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Effect of Extrusion Temperature on Properties and Surface of AA6063 Chips

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Abstract

Aluminum (Al) offers excellent workability and recyclability, and further applications of recycled Al are anticipated. However, because conventional recycling methods rely on casting processes, the removal and neutralization of impurities during remelting remain significant challenges. To mitigate impurity contamination associated with casting, horizontal recycling via solid-state processing using plastic working techniques, such as extrusion, has attracted increasing attention. This study aims to achieve hot extrusion processing for the direct recycling of AA6063 alloy chip scrap using a unique die structure termed a pseudo-porthole die. Application of this die structure induces flow separation and compression within the container, enabling chip extrusion by imparting strong shear deformation. Hot extrusion experiments were conducted using billets fabricated by compacting AA6063 alloy chips. The effects of extrusion temperature on extrusion behavior, including extrusion force, product surface quality, and tensile properties, were investigated. Increasing the extrusion temperature reduced the extrusion force. Higher extrusion temperatures improved inter-chip adhesion, suppressed surface defects, and enhanced the tensile strength of the extruded product.

1 Introduction

Aluminum (Al) is widely used in diverse fields, such as residential building materials and transportation equipment, owing to its light weight and high workability (Czerwinski, 2012). However, the substantial energy consumption required to extract Al from alumina during primary production poses a major challenge, making the use of recycled materials an urgent necessity (Wagiman et al., 2020). Al exhibits excellent recyclability, and the use of recycled Al can reduce energy consumption by up to 95% (Blomberg and Söderholm, 2020). Conventional Al recycling is based on casting processes involving remelting; consequently, existing research has primarily focused on adjusting material composition to remove or neutralize impurities during casting and on suppressing casting-related defects (Capuzzi and Timelli, 2018).

It has been suggested that eliminating the casting process and recycling materials solely through solid-state processes, such as extrusion or forging, could further reduce energy consumption and waste generation. Extrusion is a plastic working process that has also been applied as a solid-state forming method for chip materials (Wan et al., 2017; Shamsudin et al., 2017), with the aim of directly recycling Al waste materials such as machining chips. However, solid-state recycling of Al chip materials has not yet been fully realized because of the frequent occurrence of defects, including insufficient inter-chip bonding strength, internal voids, and surface defects such as chipping and cracking. These defects are attributed to the inability to sufficiently apply the stresses and strains required to disrupt the oxide film inherently present on Al chips during forming (Yu et al., 2025).

Funazuka et al. proposed a pseudo-porthole die as a method to “simulate” porthole extrusion (Funazuka et al., 2020). This pseudo-porthole die reproduces the flow separation and crimping behavior characteristic of porthole extrusion, thereby imparting strong shear deformation to the material and promoting grain refinement. In studies on the extrusion of AA6060 alloy billets using similar die structures, Tekkaya et al. demonstrated through a series of investigations that the use of porthole dies imposes significant shear stress on the material. This shear stress is effective in breaking the oxide layer on Al, thereby enhancing interfacial bonding strength (Tekkaya et al., 2009; Güley et al., 2013).

The authors previously conducted hot extrusion of AA6063 chips using a pseudo-porthole die with the aim of achieving direct horizontal recycling of sash materials. These studies evaluated the effectiveness of the pseudo-porthole die for chip material extrusion and examined the influence of chip material density (Funazuka et al., 2024). The strong shear deformation imparted by the pseudo-porthole die disrupts the oxide layer on the billet surface, thereby promoting adhesion between individual chips. Moreover, it was reported that larger billet sizes and densities approaching Al’s intrinsic density of 2.7 g/cm³ lead to a reduction in surface defects in the extruded products. Building on these findings, the present study investigates the influence of extrusion temperature as a key processing parameter for optimizing chip extrusion. AA6063 chips were produced by turning and subsequently subjected to compression molding to fabricate billets. The effects of extrusion temperature on extrusion performance, including extrusion force, product surface quality, and tensile properties, were systematically examined.

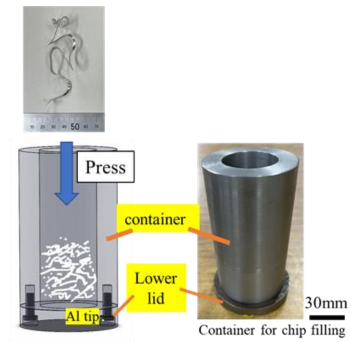
2 Experimental conditions

In this study, AA6063 alloy, whose chemical composition is shown in Table 1, was used as the chip material.

