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Thixo forging process of wrought aluminum alloy fabricated by rotational helical shape stirrer

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Abstract

The manufacture of rheology materials from wrought and casting aluminum alloys using controlling solid fraction and crystal grain is demonstrated in this paper. The equipment to form the rheology material was designed so that shear force and applied pressure could be carefully and simultaneously applied using a mechanical stirrer. The problems caused by using this method with the thixo forging process were studied by investigating the mechanical properties of a sample that had a controlled solid fraction of 45-50 %.

Keywords: Thixo forging; Solid fraction; Rheology material; Shear force; Spiral designed stirring tool

1. Introduction

Difficulties in the near net-shape manufacturing of materials, such as the forming limit of materials, were overcome, and green manufacturing processes, which are defined as clean manufacturing processes, have become an important and absolutely necessary technology. Recently, light-weight parts have been required by the car industry to improve gas mileage and reduce the environmental impact of emissions that have contributed to the depletion of the ozone layer, increasing greenhouse gases, and producing acid rain. Consequently, light-weight alloys have recently been increasingly used in the civil transport, the computer, and electronic hardware industries. However, the replacement of steel alloys with light-weight alloys has caused other problems, such as increased costs and decreased mechanical properties, which prevent their application to engineering [1]. To solve these problems, investigations concerning die standardization and the effects of injection conditions on liquid segregation and mechanical properties were conducted so that grain boundary forging technology, which controls the crystal grain of an Al alloy, can be provided to industry, and core parts can be produced using a horizontal die casting machine [2]. The important factors in developing rheology products consist of the material forging equipment, the method of reheating the material, the machine specifications, and the conditions of the design process. It is well known that when rheology forging and the die casting processes are used with the appropriate process variables, precise net-shaped parts, even those with complex shapes, can be produced without defects such as porosity [3-4].

To date, most research has been focused on studying thixo forming, which reheats solid billets to a semi-solid state and subsequently forms them into shapes. A great deal of research has been reported worldwide, but equipment design and its application technology have remained at the introductory stage,

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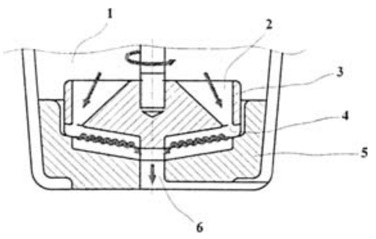
and the studies concerning forming technology, which simultaneously pressurizes rheology material in a die cavity by both shear force and applied pressure, have not been reported yet [5-6].

Therefore, a method for manufacturing rheology material that controls both the solid fraction and crystal grain by using a specially-designed helical stirrer for continuous production has been demonstrated. This study proposes the conditions for fabricating the rheology material of cast A356 alloy and wrought A6061 alloy using the equipment developed in this study. Moreover, a thixo forging experiment has been performed to determine the applicability of the forming of rheology material. The possibility of producing automobile components has been examined by investigating the mechanical properties that result from heat treatment.

2. Thixo forging experiment

2.1 Experimental apparatus

The reheating experiment was first performed so that subsequent thixo forging tests on the rheology material of Al alloys fabricated by the specially-designed helical stirrer could be performed. Prior to reheating, rheology material was manufactured using a mechanical helical stirrer. Fig. 1 shows the helical stirrer. Molten metal was poured into the helical stirrer where it passed through the gate along the spiral inclined plane to the upper stirrer. A vortex flow occurred in the spiral gap between the upper and lower stirrers. Molten metal flowed to the center of stirrer and exited through the outlet. The mechanically stirred molten metal was water-quenched and the morphology of its microstructure was evaluated to investigate optimal stirring conditions (discussed later).



(1) Molten metal
(2) Spiralincline plane
(3) Upper stirrer
(4) Gate
(5) Lower stirrer
(6) Exit gate

Fig. 1. Moving direction of molten metal during mechanical stirring to control solid fraction.

