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Direct recycling of AA6063 chips by hot extrusion applying pseudo porthole die

FUNAZUKA Tatsuya[1,a *], YAMASHITA Syun[2,b], URAKAWA Takumi[2,c], SHIRATORI Tomomi[1,d], TAKATSUJI Norio[1,e], and DOHDA Kuniaki[3,f]

[1] Academic Assembly Faculty of Engineering, University of Toyama, Toyama, Japan

[2] Graduate School of Science and Engineering for Education, University of Toyama, Toyama, Japan

[3] Department of Mechanical Engineering, Northwestern University, Evanston, Illinois, USA

[a] funazuka@eng.u-toyama.ac.jp; [b] m22c1505@ems.u-toyama.ac.jp; [c] s2070414@ems.u-toyama.ac.jp; [d] shira@eng.u-toyama.ac.jp; [e] michinori0204@gmail.com; [f] dohda.kuni@northwestern.edu

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Abstract. To obtain recycled aluminum from sash waste with A6063 alloy, which is used for aluminum sashes, it is necessary to perform hot extrusion after a casting process. Impurities introduced during casting constitute a problem in this process, and recycling without casting is necessary to control the effects of these impurities. The purpose of this study is to develop a recycling method for aluminum alloys, which does not involve the casting process, using hot extrusion from scrap materials, such as the cutting chips of A6063 alloy. In the extrusion process of waste materials such as cutting chips, the chips should be kept in close contact. To achieve this, a pseudo porthole die that provides a large shear deformation is used as the die shape for the extrusion process. The chips were compression-filled in advance to determine the filling ratio, and then extruded using a pseudo porthole die. The use of a pseudo porthole die resulted in an extrusion force 1.5 times greater than that of a solid die. A simulation of the shear strain and observation of the stress imparted to the material by the pseudo porthole die revealed that the flow-diverting and crimping mechanisms inside the pseudo porthole die resulted in a large amount of stress on the material. No defects were observed on the extruded product surface of the chip material produced using the pseudo porthole die. Four types of chip materials with different densities were used to examine the effect of the chip material density. We found that defects did not occur on the surface of the product when the density of the chip material was 2.5 g/cm^3 or higher.

Introduction

Aluminum (Al) is one of the most widely used metal materials worldwide and is expected that its use would continue to increase in the future owing to its light weight and high workability [1]. Until now, Al-elongated materials have mainly been applied to residential building materials such as aluminum sashes; however, they are now being actively used in transportation equipment such as automobiles and aircraft to replace steel materials owing to their lightweight property [2, 3].

A major drawback of Al production is that a large amount of energy is required to extract Al from alumina [4]. However, Al is highly recyclable, and the use of recycled Al can reduce energy consumption by 95% [5]. Existing Al recycling technologies include remelting and refining. In the case of recycling by remelting, the removal and detoxification of impurities during casting are major issues, and research is being conducted on how to adjust the material composition and control casting defects [6]. In the case of recycling expanded materials with high Al purity such as aluminum sashes, there are many cases in which the materials are recycled into low-purity casting materials by remelting (cascade recycling). The total amount of horizontally recycled aluminum sash in Japan is only 10% [7]. It has been reported that a further reduction in energy consumption can be achieved if recycling is possible by extrusion or forging only without casting [8].

To eliminate the casting process, the products should be obtained from the chip material after crushing by solidification compaction only. Extrusion is a material processing method used for the solidification and formation of chip materials [9-11]. Despite the demands in the industry, this method has not yet been realized.