The chips were produced by turning a cast AA6063 billet. The cutting conditions were a depth of cut of 0.5 mm and a rotational speed of 920 rpm, yielding chips with a width of approximately 2 mm. The chips were compacted and preformed using a 300 kN Amsler-type universal testing machine under a load of 30 kN, as shown in Figure 1(a) (Funazuka et al., 2024). The compacted chips were inserted into the container to form a preformed chip billet with a diameter of 38.5 mm and a length of 80 mm.

Table 1: Chemical composition of AA6063 [mass%]

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
AA6063	0.49	0.18	0.02	0.02	0.54	0.01	0.01	0.01	Bal.



(a) (b)

Figure 1: (a) 300 kN Amsler-type universal testing machine, (b) Schematic view of pre-solidification compacting (Funazuka et al., 2024)

After preforming, the billets were solidified and formed using a 2000 kN horizontal hydraulic extrusion press, as shown in Figure 2(a). Based on previous studies, the solidification forming conditions were selected to achieve the highest billet density (Funazuka et al., 2024). The ram speed was set to 0.5 mm/s, the test temperature to 200 °C, and the applied load to 1000 kN. Figure 2(b) shows schematic diagrams of the compaction molding and extrusion experiments. A cartridge heater and a thermocouple were installed inside the container, and the billet temperature and ram speed were controlled using a controller. The extrusion force during hot extrusion was measured using a pressure sensor attached to the hydraulic controller of the press, and the ram stroke was measured using a laser displacement meter. For compression molding, an extrusion die without a die hole was used as the compacting die.

Figure 2(c) shows the chip billet obtained by solidification molding, with a density of 2.607 g/cm³. The obtained billet was prepared as samples with a diameter of approximately 41.5 mm and a length of approximately 30 mm, taking into account the container diameter used in the extrusion experiments. During hot extrusion, the billets were stacked to a specified length, resulting in an overall billet length of approximately 100 mm. The extrusion temperatures investigated in this study were 400 °C, 450 °C, and 500 °C. For each condition, the die was heated to the same temperature as the billet. The ram speed during extrusion was maintained at 0.5 mm/s.

A pseudo-porthole die was used for the extrusion experiments, as shown in Figure 3(a) (Funazuka et al., 2020). The pseudo-porthole die developed in this study was simplified by removing the mandrel section that forms the hollow region in a conventional porthole die. This simplification enabled clear reproduction of the crimping process within the chamber section, allowing the die to reproduce only the flow diversion and crimping processes.

The port length and port thickness of the pseudo-porthole were 25 mm and 6 mm, respectively. The inner diameters of both the port and chamber sections were φ25 mm, and the chamber section length was 20 mm. The extruded profile was a plate-shaped solid material with a width of 18.6 mm and a thickness of 1.5 mm, as shown in Figure 4(b). To investigate heat generation during hot extrusion, a thermocouple was installed at the center of the bearing section.

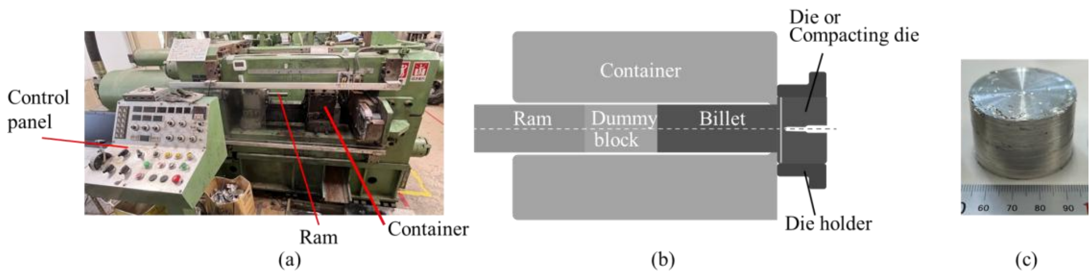


Figure 2: (a) 2000 kN horizontal extrusion machine, (b) Schematic view of compacting and extrusion, (c) Chip billet (Density：2.607g/cm^3)