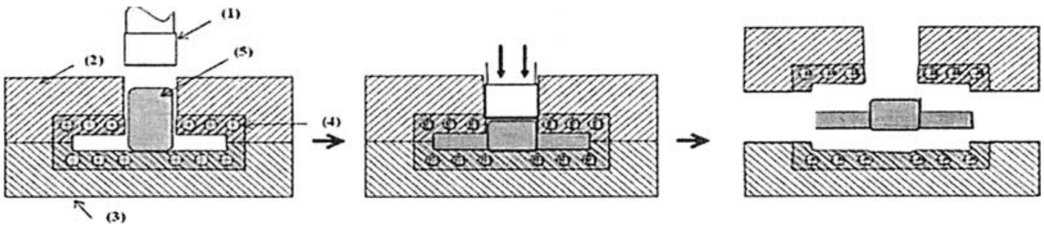
2.2 Experimental conditions for indirect thixoforging process

In order to investigate the effects of mechanical stirring on the fluidity of the rheological material and the effects of applied pressure on compression, indirect thixoforging was carried out. A356 and A6061 alloys were used to fabricate rheology materials in this study. The manufacturing conditions for the A356 alloy were 300 seconds of stirring time, 60 rpm of stirring velocity, and 620℃ of pouring temperature. The manufacturing conditions for the A6061 alloy were the same as the A356 alloy for the stirring time and velocity, but the pouring temperature was 650℃. By reheating both the A356 and A6061 alloys to a predetermined temperature of 595℃, which corresponded to a 49 % solid fraction, and 652℃, which corresponded to a 45 % solid fraction, respectively, without distorting the billet shape, appropriate stirring time and electrical current for the stirrer were set. Then, indirect thixoforging experiment was performed.

Fig. 2 shows the schematic of indirect thixoforging process. The indirect thixoforging die consisted of upper and lower dies. The thixoforging system was designed so that lower die was fixed to the lower plate of the press and the punch was connected to the main cylinder to transfer cylinder-driven forging pressure to the rheological billet in the die. A cartridge heater was used to control the die temperature, which was maintained to 250℃. The A356 alloy, reheated to 595℃, and the A6061 alloy, reheated 652℃, were thixoforged with 220 MPa of forging pressure.

2.3 Indirect thixoforging experiments

Practical thixoforged parts used in the industry are mostly complex shapes. To investigate the effects of the filling behavior and pressing characteristics on the mechanical properties, the specimens were fabricated. The fabricated specimens were solution-heat treated (A 356: 520 ℃, 3 hr; A 6061: 530 ℃, 1.5 hr), and subsequent aging was conducted for the A356 alloy at 170℃ and the A6061 alloy at 177℃. The solution heat-treated material was T6 heat-treated using varying aging times from 0 to 12 hours, and then the heat-treated specimens were tensile tested to investigate optimum aging time and thereby mechanical properties. Fig. 3 depicts positions for the tensile specimens, A and B. Position A represents the



(a) Inserting of billet (b) Thixo forming (c) Extracting

Fig. 2. Schematic of indirect rheo-forging process: (1) punch (2) upper die (3) lower die (4) heater (5) rheo slurry.

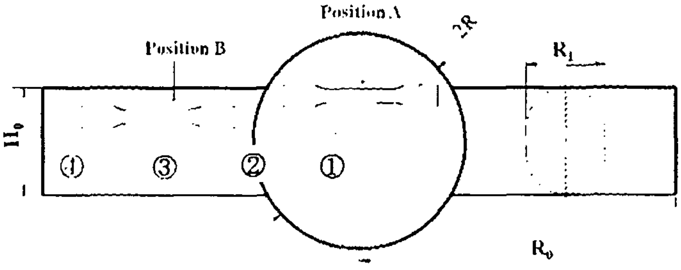


Fig. 3. Schematic of positions of the specimens for tensile test and microstructure observation.

area where the rheo material was in contact with the punch, and position B represents the area filled by pushing the rheo material. To investigate the liquid segregation and microstructural morphology of the thixoforged products, microstructural observation was performed on the specimens taken at positions ①, ②, ③, and ④ of the rheoforged sample.

3. Experimental results

Fig. 4 shows microstructures of thixoforged A356 alloy magnified 100 times to investigate the liquid segregation and microstructural morphology. The liquid segregation was observed at positions ③ and ④. It is thought that this phenomenon occurred due to the fast flow of the liquid phase during compression, and occurred vigorously when the solid and liquid phases separated due to the increase in the compression rate. However, if the closed die was completely filled with the semisolid material at 84 % of compression rate, the distribution of the solid and liquid phases was uniform. Microstructures at position ② illustrate this phenomenon. On the other hand, it was confirmed that with forging pressure, liquid segregation decreased and solid particles compressed. This was confirmed at position ① where the material was directly compressed by the punch during compression.