The author conducted research on Al product surface defects, such as pickup defects, during the extrusion of sash materials [12]. In general, a porthole die is used to extrude hollow materials with complex shapes, such as sash materials, from solid billets. To obtain a hollow material, a porthole die enables the formation of complex shapes by means of a port section that diverts the material and a chamber section that crimps the material. In this study, a pseudo porthole die is proposed to reproduce "pseudo" porthole extrusion, and the generation mechanism of blistering defects is determined after reproducing the flow-diverting and crimping behavior. This study also demonstrated that the material inside the pseudo porthole die underwent strong shear deformation owing to flow-diverting and crimping behaviors, resulting in grain size reduction. Tekkaya et al. reported that the use of a porthole die can solve the technical problems of chip extrusion, which have been considered difficult for industrial implementation due to problems of material adhesion and internal defects in the product [13-15]. This is because a porthole die applies high shear stress to the material, which destroys the oxide film of Al and increases its adhesion strength. The increase in the adhesion strength also improves the bonding strength and surface quality of the material. However, no detailed study has been conducted on the density of the chip material. Although previous studies concluded that a larger density is better, these existing studies reported different values. In addition, there were only a few cases in which the density was varied significantly and its limiting values were investigated.

In this study, AA6063 chips were hot-extruded using a pseudo porthole die to achieve direct horizontal recycling of sash material. The chip material was fabricated by turning AA6063 ingots and compressing them into billets for extrusion. Extrusion experiments were conducted by quantitatively varying the density of the chip material and the strength of compression forming. The effects of extrusion formability and chip density on the surface properties of the product were evaluated by applying a pseudo porthole die.

Experimental Methods

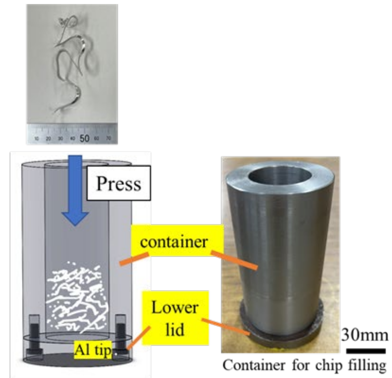
In this study, AA6063 was used as the chip material. Table 1 lists the chemical composition of the AA6063 used in this study.

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.

The chips were extracted by turning a cast AA6063 billet into a billet of chip material. The cutting conditions were a depth of cut of 0.5 mm and rotation speed of 920 rpm, and chips with a width of approximately 2 mm were extracted. The chips were compacted and preformed on a 30 t Amsler-type universal testing machine with a load of 3 t, as shown in Fig. 1 (a). The chips were inserted into the container, and a preformed chip billet with a diameter of 38.5 mm and length of 80 mm was formed.

(a)

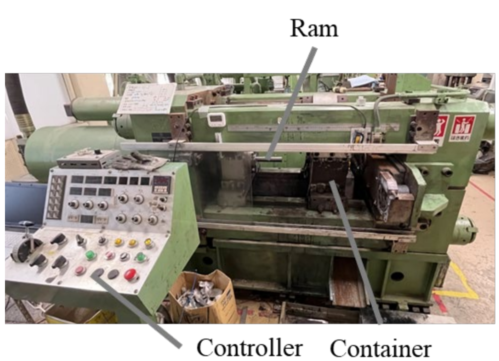


(b)

Fig. 1 (a) 30 t Amsler-type universal testing machine, (b) Schematic diagram of pre-solidification compacting

After pre-solidification and formation, the billets were solidified and formed in a 200 horizontal hydraulic extrusion press, as shown in Fig. 2 (a). A cartridge heater and thermocouple were mounted inside the container, and the billet temperature and ram speed were controlled using a controller. The extrusion force during the 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. The solidification-forming die shown in Fig. 2 (b) was used for solidification forming. The solidification forming conditions are listed in Table 2. The ram speed was 0.5 mm/s. To change the density of the solidified compact, the billet and die temperatures were set to 25 °C, 100 °C, and 200 °C, and the load values were 15 t, 50 t, and 100 t. The obtained solidified and molded billets were sampled with a diameter of 41.5 mm and a length of approximately 30 mm considering the container diameter during the extrusion experiment.

