching [21]. This results in a reduction of up to 10% in tensile properties for certain alloys. Secondly, it has been shown that natural aging following the solution treatment reduced the age hardenability of Al-Mg-Si wrought alloy AA6016 [22]. This was ascribed to solute clustering during natural aging, and the dissolution of these clusters during subsequent artificial aging. The extent of the loss was recovered by precipitation of β'' particles upon further aging [22]. Taking into account Figures 4 and 5, it is seen that for alloy A356, the hardness values of naturally aged samples are also recovered with further artificial aging. The mechanism of the formation of coarser precipitates that leads to a decrease in tensile properties [21] does not allow for a full recovery in hardness. It is therefore concluded that reversion of the solute clusters is also responsible for the initial slow artificial aging response in naturally aged alloy A356 [9–11].

When no natural aging occurs, a plateau (between ∼1–5 h) is maintained once the maximum hardness is reached during artificial aging (Figure 4), whereas a hardness peak is observed after approximately 4 hours when prior natural aging occurs (Figure 5) (also see [10]). The significant conclusion is that the influence of any natural aging prior to artificial aging can be removed by a 4-hours 180°C artificial aging treatment in both dendritic and globular A356.

Figure 6 compares the hardness values of A356-T6 (540°C-1 h, 0 or 120 h NA, 180°C-4 h) as a function of the Mg-content of the castings (between the upper and lower limits of the specification—Table 1). Figure 6 includes

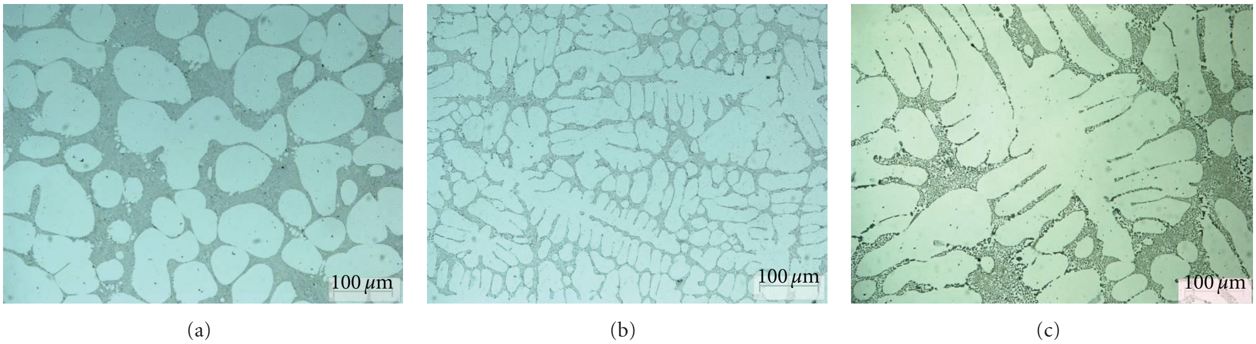

Figure 2: Optical micrographs of A356 in the as-cast condition produced by (a) SSM-HPDC, (b) GDC, and (c) IC.

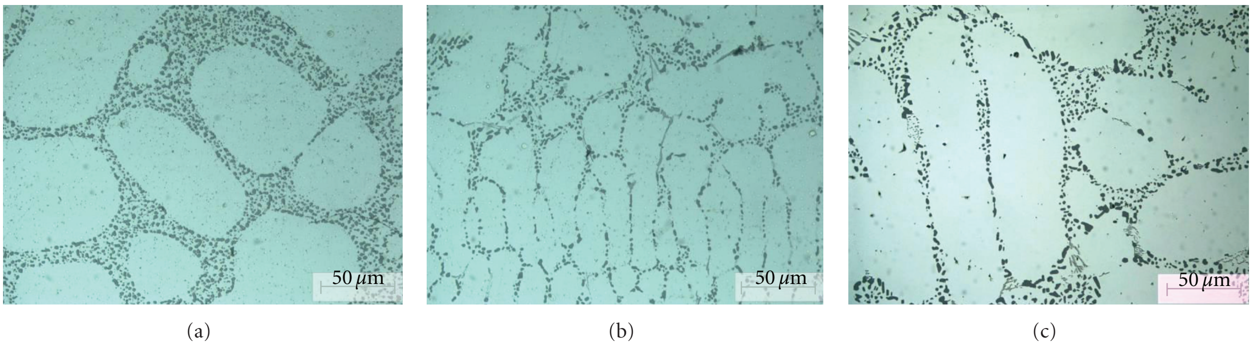

Figure 3: Optical micrographs of A356 in the T6 condition produced by (a) SSM-HPDC, (b) GDC, and (c) IC.

