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Semisolid forming of thin plates with microscale features

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Abstract

Thin plates (150 × 150 × 1.2 mm) with embedded corrugation are fabricated using semisolid forming. The die cavity used in the forming is designed using fluid analysis. A semisolid slurry is prepared by a cooling with EMS and heating process. The slurry is then injected into a forging die attached to a 200 tonf hydraulic press. Subsequently, the slurry is compressed by a punch, flown into the die cavity, and then solidified. A356 (cast Al alloy) and AA6061, AA2024, and AA7075 (wrought Al alloys) are used.

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Keywords: Semisolid forming; Thixoforging; Rheoforging; Thin plate; Aluminium alloy

1. Introduction

Semisolid forming (SSF) is a combined forming method for alloys; this method utilises the advantages of both casting and forging processes in order to form a semisolid slurry, which is characterised by a distinct boundary between the solid and liquid states (a semisolid method results in coexisting solid and liquid regions, as shown in Fig. 1). SSF is a near-net-shape manufacturing process that is performed on metallic alloys in the semisolid state. The alloy subjected to SSF must possess an appreciable melting range, as it enhances the formation of a microstructure that ideally consists of primary non-dendritic metal spheroids in a liquid-phase matrix, as shown in

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Fig. 2 (a); this mixture is called a semisolid slurry. The dendritic microstructure is shown in Fig. 2 (b) for comparison (Bolouri and Kang, 2013).

In the semisolid state, an alloy behaves as a thixotropic material, i.e. its viscosity decreases when a force is applied and it starts flowing; however, it behaves as a solid in the absence of any applied force (Bolouri et al., 2013). Indeed, a semisolid method (SSM) benefits from the advantages of both conventional casting and forging processes (Kim et al., 2007). This extraordinary thixotropic behaviour of metallic materials was first discovered at MIT (Flemings, 1991); since then, there has been a very strong interest among scientists and industries to develop this behaviour for different alloys (Meng et al., 2012). Similar to squeeze casting, most SSMs use high-pressure die casting machines to inject a semisolid slurry into reusable, hardened steel dies. However, SSF offers several advantages over conventional die casting, such as lower temperature die filling with a slurry that flows in a nonturbulent manner (Fig. 3) (Bolouri et al., 2014). Therefore, it is expected that SSM would reduce the occurrence of shrinkage microporosities because of the presence of a primary solid phase prior to die filling at a much lower temperature than that in conventional die casting (Jin et al., 2014). Moreover, it is expected that the amount of entrapped gases in SSM would be significantly lower than that in high-pressure die casting (Fig. 3). SSM has been basically developed for light structural alloys such as those of aluminium and magnesium. Commercial SSM casters utilize both horizontal and vertical injection systems, although horizontal injection is more common. Further, SSM casters often use horizontal die casting machines fitted with real-time controlled injection units, which provide the necessary control to avoid turbulence during the injection of a semisolid slurry into the cavity. As with squeeze casting, the metal is typically fed into the cavity through relatively massive runners and gates, which provide paths for the feeding of solidification shrinkage. The advantages and disadvantages of SSM are listed in Table 1.

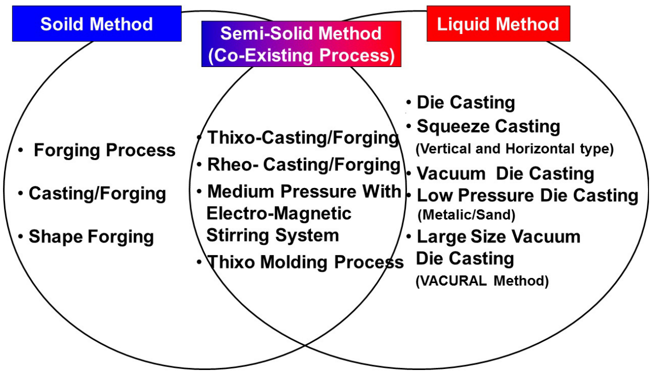

Fig. 1. Conception of semisolid forming.

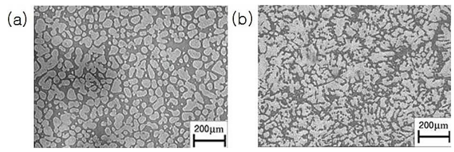

Fig. 2. (a) Globular microstructure and (b) dendritic microstructure.

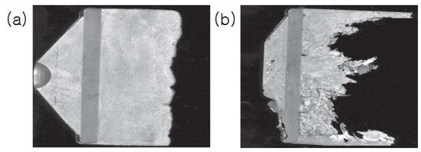

Fig. 3. Filling behaviour (a) semisolid casting and (b) die casting.

Table 1. Advantages and disadvantages of semisolid method.

