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Precipitation hardening of A356 Al alloy produced by gas induced semi-solid process

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ABSTRACT

Aged hardening of semisolid cast A356 Al alloy produced by gas induced semi-solid (GISS) process was studied. It was found that maximum hardness and tensile strength could be achieved from specimens aged at 165 °C for 18 h of which the average maximum hardness, the average ultimate tensile strength and the average percent elongation were 96.4 HRE, 312 MPa and 7.6%, respectively. The higher aging temperature of 195 °C for 3 h led to a slightly lower average tensile strength of 305 MPa together with a higher average elongation of 9.8%. The strain hardening exponent of specimens aged at both sets of conditions was lower than that of the as-cast specimen as well as the as-cast specimen aged at 225 °C for 15 min. The mechanical properties of the alloys in this study were comparable to those of typical thixoformed products. β'' phase was mainly responsible to the strengthening of the peak aged alloy. Elongated precipitates were formed in the specimen after prolonged aging at 195 °C for 16 h. The activation energy for the precipitation hardening process of the alloy derived in this research was 128,717 J/mol.

1. Introduction

Light weight casting aluminium alloy has been extensively adopted for a variety of usage as automotive components in view of the need to lower the weight of vehicles. Nevertheless, preserving performance of the alloy and cost investment still have been the objectives for the industries. It was pointed out by Thanabumrungkul et al. [1] that conventional A356 Al cast products normally contain more porosities than semisolid A356 Al products. The presence of porosities was believed to be harmful to ductility of A356.2 Al alloy [2] and also to the tensile strength of A356 Al alloy according to Lee [3]. Therefore, semisolid casting is a promising process for providing higher quality aluminium alloy castings [4]. An alternative rheocasting process has been steadily of interest because of low material cost and single step forming process. The study of slurry semisolid alloy was published as early as 1972 [5]. Various techniques were later proposed such as cooling slope [6], and electromagnetic stirrer [7].

A novel approach, gas induced semi-solid (GISS) technique, has been proposed by the Innovative Metal Technology (IMT) team at the Prince of Songkla University. This technique involves the flow of very fine inert gas bubbles out of porous graphite to the liquid aluminium. It has since been proven a simple, economical and efficient process. Additionally, this technique has succeeded to produce globular structure in A356 alloy [8].

Though selections of the right alloy and suitable casting process are important, proper tempering condition for the alloy is also crucial in achieving the required properties. Responses to heat treatment of A356 Al alloy and other Al alloys had been reported in many earlier studies [9,10].

The aim of this work is to investigate the effect of artificial aging temperature and time on the mechanical properties and microstructure of the rheocast A356 Al alloy produced by the GISS process. This study focuses on the determination of the optimum aging condition of the alloy.

2. Experimental method

The material used in this study was semisolid A356 Al alloy produced by the GISS process. Schematic of the GISS process is shown in Fig. 1.

In this process, the alloy ingots were melted in a graphite crucible using an electric resistance furnace. The melt was fluxed at 700 °C before casting. About 500 g of the molten alloy was taken out from the furnace using a ladle cup. A graphite diffuser was immersed in the liquid alloy at the rheocasting temperature of 620 °C for 20 s to produce a semi-solid slurry. The slurry was then poured into a die cavity, which was preheated to 280–300 °C. A squeeze cast was subsequently applied at a pressure of approximately 20 MPa. The as-cast circular plate shape had a dimension of

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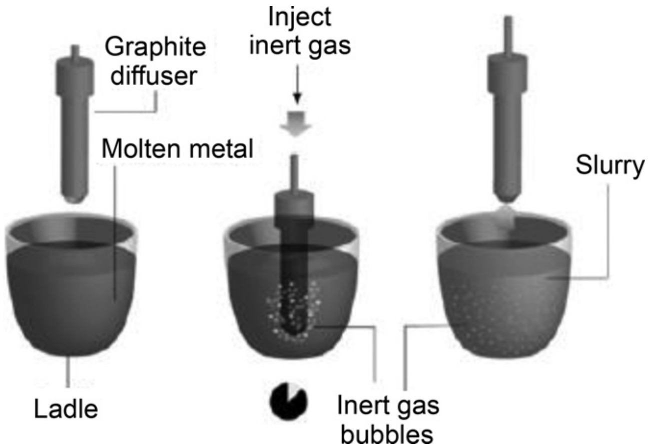

Fig. 1. Schematic of the GISS process [11].

200 mm in diameter and 15 mm in thickness. The chemical composition of the as-cast A356 Al alloy is shown in Table 1.

T6 heat treatment process was used in this study at the solution treated temperature of 540 °C for 4 h. After quenching in room temperature water, the as-quenched specimens were aged at 165 °C, 195 °C and 225 °C under varying time durations. The microstructure of the as-cast and the solution heat treated specimens were examined using optical microscopy. Hardness was measured using Rockwell hardness (scale E) test from three specimens under each aging condition and from 10 different points on each specimen. Tensile specimens were machined into a dumbbell shape with a gauge length of 30 mm and a diameter of 6 mm. Tension test was performed under a strain rate of 0.001 s^{-1}.