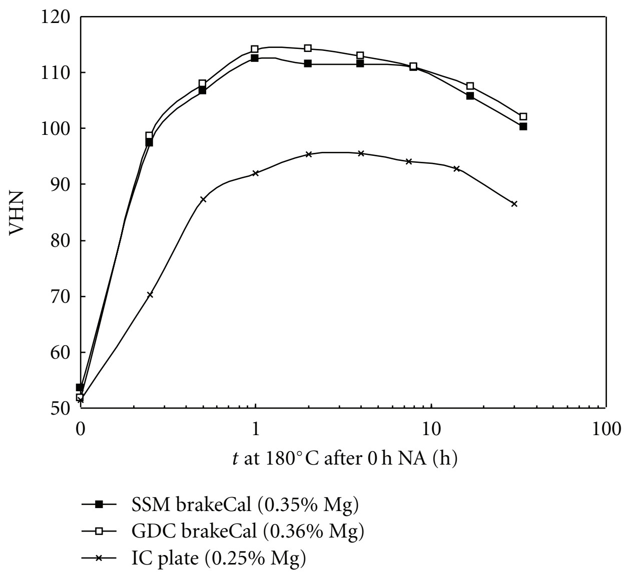

Figure 4: Artificial aging curves at 180°C for alloy A356 cast using different casting techniques (after 0 h prior natural aging time).

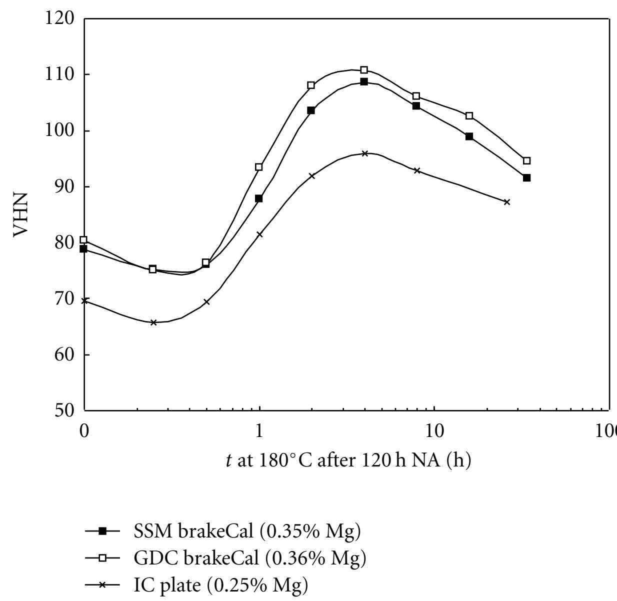

Figure 5: Artificial aging curves at 180°C for alloy A356 cast using different casting techniques (after 120 h prior natural aging time).

hardness values of SSM-HPDC plates [9–11] and brake calipers (Figures 4 and 5), GDC brake calipers (Figures 4 and 5), and IC plates (Figures 4 and 5). Globular and dendritic microstructures are, therefore, included as well as variations in natural aging time periods. It is seen that a strong linear correlation between T6 hardness and wt% Mg exists (especially for the low Mg-concentration range), regardless of the casting technique used (globular or dendritic microstructure) or natural aging time period employed before artificial aging (0 or 120 h NA). This is