Advantage	Disadvantage
Forming high melting point material	High billet cost fabricated by electro magnetically process (Thixo)
Extending die life	Initial investment high to mass production (Thixo)
Less casting defects (shrinkage voids, oxides, porosity)	Cycle time control to mass production
Laminar filling behaviour, Fine grain structure	Increment of number induction heating stage to solve the cycle time (Thixo)
Forming intricate parts, Lower power of forming	Liquid segregation after forming

Currently, two SSF processes are in use: thixoforming and rheoforming. Rheoforming produces a grain-size-controlled semisolid slurry via the stirring of a cooling molten metal to a semisolid state, as shown in Fig. 4 (a). Thixoforming, on the other hand, produces billets via electric stirring and involves reheating them into a semisolid state, as shown in Fig. 4 (b). While thixoforming offers high mechanical strength of the formed products, it also has some disadvantages such as the high cost of initial billets and a loss of costs due to the induction heating process. The recent trend in semisolid processing is to apply the rheoforming method (Fig. 5). Flemings (1991) was the first to report a method for producing a semisolid slurry; the various methods developed till now include mechanical stirring, slope plate process (Haga and Kapranos, 1987), electromagnetic stirring (EMS) (Lee and Kang, 2011), continuous rheocasting process (CRP) (Wiesner et al., 2006), continuous rotational pressure process (CR2P) (Seo et al., 2006), twin screw slurry maker (Ji et al., 2001), viscosity control (Lashkari and Ghomashchi, 2007), seed process (Nasfisi and Ghomashchi, 2006), rotational barrel process (Seo et al., 2009), SSRTM process (Curle et al., 2011), gas-induced semisolid (GISS) process (Wannasin et al., 2010), and ultrasonic vibrations (Jian et al., 2005). A lot of research has been carried out so far on various die designs and processes that can enhance the mechanical properties and control the microstructure of the products fabricated using the semisolid process. However, the application of the semisolid process has been limited to large-volume products used in the automobile, aircraft, and electronic parts industries, and no research involving thin plates fabricated using the semisolid process has been carried out yet.

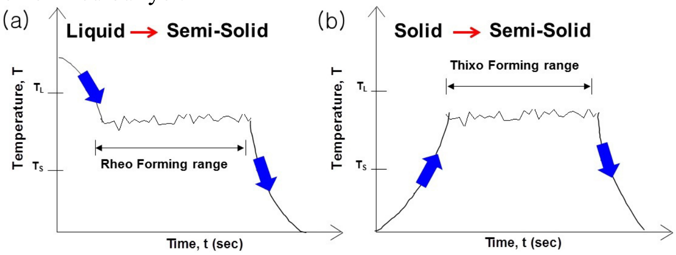

Fig. 4. (a) Rheoforming and (b) Thixoforming.

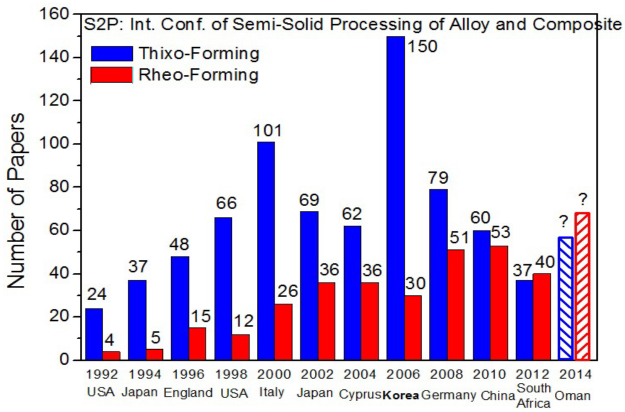

Fig. 5. Research trend for semisolid process.

This study presents semi-solid techniques to fabricate 1.2 mm-thick thin plate with arrays of micro flow channel. Thin plates with microflow channels, such as corrugated plates, can be used in electrical components, automobile parts, plate heat exchangers, and fuel cell bipolar plates. In particular, bipolar plates serve several functions in a fuel cell stack. The weight, volume, and cost of bipolar plates can be reduced significantly by improving the layout configuration of the flow field and by using lightweight materials. Further, a fabrication method that is capable of mass production is required. In the last few years, studies have been conducted on various fabrication methods for metallic bipolar plates, including stamping (Kwon et al., 2013), hydroforming (Mahabunphachai et al., 2010), microelectrical discharge machining (EDM) milling (Hung et al., 2011), rubber pad forming (Lim et al., 2013), electrochemical micromachining (Lee et al., 2008), and vacuum die casting (Jin and Kang, 2011). Stamping, rubber pad forming, and hydroforming are mass production methods; however, these methods suffer from forming limitations in terms of spring-back and flatness after forming. Machining allows for precision fabrication of channels, but the processing time and cost involved are similar to those required for forming graphite plates, making machining unsuitable for mass production. SSF offers a great potential for manufacturing near-net-shape alloys with thin cross-sections. In this paper, die design for SSF and the formability, microstructure, and mechanical properties of products as determined using various parameters are discussed.