Fig. 5 shows the microstructures of the thixoforged A6061 alloy at positions ①, ②, ③, and ④ depicted in Fig. 3 to investigate the liquid segregation and microstructural morphology. The liquid segregation was observed at positions ② and ③, and compressed solid particles were observed at position ①. Due to forging pressure, the liquid phase decreased and solid particles were compressed at position ①, where the punch was in contact with the semisolid material of A356 and A6061 alloys during compression. Moreover, the liquid and solid phases were distributed uniformly at positions ③ and ④, where filling occurred by pushing melted material through the punch. This behavior occurred due to the fast flow of the liquid phase during compression. In particular, uniform distribution of the solid and liquid phases occurred at edge region of the sample when it was 0.4-0.5 of solid fraction.

Fig. 6 shows the tensile test results of the thixoforged A356 alloy at positions A and B as a function of aging time. In Fig. 6, 'legend, without', means that there was no T6 heat treatment, and aging time of 0 hours means 3 hours of solution heat treatment at 520℃. The numbers 4, 6, 8, and 10 hours on the axis, mean the aging time after the solution heat treatment. Higher strengths were measured at position B, where the liquid and solid phases distri-

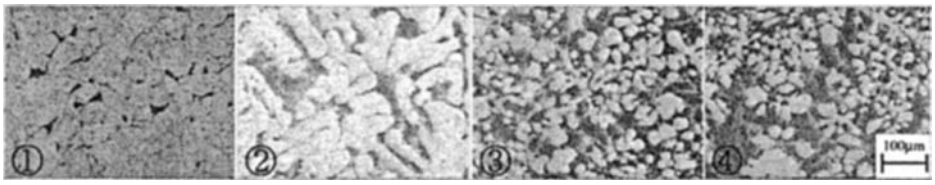


Fig. 4. Microstructures of thixoforged A356 alloy.

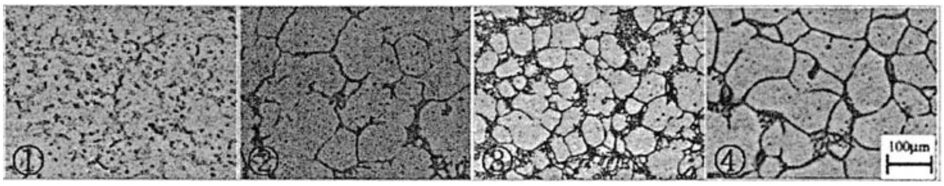
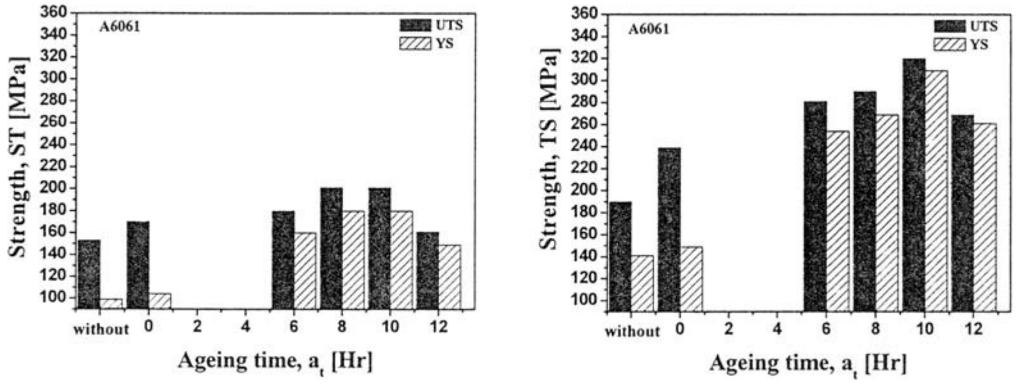


Fig. 5. Microstructures of thixoforged A6061 alloy.



(a) Specimen Position A

(b) Specimen Position B

Fig. 6. The results of tensile test of A356 alloy for variation of ageing time.

