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Characteristics of thixoformed A356 aluminum thin plates with microchannels

Amir Bolouri[a,1], Chung Gil Kang[b,*]

[a]Graduate School of Mechanical and Precision Engineering, Pusan National University, Busan 609-735, Republic of Korea
[b]School of Mechanical Engineering, Pusan National University, Busan 609-735, Republic of Korea

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ABSTRACT

A356 aluminum thin plates with a thickness of 1.2 mm were produced via thixoforming process under different temperatures ranging from 585 °C to 610 °C. In addition to large primary α-Al grains, unique fine secondary α-Al grains (equivalent diameter below ~8 μm) were revealed through microstructural examinations. These secondary α-Al particles exhibited irregular morphology at 590 °C, which gradually transformed into equiaxed/globular grains at higher thixoforming temperatures of 605 °C and 610 °C. On the other hand, their size (the equivalent diameter of the grains) continuously increased from 3.2 ± 0.16 μm at 590 °C to 8.1 ± 0.4 μm at 610 °C. Energy dispersive X-ray spectroscopic analyses showed that the Si concentration gradually increased within these secondary α-Al grains. A quenched modified morphology consisting of angular and finely branched eutectic silicon was observed at the thixoforming temperature of 590 °C, which seemed that it changed to a fibrous morphology at 605 °C and 610 °C. By increasing the thixoforming temperature, the elongation of the thixoformed plates monotonically increased to 12.6 ± 0.4% at 610 °C, whereas the ultimate tensile strength reached its highest value of 280 ± 12 MPa at 600 °C then experienced the sharp reductions at 605 °C and 610 °C.

1. Introduction

Semisolid metal (SSM) processing is a net-shape manufacturing process that is performed in the semisolid state of metallic alloys. In SSM processing, the alloy must possess an appreciable melting range, which enhances the formation of a microstructure that ideally consists of primary non-dendritic metal spheroids in a liquid-phase matrix; this mixture is called semisolid slurry. In this state, the alloy behaves as a thixotropic material, i.e., its viscosity decreases when force is applied and the material starts flowing; however, it behaves as a solid in the absence of any applied force. This extraordinary thixotropic behavior of the metallic materials was first discovered at MIT [1], and since then there has been a very strong interest among scientists and industries to develop this behavior for different alloys [2–4]. SSM processing offers several advantages over conventional die-casting, such as lower temperature die-filling with a slurry that flows in a nonturbulent manner [3,5,6]. Therefore, it is expected that in SSM processing, the shrinkage microporosities will be reduced because of the presence of a primary solid phase prior to die-filling at the much lower temperature [7]. It is also expected that the amount of the entrapped gas will be significantly lower as compared to a high-pressure die-casting process. SSM processing has been basically developed for the light structural alloys such as aluminum and magnesium alloys.

There are two basic routes in SSM processing: the rheo-route and the thixo-route. The rheo-route (rheocasting) refers to a process in which the alloy is initially in the liquid state, which is cooled to reach the semisolid state and simultaneously stirred

* Corresponding author. Tel.: +82 51 510 2335; fax: +82 51 518 1456.
E-mail addresses: amir.bolouri@pusan.ac.kr, amir.bolouri@yahoo.com (A. Bolouri), cgkang@pusan.ac.kr (C.G. Kang).
[1] Postal address: School of Mechanical Engineering, Pusan National University, Busan 609-735, Republic of Korea.

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to achieve the desired semisolid slurry [8,9]. This is followed by forming the slurry inside a die without any intermediate solidification step. In contrast, thixo-route (thixoforming) takes place with feedstock that is initially in the solid state. This feedstock is rapidly heated to a predetermined temperature in order to attain a semisolid state, which exhibits a globular microstructure in a liquid-phase matrix [10–13]. This slurry is finally formed inside a die cavity [14–19]. It is generally reported that the integrity and performance of components processed by thixoforming are better than those of the components fabricated through rheocasting [20]. Accordingly, thixoforming process has been employed for this study.

Several companies in Europe, Japan, and the USA have recently started using the thixoforming process for producing millions of components annually [21]. However, for aluminum alloys, the investigations have been primarily dedicated to the thixoforming of bulk components and focused on the evaluation of their microstructural characteristics and mechanical properties. The mechanical properties of actual components produced via thixoforming have been reported after different heat treatments [22,23]. Nevertheless, the thixoforming of A356 alloy has been limited to the temperatures below 590 °C. Meanwhile, it has been generally reported that thixoforming offers a great potential for producing high-quality thin cross section of alloys due to the non-turbulent die filling at high injection speeds [23].