The aged specimen with a dimension of 15 mm × 15 mm × 50 mm was machined into a rod with a diameter of 3 mm for the TEM specimens. This rod was sliced into many disk-shaped specimens by using the Brillant 220 cutting machine. The disk-shaped specimen was polished down to a thickness of 40–80 μm thin foil using 1200 grit SiC sand paper and 5 μm micro-polishing alumina powder. TEM thin foils were then prepared by twin-jet electro polishing in a mixture of 20 vol.% nitric acid and 80 vol.% methanol at a cooling temperature range of −15 °C to −30 °C employing liquid nitrogen, an applied current of 150–250 mA, a flow rate of 4.4–5.5 and a sensitivity of 3–5. The electro-polishing parameters were varied depending on the heat treatment condition and the thickness of each thin foil. The thin foils were examined on a JEOL JEM-2010 transmission electron microscope, operating at 200 kV.

3. Results and discussions

3.1. As-cast and solution heat treated specimens

The non-dendritic microstructure of the as-cast A356 0Al alloy was obtained from the GISS process under 10% solid fraction in melt coupled with low pressure squeeze cast. Canyook et al. [12] believed that dendritic α-Al phase was fragmented through the GISS process by a remelting mechanism leading to form the rheocast structure. The microstructure of the as-cast alloy mainly consists of primary α-Al phase (white contrast) surrounded by lamella eutectic phase of acicular-like Si particles (grey phase) and α-Al phase (white phase), as clearly revealed in Fig. 2(b). After solution heat treatment at 540 °C for 4 h, the acicular-like silicon particles exhibit disintegration and roundness, as depicted in Fig. 2(c) and (d). It was believed that the morphology of silicon particles has an influence on the fracture elongation of the alloy [13]. In another view, the properties of A356 Al alloy were controlled by either the Si morphology or the alloying elements, or a combination of both factors depending on the heat treatment conditions [14].

3.2. Aged hardening specimens

The variations of hardness when exposed to different aging temperatures at different aging durations are shown in Fig. 3. The figure shows that the hardness of each specimen increases with increasing aging time until a peak hardness is obtained. Then the hardness tends to decrease upon further aging time. This result could be explained by precipitation hardening process of the aged specimen which depends greatly on the aging time and aging temperature. A peak hardness value of 96.4 HRE was obtained from the specimen aged at the temperature of 165 °C for 18 h. This is in agreement with the peak hardness time of SSM-High-Pressure Die Casting (HPDC) A356 Al alloy [15]. In their study, the peak hardness of about 97 HRE was obtained after T6 aging at 160 °C for 24 h (Fig. 3) shows that peak hardness of 94.5 and 94.1 HRE was obtained from the specimen aged at higher temperature of 195 °C and 225 °C, respectively. This value was slightly lower than that of the specimen aged at 165 °C as mentioned before. The lower in the hardness at higher aging temperature was the result of the absence of GP zone formation in the early stage of aging leading to a lower precipitate density at the peak condition, and hence the lower hardness and lower strength of the alloy. However, the required aging time to the peak condition was shorter at higher aging temperatures; 3 h and 15 min for 195 °C and 225 °C, respectively. It can be explained that the shorter aging time at higher aging temperature was due to a higher diffusion rate for precipitate formation at higher temperature.

The average yield strength, tensile strength, and percent elongation of the alloy after aging to the peak hardness at different aging temperatures of 165 °C, 195 °C, and 225 °C are tabulated in Table 2. The highest average ultimate tensile strength (312 MPa) and yield strength (277 MPa) with an average elongation of 7.6% were obtained from the specimens aged at the optimum condition of 165 °C–18 h. It can be noticed from Table 2 that the specimen aged at the condition of 195 °C–3 h had a slightly lower average tensile strength and yield strength of 305 MPa and 272 MPa, respectively. These strength values were lower than those of the optimum aged (165 °C–18 h) specimen, however, its elongation increased to 9.8%. With further increasing aging temperature to 225 °C at aging time of 15 min, the elongation of this aged specimen increased further to 14.9% at the expense of tensile strength and yield strength down to the values of 226 MPa and 125 MPa, respectively. For comparison, the typical tensile properties of A356 alloy in selected literatures are also listed alongside in Table 2 [13,16,17]. Although the average tensile strength and the yield strength of the as-cast GISS-processed alloy were lower than those of the as-thixoformed products [16], these strength values of the GISS-processed specimen were improved and were apparently higher than those of the thixoformed products [16] after passing T6 heat treatment. The strength of the T6-thixoformed products as reported in Ref. [13]

Table 1
Chemical composition of the as-cast A356 Al alloy.

Elements	Si	Mg	Fe	Cu	Mn	Zn	Ti	Al
Composition (wt%)	7.00	0.35	0.2	0.2	0.1	0.1	0.23	Bal.