In this study, a 200 horizontal hydraulic extrusion press was also used for the hot extrusion experiments, as shown in Fig. 2 (a). A solid die, shown in Fig. 3 (a), and a pseudoporthole die, shown in Fig. 3 (b), were used in the extrusion experiments [12]. To reproduce the joining process in the chamber section in an easy-to-understand manner, the pseudo porthole die developed in this study was simplified by eliminating the mandrel portion that formed the hollow section of the general purpose porthole die and designed to reproduce only the flow-diverting and joining processes inside the die. The port length of the pseudo porthole die was 25 mm and the thickness of the port section was 6 mm. The inner diameter of the port and chamber section was φ25 mm and the length of the chamber section was 20 mm. The shape of the extruded profile was a solid plate with a width of 18.6 mm and a thickness of 1.5 mm, as shown in Fig. 3 (c).



(a)

(b)

Fig. 2 (a) 200 t horizontal extrusion machine, (b) Compacting die

The experimental conditions for the extrusion are listed in Table 2. The extrusion temperature was 500 °C and the ram speed was 0.5 mm. The billet dimensions were φ41.5 mm and length of 90 mm, which was obtained by stacking three solidified and molded billets, as shown in Fig. 2. The billet material was AA6063 solid billet (virgin material) and AA6063 chip billet under four conditions, and the die configuration was a solid die (Fig. 3 (a)) and a pseudo porthole die (Fig. 3 (b)).

The surface defects at the head, middle, and end of the extrudate obtained in the extrusion experiments were observed. An optical microscope (Optical microscope, OM; Nikon ECLIPSE LV150N) was used to observe the surface of the extrudate.

Table 2 Compacting and extrusion conditions

Compacting condition	
Billet material	AA6063
Billet temperature [°C]	25, 100, 200
Die temperature [°C]	25, 100, 200
Ram speed [mm/s]	0.5
Die shape	Compacting die
Compacting force [t]	15, 50, 100
Extrusion condition	
Billet material	AA6063 solid (virgin material) AA6063 chip
Extrusion temperature (billet and die) [°C]	500
Ram speed [mm/s]	0.5
Die structure	Solid die Pseudo porthole die

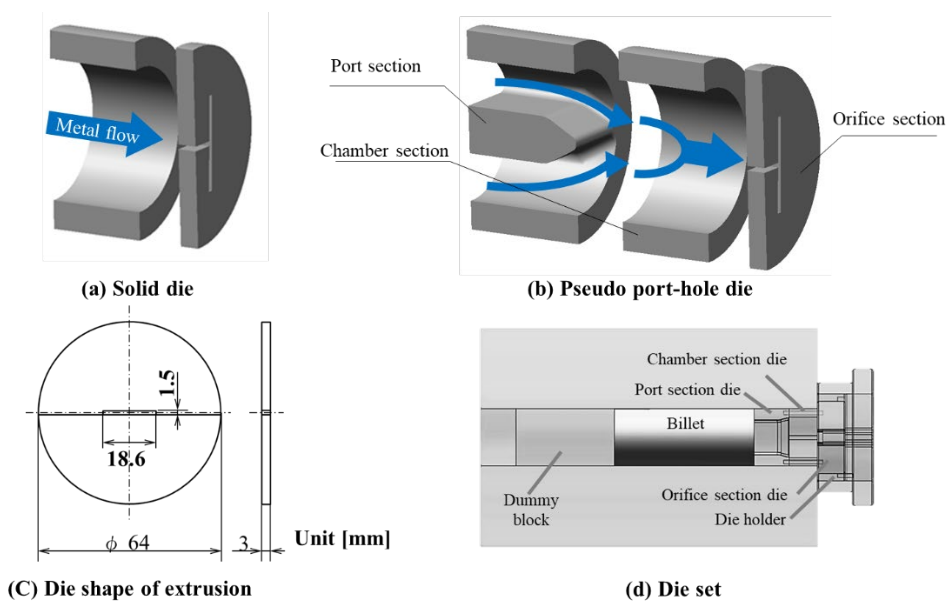


Fig. 3 Schematic diagram of the die and die set used in the hot extrusion experiments [12]

The conditions for the hot extrusion simulations are listed in Table 3. DEFORM-3D was used as the simulation software and the Lagrangian simulation method was used. The material used was AA6063 and the shear friction coefficient was derived from a friction test developed for hot plastic forming based on a previous study [16]. Because the internal structure of the die was symmetrical, the billet and die set in the simulation were modeled as one-quarter models. During the hot extrusion simulation, we observed the stresses applied to the material in the solid die and pseudo porthole die.