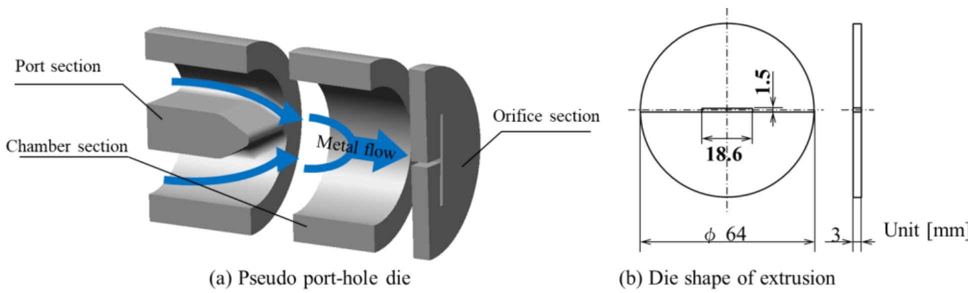


Figure 3: Schematic of die and die set used in hot extrusion experiments (Funazuka et al., 2020)

The extrudate obtained from the extrusion experiments was approximately 3600 mm in length. The extrudate was divided into three regions for observation: the head, middle, and end, located at distances of 600 mm, 1800 mm, and 3000 mm from the extrusion tip, respectively. Surface observations were performed using an optical microscope (OM; Nikon ECLIPSE LV150N, Tokyo, Japan).

Tensile strength measurements were performed using a tensile-testing machine (Shimadzu Autograph AGS-X) with a load capacity of 10 kN. The loading method employed direct, high-precision constant-speed strain control using a backlashless precision ball-screw drive. During testing, the specimens were gripped using a fixed wedge-type gripper. Tensile loading was applied, and the stresses and strains at fracture were recorded. Tensile tests were conducted at room temperature at a crosshead speed of 1.0 mm/min and were repeated three times for each condition. The specimens were dumbbell-shaped type 14B specimens prepared in accordance with JIS Z2241. The parallel section length, width, and thickness were 24 mm, 1.5 mm, and 6.0 mm, respectively. After fracture, the fracture surfaces were examined using scanning electron microscopy (SEM; JEOL NeoScope™ JCM-700).

3 Experimental results

Figure 4 shows the extrusion force–ram stroke diagrams obtained at billet temperatures of 400 °C, 450 °C, and 500 °C with an extrusion speed of 0.5 mm/min, together with the die temperature during processing. At all billet temperatures, the extrusion force exhibited a two-stage increase. The first increase occurred as the billet passed through the port section of the pseudo-porthole die, whereas the second increase occurred after the billet entered the forming section. The maximum extrusion forces at billet temperatures of 400 °C, 450 °C, and 500 °C were 1263, 1059, and 1037 kN, respectively. The reduction in maximum extrusion force with increasing billet temperature reflects the decrease in deformation resistance at elevated temperatures.

The temperature evolution during processing showed approximately isothermal conditions during the first increase in extrusion force. During the second increase in force, gradual heating was observed, and as extrusion approached a steady state, the rate of temperature increase decreased. The maximum measured temperatures at billet temperatures of 400 °C, 450 °C, and 500 °C were 321.8 °C, 367.8 °C, and 392.6 °C, respectively.

The temperature remained nearly constant during the first force increase because the thermocouple was positioned in the die bearing section. During the second force increase, material deformation and formation occurred in the bearing region, resulting in observable heat generation. The temperature rise values were 62.9 °C at 400 °C, 70.8 °C at 450 °C, and 74.8 °C at 500 °C.

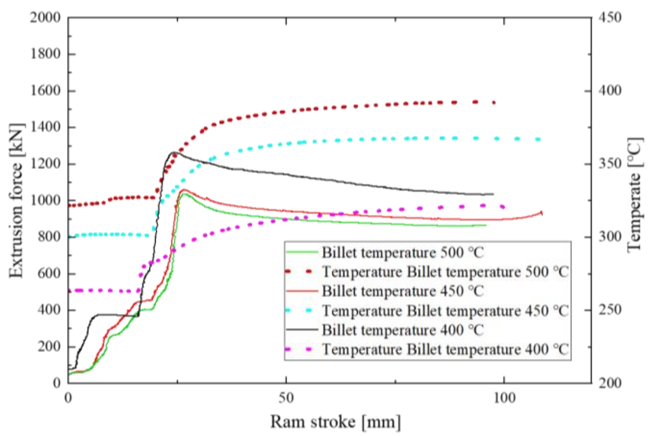


Figure 4: Extrusion force-ram stroke diagram in each billet temperatures (billet temperature of 400 ºC, 450 ºC, and 500 ºC, and ram speed of 0.5 mm/s)