2. Thin plate forming by semisolid forging

2.1. Die design

Die design by computer simulation has many advantages over conventional methods that are dependent on the designer's experience and trial and errors. To reduce the time and cost required for die design, a commercial package was used. For the fabrication of thin plates by semisolid forging, the die structure and design technology are very important aspects for manufacturing parts that could satisfy the characteristic values required by the end user. Fig. 6 shows a flow chart of the optimization algorithm for designing a semisolid forging die used for thin plate fabrication. After the projected area and semisolid slurry particle size suitable for obtaining a product with the required characteristics have been decided, the die structure is determined considering die life, extract gradient, prevention of gas inclusions, and size of tapered tip for removing the oxide skin. After the die structure has been determined, defects during filling and solidification in the part can be predicted by a computer simulation. To develop a die and thin plates by semisolid die forging, process parameters such as press specification, parting line of the die, sleeve design to remove the oxide skin, gating system, overflow shape, and heating system of the die were progressively designed as shown in Fig. 6. Fig. 7 shows the die cavity shape and filling behaviour of a semisolid material in the die cavity. The area and depth of the cavity in which the thin plate is formed are 150 × 150 mm and 1.2 mm, respectively. The channel is 70 mm wide and 70 mm long, and its depth is 0.3 mm.

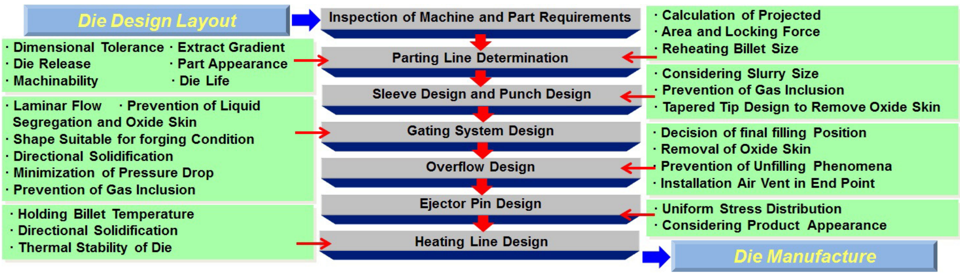

Fig. 6. Flow chart for designing semisolid forging die used for thin plate fabrication.

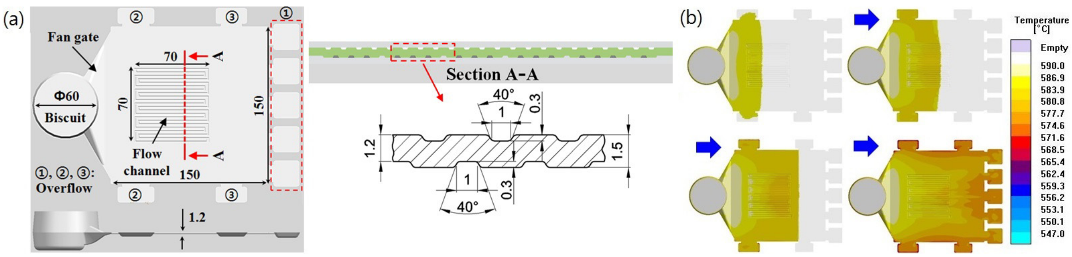

Fig. 7. (a) Die cavity for thin plate and (b) filling behaviour.

2.2. Thin plate forming by rheoforging

A semisolid slurry was formed using A356 and A6061 alloys and an electromagnetic stirrer. This stirrer consists of three phases and three poles with its coil placed vertically to the core. Each phase (P, R, S) is placed in a cylindrical direction to let the current move alongside the coil, and an electromagnetic force is generated in the cylindrical direction, thereby stirring the molten metal. The stirring force generates shear stress in the molten aluminium, thereby controlling the size of the primary particles and making them globular. A semisolid slurry is then obtained in which liquid and solid particles are mixed. The process for preparing a semisolid slurry with EMS is as follows. First, the cup is inserted into the stirrer, and then a ladle is used to scoop up the molten metal from the furnace. Then, stirring starts as the electric current is applied at the same time as the molten metal is being poured into the stirring cup (Fig. 8). Semisolid slurries with 600 °C /35% *f*s, 590 °C/45% *f*s, and 578 °C/55% *f*s for A356 and 548 °C/50% *f*s for A6061 were fabricated. Fig. 9 shows the microstructures of semisolid slurries prepared with and without EMS. The microstructure of the slurry prepared with EMS showed fine and globular primary aluminium particles that were distributed evenly overall. In contrast, the microstructure of the slurry prepared without EMS showed a large number of rosette particles and a few distributed fine-globular particles.