Table 3 Simulation conditions

Analysis method	Lagrangian
Billet material data	AA6063
Billet temperature [°C]	500
Number of elements	100000
Ram speed [mm/s]	0.5
Share friction coefficient *m*	1.0
Heat transfer coefficient [N·mm/(s·°C)]	11
Die structure	Solid die Pseudo porthole die

Experimental Results

Fig. 4 shows the solidified compacts compacted at room temperature (25 °C) and 15 t (density: 1.640 g/cm^3), at 100 °C and 50 t (density: 2.151 g/cm^3), at 100 °C and 100 t (density: 2.466 g/cm^3), and at 200 °C and 100 t (density: 2.607 g/cm^3). The solidified compacts were compacted at 100 °C and 100 t (density: 2.466 g/cm^3) and at 200 °C and 100 t (density: 2.607 g/cm^3). The density of Al (2.7 g/cm^3) approached that of Al at higher compressive temperatures and forces.

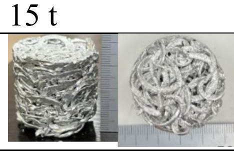
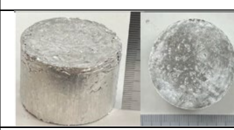
Compression conditions	Room Temperature (R.T.) 15 t	100 ℃ 50 t	100 ℃ 100 t	200 ℃ 100 t
Appearance				
Density [g/cm^3]	1.640	2.151	2.466	2.607

Fig. 4 Solidified compacts at each compression condition

Hot extrusion experiments were conducted using AA6063 chip billets and chip billets (density: 2.607 g/cm^3) to determine the extrudability of the solid die and pseudo porthole die. The extrudability was determined by examining the extrusion force and appearance of the extruded product. In the extrudate appearance investigation, we determined the presence or absence of defects on the surface of the chip material and the size of the defects.

Fig. 5 shows the extrusion force–ram stroke curve for the hot extrusion of a chip billet (density: 2.607 g/cm^3) and a solid billet. The maximum extrusion force was 94.7 t using the pseudo porthole die, which is approximately 1.5 times that of the solid die. In the case of extrusion using the pseudo porthole die, the extrusion force increased in two stages, and it is considered that the billet passed through the port section at the first increase in force and passed through the forming section after the second increase in force. No large force difference was observed between the pseudo porthole die and the solid die for the chip and solid billets.

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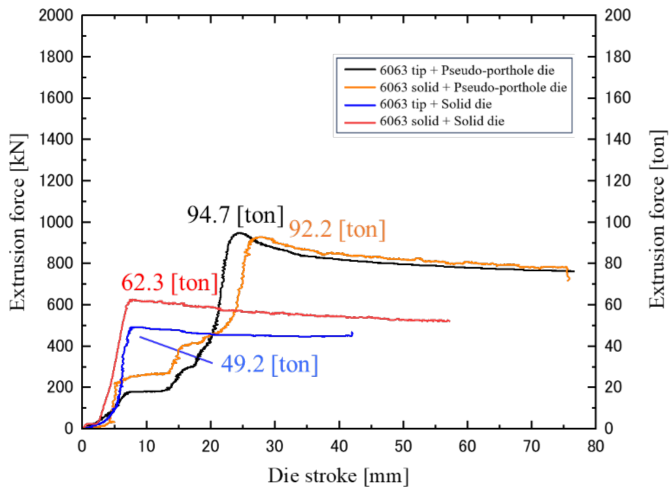

Fig. 5 Extrusion force–ram stroke curve
(Extrusion temperature: 500 ℃, ram speed: 0.5 mm/s)

Fig. 6 shows the appearance of the products extruded from the chip billets (density: 2.607 g/cm^3) using a solid die and a pseudo porthole die. It was confirmed that the material extruded for the solid die had defects on its surface, which were similar in shape to voids, whereas no defects were observed for the pseudo porthole die. For the solid die, the bonding strength of each chip was weak, and large defects were generated on the surface because the poorly bonded parts were extruded as they were. However, the complex plastic flow (flow separation and crimping) for the pseudo porthole die increased the adhesiveness of the chip materials, and the defects caused by poor adhesiveness were suppressed.