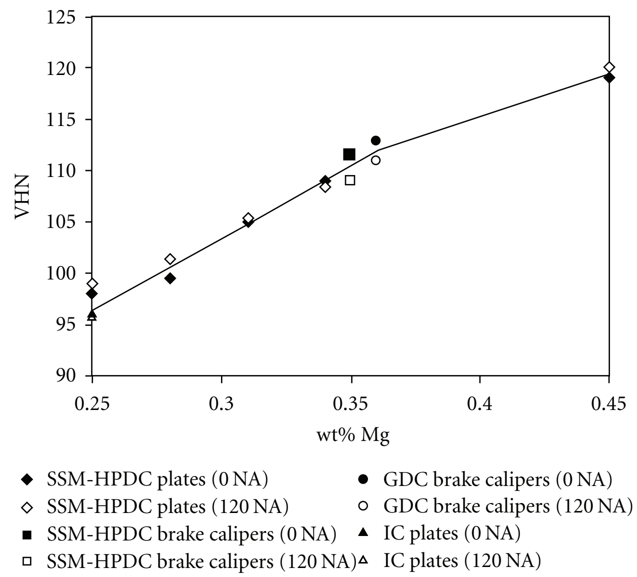

Figure 6: T6 (540°C-1 h, 0 or 120 h NA, 180°C-4 h) hardness values as a function of the Mg-content of A356 produced using different casting techniques.

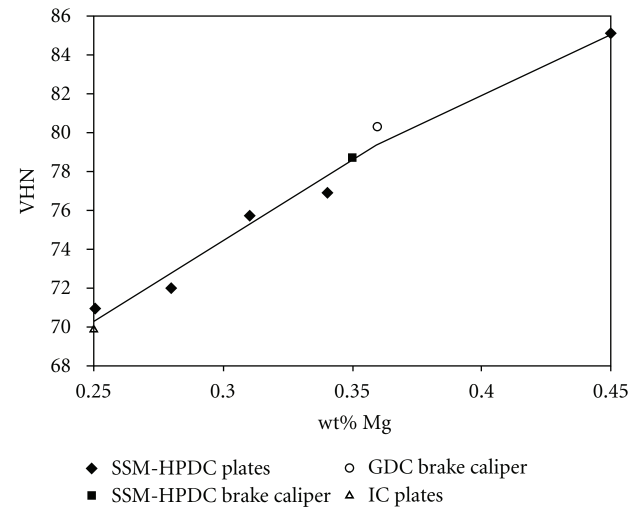

Figure 7: T4 (540°C-1 h, 120 h NA) hardness values as a function of the Mg-content of A356 produced using different casting techniques.

a noteworthy finding, given the appreciable differences in microstructures obtained using the different casting techniques (Figures 2 and 3). This suggests that the Mg-content primarily controls the hardening response by controlling the volume fraction of strengthening β''-Mg_5Si_6 in this alloy. Note that A356 contains an excess of Si that is required to form stoichiometric Mg_2Si or the strengthening Mg_5Si_6 [23]. It also reinforces the earlier observation that the effects of any natural aging preceding artificial aging can be removed by a 4-hour artificial aging treatment at 180°C in both dendritic and globular A356. The lower increase in hardness for the high Mg-concentration range in Figure 6 has been studied in detail by the authors before [20]. It was shown that the Mg-containing π-phase ($Al_8FeMg_3Si_6$) cannot be fully removed by solution treatment at 540°C in alloys which contain more than ~0.4% Mg. The π-phase removes the strengthening solute Mg from solid solution and this has a detrimental effect on the aging behaviour.

Figure 7 compares the hardness values of A356-T4 (540°C-1 h, 120 h NA) as a function of the Mg-content of the castings. Figures 6 and 7 include hardness values of SSM-HPDC plates [9–11] and brake calipers (Figure 5), GDC brake calipers (Figure 5), and IC plates (Figure 5). The T4 hardness values in Figure 5 are the data points at $t = 0$ h (i.e., before the start of artificial aging). A strong linear correlation between T4 hardness and wt% Mg is also found, regardless of the casting technique used. The lower increase in hardness at higher Mg-levels in Figure 7 is once again due to the π-phase [20].

4. Conclusions

(1) The natural aging (T4) and artificial aging (T6) responses of alloy A356 are not influenced by having a globular or dendritic microstructure.

(2) The influence of any natural aging prior to artificial aging can be removed by an artificial aging treatment of 4 hours at 180°C in both dendritic and globular A356.

(3) A strong linear correlation is found between T6 hardness and wt% Mg of A356, regardless of the casting technique used (globular or dendritic microstructure) or natural aging time period employed before artificial aging (0 or 120 h NA).

(4) A strong linear correlation is also found between T4 hardness and wt% Mg of A356, regardless of the casting technique used.

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