Figure 5 shows the appearance of the extruded material at three positions along the extrudate—the head, middle, and end—for each billet temperature. At billet temperatures of 400 °C and 450 °C, surface defects were observed, indicating insufficient chip adhesion. At 400 °C, relatively large surface defects were present along the entire length of the extrudate. At both 400 °C and 450 °C, the defect size decreased progressively from the head toward the end of the extrudate. In contrast, at a billet temperature of 500 °C, no surface defects were observed at any position.

Figure 6 shows the nominal stress-nominal strain diagram comparing the results from the middle region of each condition. At a billet temperature of 400 °C, the tensile strength was 128.8 [MPa] and the elongation at break was 0.19 [-]. At a billet temperature of 450 °C, the tensile strength was 117.1 [MPa] and the elongation at break was 0.15 [-]. At a billet temperature of 500 °C, the tensile strength was 192.8 [MPa] and the elongation at break was 0.13 [-]. Increasing the billet temperature from 400 °C to 500 °C resulted in an approximately 43.1% increase in tensile strength. Conversely, elongation at break decreased as the billet temperature increased.

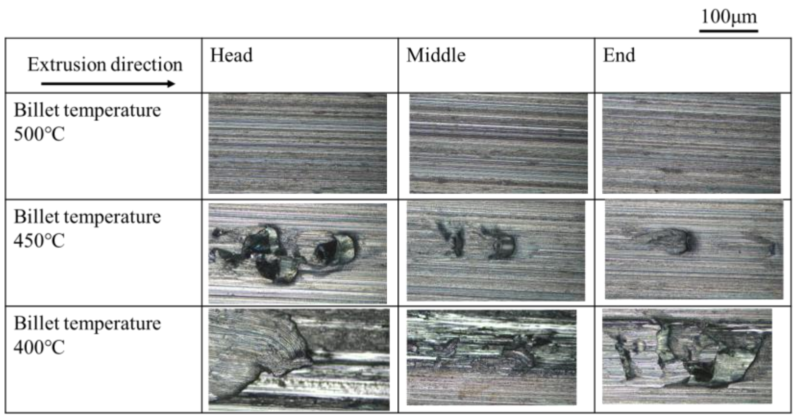


Figure 5: Appearance of extruded products fabricated from chip billets at different billet temperatures.

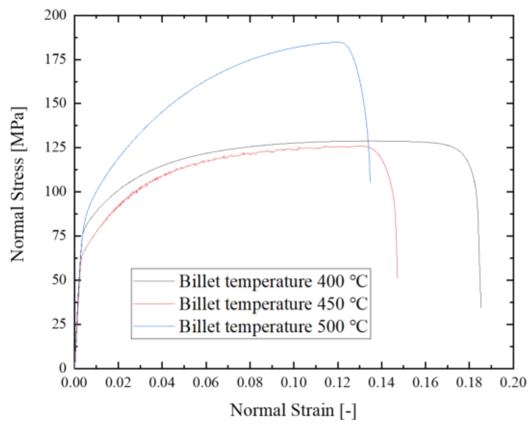


Figure 6: Comparison of nominal stress–nominal strain curves of extruded products at different billet temperatures.

Figure 7 shows the fracture surfaces of the tensile specimens corresponding to the results in Fig. 6. Under all conditions, the fracture surfaces exhibited ductile fracture features; however, numerous internal defects, likely voids, were also observed. At billet temperatures of 400 °C and 450 °C, voids with sizes ranging from approximately 50 µm to 150 µm were identified on the fracture surfaces. In contrast, at a billet temperature of 500 °C, the size of internal defects was less than 50 µm in all observed cases.