Fig. 6 Appearance of extruded product using chip material (density: 2.607 g/cm3) in pseudo porthole die and solid die

Fig. 7 shows the equivalent stresses obtained from the extrusion analysis using a solid die and a pseudo porthole die. The solid die exhibited high stress only near the die-forming area, similar to the study by Tekkaya et al., whereas the pseudo porthole die exhibited high strain throughout the material from the port to the chamber area, confirming the effect of complex plastic flow [13, 14]. In the case of a pseudo porthole die, strong shear deformation can be applied over a wide range inside the die structure, which increases the bond strength of each chip and prevents the extruded material surface from forming, as shown in Fig. 6.

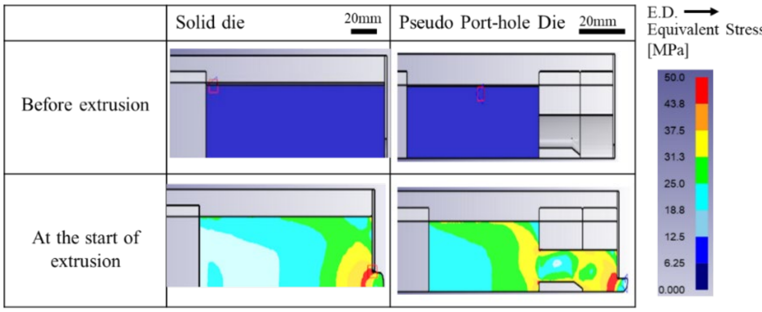

Fig. 7 Equivalent stresses inside a solid die and a pseudo porthole die

Fig. 8 shows the extrusion force–ram stroke curve for the chip billet shown in Fig. 4 using a pseudo porthole die. The maximum extrusion force was 93.9 t for chip billets (density: 1.640 g/cm^3), 79.5 t for chip billets (density: 2.151 g/cm^3), 78.7 t for chip billets (density: 2.466 g/cm^3), and 92.8 t for chip billets (density: 2.607 g/cm^3). The maximum extrusion force was 78.7 t for the billet length. Although the maximum extrusion force is significantly affected by the length of the billet, it is approximately the same and all the extrusion force curves had a similar shape.

Fig. 9 shows the appearance of the extruded product for each chip billet. Chip billets (density: 2.466 g/cm^3) and chip billets (density: 2.607 g/cm^3) had no defects on the product surface, resulting in a beautiful, defect-free product. Chip billets (density: 2.151 g/cm^3) had surface defects in the first half of the extrusion (Head), and chip billets (density: 1.640 g/cm^3) had surface defects from the first half (Head) to the middle of the extrusion (Middle). This indicates that as the density of the chip billet approached that of Al (density: 2.7 g/cm^3), no surface defects were observed on the product. In addition, for all billet densities, no product surface defects were observed in the latter half (end) of the extrusion process. For low-density chip billets, large product surface defects occurred in the first half of the extrusion (Head), and the size of the defects decreased in the middle of the extrusion (Middle). In the case of extrusion with a chip billet, the amount of strain due to shear deformation in the container and inside the pseudo porthole die increased as the ram stroke progressed, which increased the adhesion strength of the chip during forming, decreased the size of the product surface defects, and suppressed the defects toward the end of the extrusion process.