The semisolid slurry prepared with EMS was injected into the forging die equipped with a 200-t hydraulic press for thin plate forming. The process of thin plate forming using a semisolid slurry is shown in Fig. 10. The die temperature was maintained at 290–300°C by using a cartridge heater. The press punch pressure was set at 100, 150, 200, or 250 MPa, and its speed was set either at a low value of 30 mm/s or at a high value of 300 mm/s. The semisolid slurry was injected into the die, compressed with the punch, and then the pressure was maintained for 5 s. To ensure that the formed plate was not deformed by the ejector pin, the die was left open for 10 s to allow solidification to a certain level, and then the plate was taken out of it and immediately cooled down in water. During filling, the semisolid material can cause sticking owing to its viscosity at the gate where the speed is high. Therefore, a graphite lubricant was sprayed in the die cavity. Fig. 11 shows the formability results. As can be seen in the images of the samples below the chart, ● denotes complete forming, ■ represents forming with short shots on the overflow, ▲ indicates overall forming with partial short shots, and X indicates overall short shots in the cavity. It was impossible to form a thin plate at the punch velocity of 30 mm/s. It was confirmed that higher the punch pressure, easier it is to achieve formability. The gate transformed pressure energy into velocity energy, and thus, when a higher pressure was applied, the semisolid slurry became compressed and entered the cavity faster. Fig. 12 shows the microstructures of thin plates formed using a semisolid slurry with and without EMS. The punch velocity and applied pressure were 300 mm/s and 150 MPa, respectively. The microstructure of the thin plate fabricated using a semisolid slurry at 590 °C with EMS was homogenous and contained evenly distributed fine primary particles. For the thin plate fabricated using a semisolid slurry at 590 °C without EMS, the distribution of primary particles within the structure was nonhomogenous. The microstructures consisted of coarse dendritic and rosette primary particles. The ultimate tensile strength (UTS) and elongation (EL) of the A356 thin plate fabricated using the slurry with EMS were 220 MPa and 13.5%, respectively, and the corresponding values for the A6061 thin plate were 161 MPa and 7.5%, respectively. The tensile strength of the thin plates fabricated using the slurry without EMS were about 33 MPa and 8 MPa lower for A356 and A6061 materials, respectively, and showed a significant difference of 2–6% in EL.

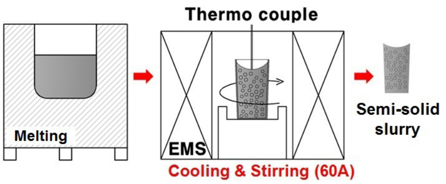

Fig. 8. Preparation of semisolid slurry using EMS.

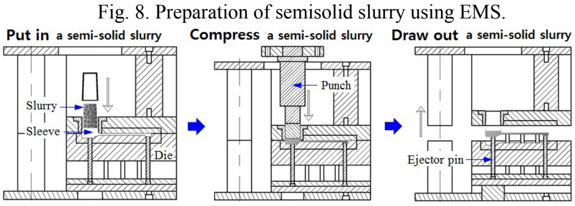

Fig. 10. Forging process using semisolid slurry.

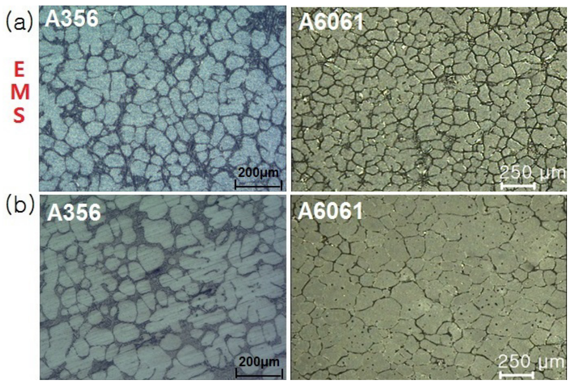

Fig. 9. Microstructure of slurry (a) with and (b) without EMS.

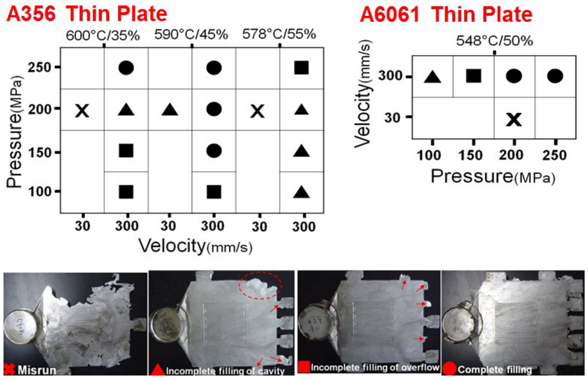

Fig. 11. Formability of thin plates formed by rheoforging.