Regarding the effect of billet temperature on chip extrusion, an increase in billet temperature resulted in a lower maximum extrusion force and a greater temperature rise due to processing heat generation. As billet temperature increased, surface defect size decreased, and no surface defects were observed at the highest temperature. Higher billet temperatures also resulted in increased tensile strength and reduced ductility. Shamsudin et al. reported that, during extrusion of AA6061 chip material, higher processing temperatures promote grain coarsening and cause internal defects to become more compact (Shamsudin et al., 2017). Previous studies have also shown that increases in tensile strength with rising temperature occur as a trade-off with ductility, and the present results follow the same trend.

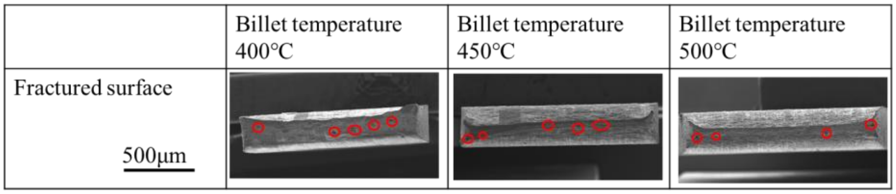


Figure 7: Fracture surfaces of extruded products obtained at different billet temperatures.

Close contact between chips requires disruption of the oxide film on chip surfaces to enable direct Al-to-Al bonding. Aluminum oxide films exhibit temperature-dependent structural changes; amorphous oxide films form at temperatures above 300 °C, leading to non-uniform thickness and subsequent crystallization (Wu et al., 2022). Increasing the temperature to 500 °C raises the proportion of magnesium oxides, such as MgO, within the oxide layer, making these oxides the dominant components (Jeurgens et al., 2002). Yu et al. reported the presence of MgO at chip boundaries during extrusion of AA6063 chip material. Strong shear deformation reduces oxide size and promotes fine dispersion of oxide particles (Yu et al., 2025). At a billet temperature of 500 °C, grain coarsening occurred and internal defects became denser, which increased the contact area between individual chips. Strong shear deformation induced by the porthole mechanism further reduced oxide size and enhanced inter-chip bonding, contributing to the increased temperature rise associated with processing heat generation. The same mechanism suppressed surface defects and increased tensile strength.

At billet temperatures of 400 °C and 450 °C, larger surface and internal defects were observed than at 500 °C, with defect size increasing as billet temperature decreased. Lower billet temperatures did not promote grain coarsening, which contributed to the formation of surface and internal defects in the extruded products. In contrast, surface defect density decreased from the head toward the end of the extrudate. As extrusion progressed, strain accumulation and processing heat generation increased due to flow diversion and compression within the container via the porthole mechanism, leading to a reduction in defect size. With respect to tensile properties, an increase in defect area fraction caused by larger defect size and higher defect density promotes crack initiation and propagation during post-yield plastic deformation, resulting in reduced tensile fracture properties and an increased tendency toward brittle fracture (Hangai et al., 2006). The differences in tensile properties observed under each condition in Fig. 6 therefore arise from reductions in tensile strength caused by crack propagation originating from coarse internal defects in the extruded products.

Despite these findings, several limitations of the present study should be acknowledged. The investigation was limited to AA6063 chip material and a fixed extrusion speed, and the mechanical evaluation focused primarily on tensile properties. In addition, defect suppression and inter-chip bonding were found to be strongly dependent on extrusion temperature, indicating that the processing window for achieving defect-free products remains constrained. Future studies addressing a wider range of alloys, processing speeds, and mechanical performance metrics would provide a more comprehensive understanding of solid-state recycling behavior.

4 Conclusion

1. At a billet temperature of 500 °C, the maximum extrusion force was the lowest, whereas the temperature rise due to processing heat generation was the greatest.
2. At billet temperatures of 400 °C and 450 °C, surface defects were observed on the extruded products. As extrusion progressed, the defect size decreased.
3. When the billet temperature increased from 400 °C to 500 °C, the tensile strength increased

by approximately 43.1%. In contrast, the elongation at break decreased with increasing billet temperature.

4. Fracture surface observations after tensile testing revealed coarse internal defects at billet temperatures of 400 °C and 450 °C.

These results demonstrate that extrusion temperature is a critical processing parameter for optimizing solid-state recycling of AA6063 chip waste. In particular, extrusion at 500 °C enables reduced forming loads, effective suppression of surface and internal defects, and enhanced mechanical performance, highlighting the potential of pseudo-porthole die extrusion as an energy-efficient alternative to conventional remelting-based recycling routes.

Acknowledgment

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