This study is part of a comprehensive investigation into SSM processing of thin aluminum plates. A356 alloy is widely used in several industries because of its high castability, corrosion resistance, and mechanical properties and was used for the current study. The microstructures of the thixoformed A356 thin plates were deeply investigated. The possible mechanisms for the microstructural evolution were proposed. Finally, the tensile properties were correlated to the corresponding microstructures at various processing temperatures.

2. Experimental Procedure

2.1. Thixoforming Procedure

Commercial continuous-cast A356 aluminum billets with composition—Si, 7.419%; Mg, 0.296%; Ti, 0.124%; Fe, 0.106%; Cu, 0.023%; and Mn, 0.26%—were used in this study. The solid content of the alloy was analyzed by using differential scanning calorimetry (DSC). According to DSC analysis, the solidus and liquidus temperatures of alloys were 558 °C and 618 °C, respectively. For the thixoforming, feedstock billets with diameters of 50 mm and lengths of 100 mm were machined from the as-received billets. The initial solid feedstock was placed inside a slurry cup before the induction rapid heating. The slurry cup was made of a nonmagnetic material. The internal and external diameters of slurry cup were 52 mm and 58 mm, respectively. Boron Nitride high-temperature lubricant was sprayed inside the cup. The slurry cup facilitated handling of the semisolid slurry into the die. Rapid heating experiments were performed using an induction heating system with 80-kW capacity. The billets were heated to temperatures of 585 °C, 590 °C, 595 °C, 600 °C, 605 °C and 610 °C corresponded to the solid contents of approximately 50%, 45%, 40%, 34%, 29% and 22%, respectively. These values were according to DSC analysis. However, it is of great importance to note that in the rapid heating, the actual solid contents of the semisolid slurries are slightly higher than the above mentioned values because the heating rate in DSC is slow and the equilibrium (ideal) condition is considered [21]. Accordingly, a range of ~45%–70% liquid fractions (~55%–30% solid contents) corresponding to 585 °C–610 °C was expected for the semisolid slurries after the rapid induction heating [24]. The rapid induction heating rate was 140 °C/min. The semisolid slurries were held isothermally for 20 s at each temperature. The total heating time was less than 300 s depending on the final heating temperature. In order to measure the temperature during the rapid heating process, a hole for a thermocouple was machined into the axis of each billet and a K-type thermocouple with a diameter of 1.6 mm was inserted into this hole. When the desired heating condition was obtained, the thermocouple was removed and the semisolid slurry was transferred into the die for thixoforming. The total time from the heating system to the press machine and thixoforming was 7–10 s. It was estimated that the temperature of the semisolid slurry was only 1–1.5° below the designed thixoforming temperature. A hydraulic press was used for the thixoforming experiments. The semisolid slurry was located in the die sleeve and subsequently, the injection was conducted by the application of pressure through a punch (Fig. 1a). The maximum forming pressure was 70 MPa and the punch speed was 300 m/s. The temperature of the die was kept approximately constant at 250 °C. The geometry of the thin plates can be clearly seen in Fig. 1b. The plate area was 150 mm × 150 mm and the thickness was 1.20 mm. Twenty plates were thixoformed at each temperature. The plates were water-quenched at the room temperature after the thixoforming was accomplished. For the reference, a typical thixoformed thin plate at 595 °C is shown in Fig. 1c. More detailed description of the thixoforming of the plates can be found elsewhere [25].

2.2. Microstructural Characterization

For the metallographic investigations, the thixoformed plates were transversely sectioned at the positions indicated in Fig. 1a for the tensile test specimens. These sections were close to the center of the gage length of the tensile test specimens. Subsequently, the samples were prepared using standard metallographic procedures down to 0.25-micrometer diamond paste and were finally etched by Keller solution. Optical micrographs of the samples were taken using a UNION VERSAMET equipped with an OLYMPUS E300 digital camera. Morphological and microchemical characterizations were made by examining the polished and etched surfaces using a scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscope (EDS). All microstructural quantitative measurements were carried out with a minimum of 500 grains in a sample by using iSolution DT software. The equivalent diameter (d) of the grains was calculated by considering the two-dimensional shape of the grains using:

$$d = 2\sqrt{\frac{A_P}{\pi}} \quad (1)$$

where A_p is the area of each grain.