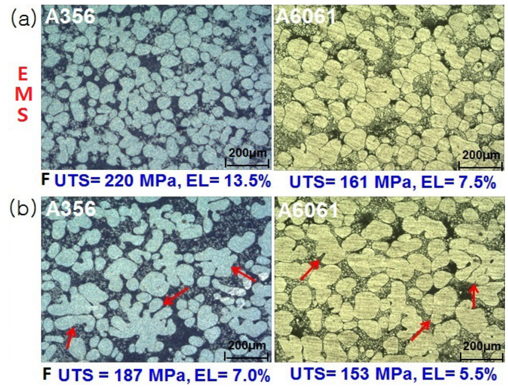

Fig. 12. Microstructures of thin plates (A356 and A6061 alloys) (a) semisolid slurry with EMS and (b) semisolid slurry without EMS.

2.3. Thin plate forming by thixoforging

The reheating process employed for preparing a semisolid slurry is shown in Fig. 13. For thixoforging, feedstock with a diameter of 50 mm and a length of 100 mm was machined from as-received billets. Rapid heating experiments were performed using an induction heating system with a capacity of 80 kW. A hole was machined at the centre of each feedstock billet, and a K-type (Ø1.6 mm) thermocouple was inserted into each hole to measure the temperature of the feedstock during heating. The feedstock billets were heated to 585 °C/50% *f*s, 590 °C/45% *f*s, and 600 °C/34% *f*s for A356 billets, 615 °C/55% *f*s, 620 °C/50% *f*s, and 625 °C/40% *f*s for A2024 billets, and 610 °C/63% *f*s, 615 °C/53% *f*s, and 620 °C/47% *f*s for A7075 billets. The semisolid slurries were isothermally held at each temperature for 30 s. When the desired heating condition was obtained, the thermocouple was removed and the semisolid slurry was transferred into the die for thixoforging. Fig. 14 (a) shows a comparison of the final states of thin plates thixoforged from various aluminium alloy slurries (punch velocity and pressure: 300 mm/s and 70 MPa, respectively). Fig. 14 clearly shows that the A356 thin plates were successfully fabricated at 590 °C. However, A7075 and A2024 failed to fill the die at owing to poor fluidity. Therefore, a vertical-filling-type die was used for the thixoforging of wrought aluminium alloys. The thixoforging force and semisolid slurry flow within the die cavity directions were parallel (Fig. 15). The plate dimensions were 110 × 85 × 1.2 mm and the channel area was 56 × 54 mm. Fig. 15 (b) shows AA7075 and AA2024 thin plates formed using the vertical filling die (punch velocity and pressure: 300 mm/s and 70 MPa, respectively). For the AA7075 alloy, the thixoforging temperature range was 610–620 °C; incomplete filling and hot tearing occurred at temperatures below 610 and 620 °C, respectively. For the AA2024 alloy, the thixoforging temperature range was 615–625 °C; incomplete filling and hot tearing occurred at temperatures below 615 and 625 °C, respectively.

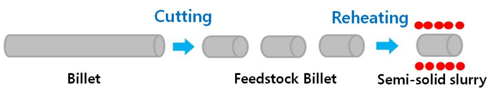

Fig. 13. Reheating process for preparing semisolid slurry.

Fig. 14. Thixoforged thin plates (a) horizontal filling die and (b) vertical filling die.

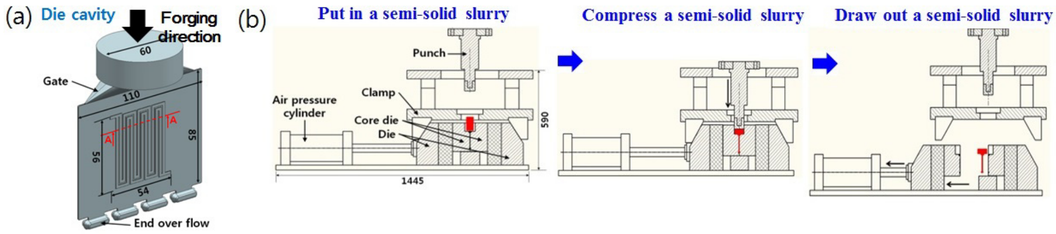

Fig. 15. Vertical filling die for thixoforging of wrought aluminium alloy.