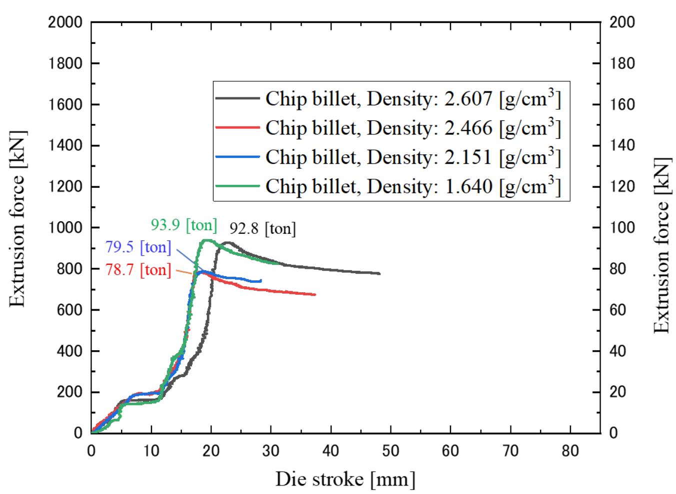

Fig. 8 Extrusion force–ram stroke curve in each chip billet
(Extrusion temperature: 500 ℃, ram speed: 0.5 mm/s, die structure: pseudo porthole die)

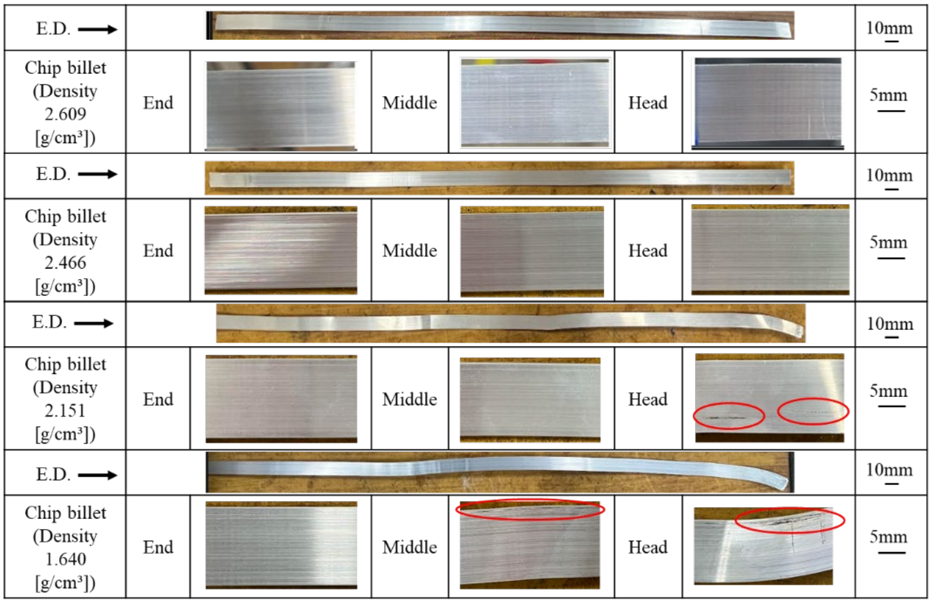

Fig. 9 Appearance of extruded product with chip billets of various densities

Conclusions

The following conclusions are drawn based on the hot extrusion, extrusion simulation, and surface observation of AA6063 chip material using a solid die and a pseudo porthole die.

1) Chip materials can be solidified to a density close to that of AA6063 by pressing at 200 °C and 100 t.
2) In the case of extrusion using a pseudo porthole die, the extrusion force was approximately 1.5 times higher than that using a solid die.
3) A higher strain was generated in the material using the pseudo porthole die than in the material using the solid die.
4) In the hot extrusion process of chip billets, the use of a pseudo porthole die suppressed the defects on the surface of the product, which occurs when a solid die is used.
5) When the density of chip billets approached that of AA6063, extruded materials without surface defects were obtained.
6) For a low density chip billets, product surface defects occurred until the middle stage of the extrusion; however, no product surface defects occurred in the latter half of the extrusion.

Future research will focus on evaluating the mechanical properties of the extruded chip billets for each density and internal porosity defects such as blister tests. In addition, the port shape of the pseudo porthole die will be varied to determine the relationship between the amount of shear strain applied to the interior and the billet density.

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