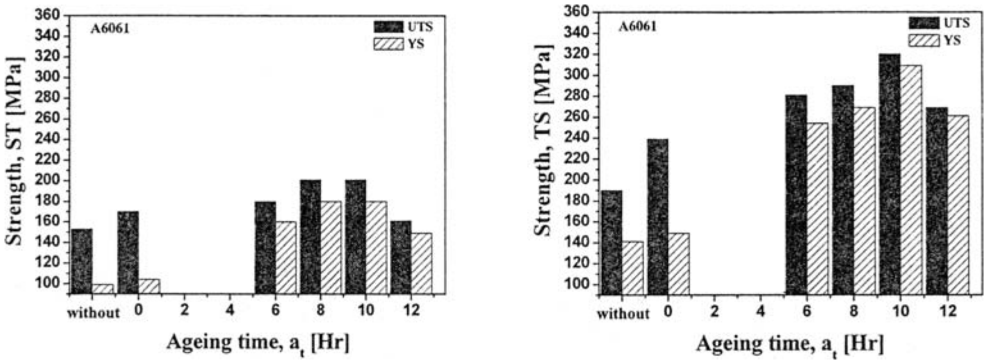
buted uniformly due to flow behavior, than at position A, where the liquid phase decreased and the solid particles were compressed due to direct compression of the material. Tensile strength was better after T6 heat treatment than before T6 heat treatment, and the maximum tensile strength, 325 MPa, of the thixoforged sample that was aged for 10 hours was obtained.

Fig. 7 shows the tensile test results of the thixoforged A6061 alloy at positions A and B as a function of aging time. The tensile strength was better after the T6 heat treatment than before, and the maximum tensile strength, 320 MPa, of the thixoforged sample that was aged for 10 hours was obtained. Fig. 8 shows the elongation of the thixoforged A356 alloy at positions A and B as a function of aging time. When aged for 4 hours, elongation at positions A and B were 15.5 % and 10.2 %, respectively.

Fig. 9 shows the elongation of the thixoforged A6061 alloy at positions A and B as a function of aging time. When aged for 8 hours, the elongation at positions A and B were 8.2 % and 5.6 %, respectively. As a result of investigating mechanical properties in terms of elongation, elongation at position A, where the material was directly compressed by the punch during compression, was higher than that at position B. This is because of the compactness of the solid particles, and reduction in the liquid phase occurred at the position A, as shown in Figs. 4 and 5.

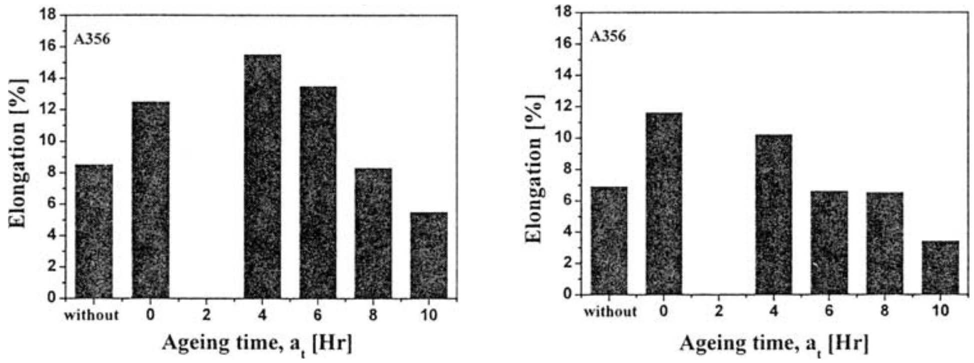
It was known that the solid fraction and heat treatment condition considerably affected the mechanical strength and elongation for the thixoforged A6061 alloy sample.

Fig. 10 shows the analysis results of the EDS of the A356 alloy that was aged for 10 hours. As can be



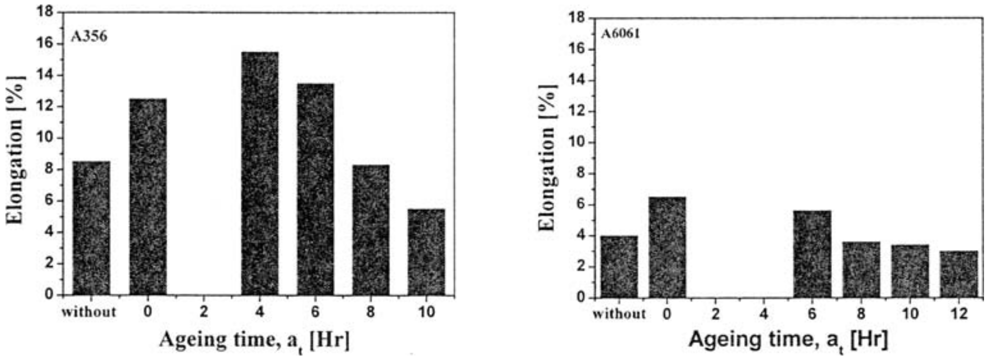
(a) Specimen Position A (b) Specimen Position B

Fig. 7. The results of tensile test of A6061 by varying aging time.