The tensile properties of the thixoforged thin plates at various thixoforging temperatures are illustrated in Fig. 16. Interestingly, at first glance, it appears that the microstructural evolution at different temperatures was clearly reflected in the tensile properties. By increasing the temperature from 590 to 595 °C, UTS improved to 278 ± 11 MPa and stayed approximately constant (280 ± 12 MPa) at a temperature of 600 °C. The former could be because of the enhancing effect of the eutectic silicon modification on UTS, whereas the latter implied that this effect could be limited. Subsequently, a noticeable reduction in UTS was observed when the temperature was increased to 605 and 610 °C. The principal reason for this reduction could be the expansion of the secondary α-Al grains (weaker phase) in the microstructure, since the morphology of eutectic silicon was estimated to be identical at 605 and 610 °C. Furthermore, the sphericity of the primary α-Al globular grains was greatly improved from being irregularly shaped grains at 585 °C to more spherical grains at 600 °C. Fig. 17 shows the tensile properties and microstructures of AA7075 and AA2024 thin plates. The yield strength (YS) values monotonically decreased with increasing temperature. However, with increasing temperature, UTS values initially decreased and then became stable. It should be noted that the initial decrease was sharp and evident for the AA7075 thin plates; however, it was small for the AA2024 thin plates. Generally, the UTS values for the AA7075 thin plates, which vary between 258 and 300 MPa, are lower than those for the AA2024 thin plates, which vary less dramatically between 301 and 315 MPa. Furthermore, the AA7075 thin plates exhibited extremely brittle fractures with EL values of 1.25% and 0.68% at temperatures of 610 and 615 °C, respectively. The largest AA7075 EL value, 2.8%, was obtained at the highest temperature, 620 °C; however, this value is negligible for the high-performance AA7075 aluminium alloy. In contrast, higher levels of EL, fluctuating between 4.6% and 5.8%, were observed for the AA2024 alloy.

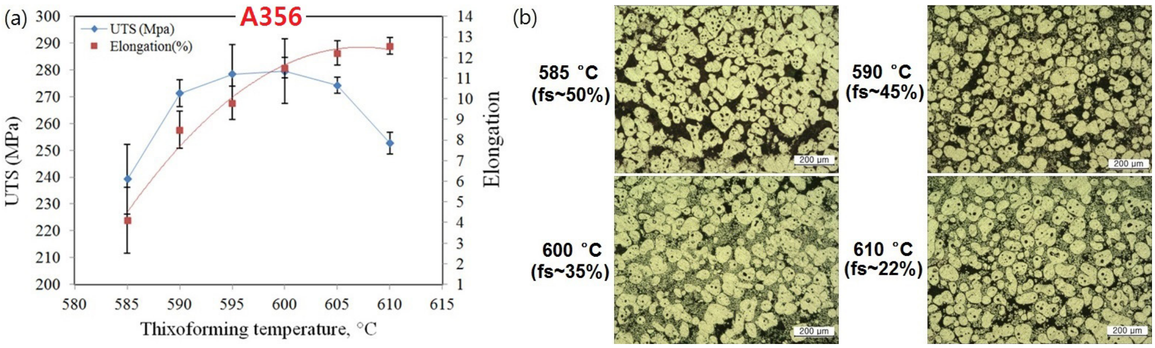

Fig. 16. (a) Tensile properties and (b) microstructures of thixoforged A356 thin plate.

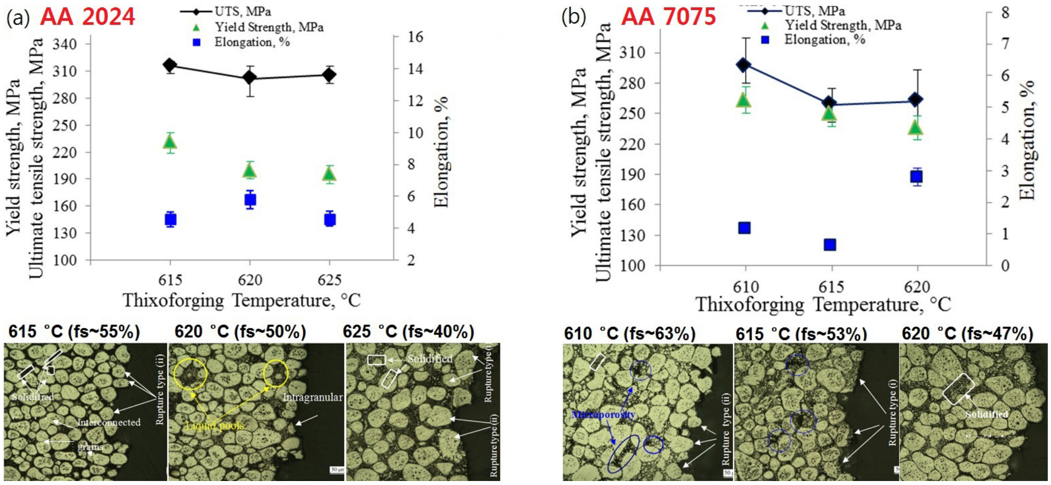

Fig. 17. Tensile properties and microstructures of (a) thixoforged AA 2024 and (b) AA7075 thin plates.

The plate thicknesses and depth of channels are reported in Fig 18. The thixo/rheo formed plates showed the least amount of variation in the thickness measurements. This caused the semisolid slurry to homogeneously flow inside the die cavity, which ultimately produced the highest dimensional stability during forming. This study showed that semisolid forming can be effectively used for net-shape manufacturing of aluminum thin plates

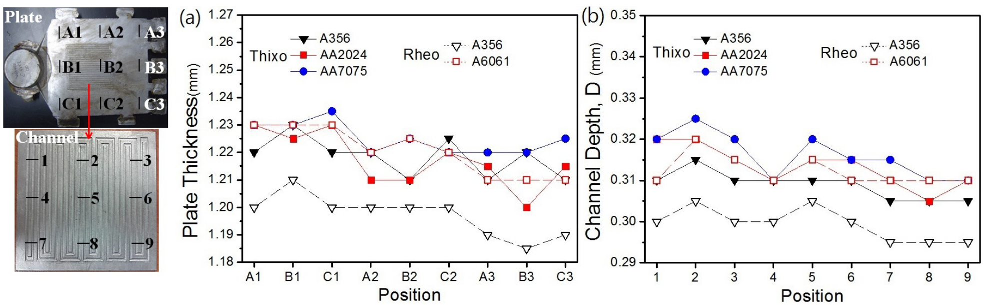

Fig. 18. Dimension of rheo/thixoformed thin plate (a) Plate thickness and (b) depth of channels.

3. Thin plate forming by casting and forging

3.1. Thin plate forming by vacuum die casting

Fig. 19 shows an aluminium thin plate (200 × 200 × 0.8 mm) with a channel (150 × 150 × 0.3 mm) fabricated by vacuum die casting. The process of vacuum die casting is shown in Fig. 18. After the molten metal was ladled into the pouring hole of the shot sleeve, the plunger moved at a low velocity to 405 mm/s in the shot sleeve, and the vacuum pump was operated at a pressure of 30 kPa. In the next step, the plunger moved in the high-speed region. The plunger moved at a high velocity to the end of the sleeve with a pressure of 50 MPa, during which time the vacuum pump was not working. After the die opened, the product was pushed out by an ejector pin. A sound sample was fabricated at a molten metal temperature, injection velocity in the high-speed region, and vacuum pressure of 700 °C, 2.5 m/s, and 30 kPa, respectively (Jin and Kang, 2011).

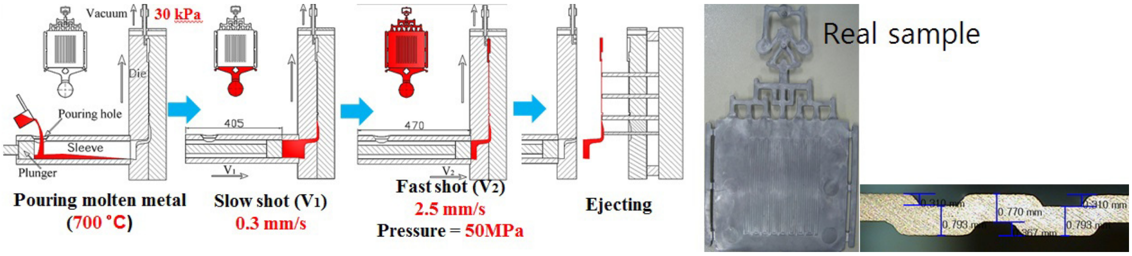

Fig. 19. Thin plate fabrication by vacuum die casting (Jin and Kang, 2012).

3.2. Thin plate forming by low-pressure die casting with EMS and a vacuum system

Fig. 20 shows an aluminium thin plate (110 × 130 × 1.0 mm) fabricated by low-pressure die casting (LPDC) with EMS and a vacuum system. The melt passes through the rasing pipe and enters the die cavity owing to the pressure of the gas fed through the gas inlet located at the top of the furnace. An EMS is attached on the outside of the rasing pipe that is connected from the furnace to the lower die. Thin plates are produced by applying a melt temperature of 615 °C/10% *f*s, a gas pressure of 15 bars, and a vacuum pressure of 60 Torr (Jin et al., 2014).

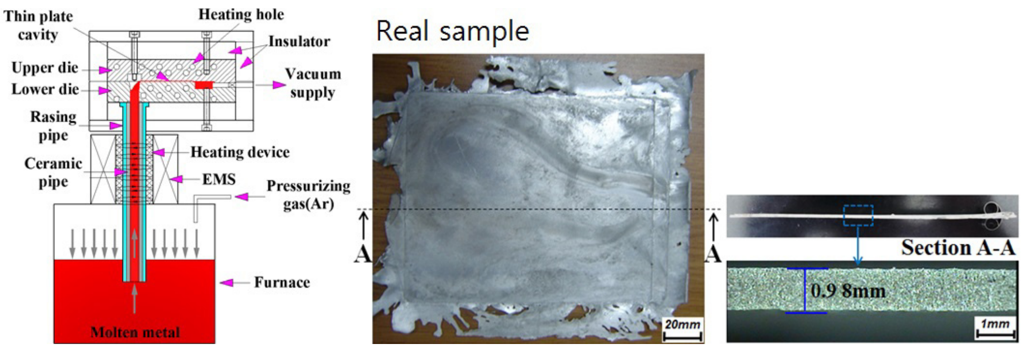

Fig. 20. Thin plate fabricated by LPDC with EMS and a vacuum system (Jin et al., 2014).