(a) Specimen Position A (b) Specimen Position B

Fig. 8. The Elongation of A356 alloy for variation of aging time.

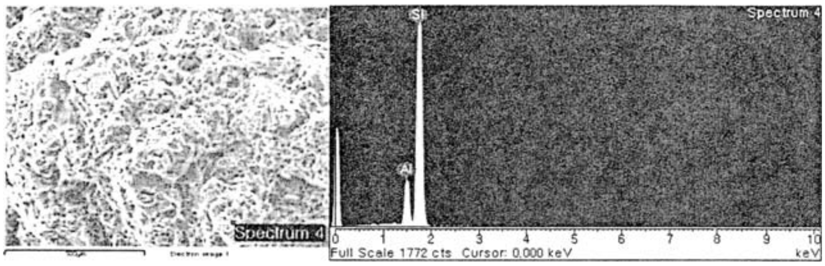


(a) Specimen Position A (b) Specimen Position B

Fig. 9. The elongation of A6061 for variation of aging time.

seen in Fig. 10(b), Si precipitates were observed. The fine Si component oversaturated in the primary-α surface was precipitated on the primary-α surface. As a consequence, the surface quality, which was clean on the primary-α surface before aging, changed due to the fine Si component that was precipitated in the oversaturated α-solution after the aging treatment. It was confirmed that Si precipitates existed because Wt% of Si was measured to be 86.96 %.

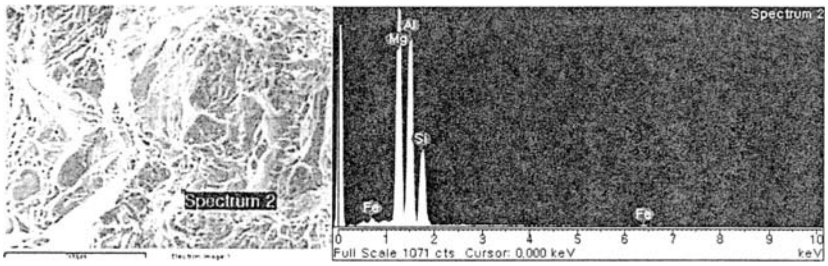
Fig. 11 shows the analysis results of the EDS of the



(a) (b)

Aging time 10 hr

Fig. 10. The analysis result of EDS of A356 alloy aged for 10 hours: (a) fractography (b) EDS analysis.



(a) (b)

Aging time 10 hr

Fig. 11. The analysis result of EDS of A6061 alloy.

A6061 alloy that was aged for 10 hours. As can be seen in Fig. 10(b), Mg precipitates were observed. The fine Mg component oversaturated in the primary-α surface was precipitated on the primary-α surface due to the aging treatment. Here, the Mg component was measured to be 31.85 Wt%.

4. Conclusions

Equipment with a specially-designed mechanical stirrer for fabrication of rheology material using cast A356 alloy and wrought A6061 alloy was developed, and the following conclusion was obtained from the thixo forging experiment using the developed equipment.

1. Through the indirect thixoforging experiment, it was observed that the same fraction of the liquid and solid phases was distributed uniformly at the region where filling occurred due only to the flow of material.
2. After indirect thixo-forging of the reheated rheology billet by using 220 MPa of pressure, 325 MPa of tensile strength, and 5.5 % of elongation for the A356 alloy were obtained, and 320 MPa of tensile strength and 8.2 % of elongation for A6061 alloy were obtained.
3. Through the forming experiment of the rheology material using the equipment with the specially-designed helical stirrer to fabricate rheology material of cast and wrought aluminum alloys, it is evident that continuous manufacture of rheology material is possible by applying mechanical stirring at the semi-solid region, and production of practical products is also possible.

Acknowledgements

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