3.3. Thin plate forming by stamping process

Fig. 21 shows a stainless steel 304 thin plate (thickness: 0.1 mm) with a channel (70 × 70 mm) fabricated by the stamping process. The dimensions of the stamping die were equal to those of the die used in semisolid forging. The channels in the plate were formed by pressing the blank with an upper die by inserting the blank between the upper and lower dies. The channel depth formed under a load of 100 kN was 0.344 mm (Kwon et al., 2013).

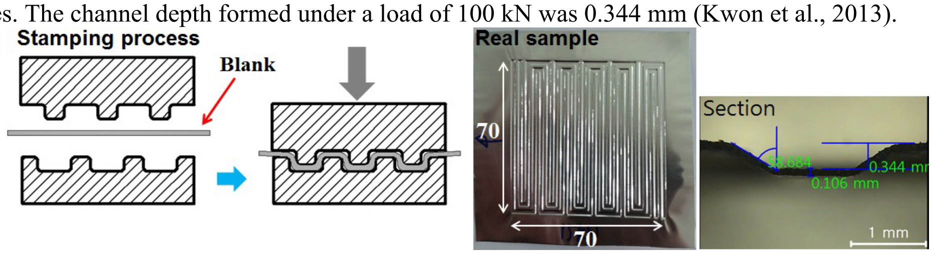

Fig. 21. Thin plate (0.1 mm thickness) with channel fabricated by stamping process (Kwon et al., 2013).

3.4. Thin plate forming by rubber forming process

Fig. 22 shows an aluminium thin plate (thickness: 0.1 mm; area: 55 × 55 mm) fabricated by the rubber forming process. The rubber forming method is different from the stamping method in that while a rigid die is used for the upper die, the lower part uses a flexible rubber pad. This method utilizes the reaction force due to the elastic deformation of the rubber pad and the force from the upper die that presses on the blank, which allows for uniform force distribution on the blank at the same time (Lim et al., 2013).

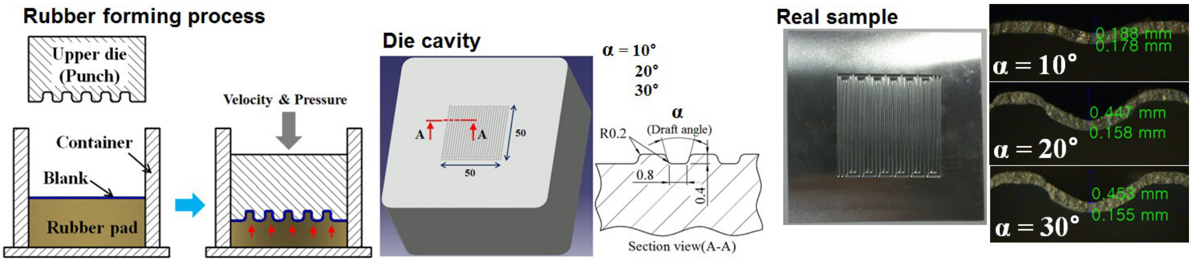

Fig. 22. Thin plate (0.1 mm thickness) with a channel fabricated by rubber forming process (Lim et al., 2013).

4. Conclusion

This study suggests that semi-solid forging can be effectively used for net-shape manufacturing of bipolar plates having arrays of channels. Channels depth fabricated by rheo/thixo forging showed a very small deviation from the designed depth. In addition the variation in the channels depth throughout the channels area was very small. This variation was less than the variation observed for bipolar plates manufactured by stamping and rubber pad forming. Thixo and rheoforged thin plates showed a near-net-shape, uniform microstructures, and excellent mechanical properties. It is expected that in the near future, such plates can be used to fabricate automobile body parts and airplane parts that require high strength. Table 2 shows a comparison of various thin-plate forming processes, showing the advantages and drawbacks of each, as well as the challenges yet to be addressed.

Table 2. Comparison of forming processes for manufacturing thin plates.

Process type	Advantage	Drawback & Remaining challenge
Semi-solid forging	Near net shape, Good formability,	Material choice limit, Thick plate (1.0 mm ~)
	High Mechanical properties, Heat treatment	High die cost, Warm up time
Vacuum die-casting	Near net shape	Material choice limit, Thick plate (0.7 mm ~)
	Medium Mechanical properties	High die cost, Warm up time
Low pressure die-casting	Material recyclability	Material choice limit, Thick plate (1.0 mm ~)
		Poor formability/Mechanical properties, Warm up time
Stamping	Thin plate (0.1 mm), Various materials	Forming limit, Flatness, Wrinkle,
	High productivity	Decreasing thick (Thinning), Extra processing
Rubber Forming	Thin plate (0.1 mm), Various materials	Forming limit, Short rubber life,
	Low cost process	Extra processing

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