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Effect of application of pseudo-porthole die in hot extrusion of AA6063 chips for direct recycling on mechanical properties of products

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Abstract. This paper's objective was to investigate the influences of the pseudo-porthole die on the mechanical properties and surface quality of hot extrusion using recycled aluminum chips. Two types of AA6063 billets (cast and chip) and two designs of nitrided SKD61 dies (solid and pseudo-porthole) were considered. The tensile tests were carried out to evaluate the mechanical properties of the extruded profiles at three locations (Head, Middle, and Tail). The optical microscope was used to examine the extruded profiles' surface characteristics and fracture surfaces. The results showed that the pseudo-porthole die improved the chip billet's density (reducing porosity). Although the extrusion forces were higher, the pseudo-porthole die enhanced the mechanical properties (increased elongations) and surface quality (reduced lumps or pickups).

Introduction

Aluminum is infinitely recyclable, requiring only 5% of the energy needed for primary production. Direct recycling methods (eliminating pre-processing by directly converting aluminum chips into final products) are the most efficient in energy use and waste reduction, balancing environmental benefits and economic feasibility [1]. Key processing methods (solid-state, semi-solid, and melt-based) with direct re-use of machining chips offer potential savings over traditional recycling routes and reduce energy costs and material waste. Nevertheless, morphology and composition problems (e.g., chip size, shape, and contamination) are encountered in these processes [2]. In solid-state recycling of aluminum chips, product quality is highly influenced by process parameters (i.e., temperature, compaction force, chip size) [3-4]. A direct conversion technique using aluminum scrap, pre-treatment, compaction, mechanical deformation, and thermal process produces high-quality recycled material with superior mechanical and physical properties [5]. The method of converting aluminum chips into sheets shows that rolling and annealing significantly enhance the sheets' weld quality and mechanical properties [6].

Hot extrusion is one of the viable, energy-efficient techniques for recycling aluminum chips [7]. Aluminum chips are compacted into billets and directly extruded without remelting, saving energy and reducing material losses [8]. Chip contamination, oxide layers, air inclusions, and process parameters (billet density, homogenization, temperature, ram speed) impact profile quality

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[9]. Porthole and semi-porthole dies are crucial tooling options in aluminum extrusion, each catering to distinct profile requirements. Porthole dies utilize multiple ports to divide the aluminum flow before it recombines within a weld chamber, enabling the complex hollow profiles with seamless or near-seamless structures. These dies are favored for structural applications demanding consistent wall thickness and robust integrity that offering advantages in extrusion speed and cost-effectiveness for high-volume production. However, they may not be suitable for all shapes and can exhibit slight weld lines and require higher extrusion forces due to higher friction and deformation [10]. Semi-porthole dies, conversely, feature a partially enclosed void with a gap, representing a hybrid between solid and hollow dies. This design makes them versatile for profiles with partially enclosed voids, potentially offering a more economical solution than full hollow dies for specific geometries. The study finds that achieving a higher density in the chip material is crucial for minimizing surface defects in the extruded product [11]. However, the complexity of the achievable void is limited can present a potential structural weakness. The selection between porthole and semi-porthole dies hinges on the desired profile's complexity, structural needs, production volume, and cost considerations. In the hot extrusion of Al-Mg-Si alloys, the high Mg content and its interaction with oxygen significantly contribute to pick-up defects [12]. Direct recycling of aluminum chips through extrusion is a viable and environmentally friendly approach to aluminum recycling. It offers a pathway to a more circular economy for aluminum, reducing reliance on primary production and minimizing environmental impact [13].

It is not yet well understood how internal and surface defects occur when aluminum chips are directly recycled through hot extrusion. To understand such defects, this paper investigated extruded aluminum profiles' mechanical properties and surface characteristics. The hot extrusion experiment considered two types of AA6063 billets (cast and recycled chips) and two extrusion die designs (solid and pseudo-porthole). The tensile test and microstructure analysis evaluated the quality of the extruded profiles at different locations.

Materials and methods

The direct recycling (DR) method of solid-state recycling (SSR) of aluminum chips by hot extrusion was investigated (Fig. 1). The 200-ton horizontal extrusion machine (Fig. 1(a)) was used to form cylindrical billets into the final shape plastically. The billet material was AA6063, which was produced by casting. The cast billet (virgin material) was then machined to make two types of billet specimens. The first type was prepared by a lathe-turning machine to have 42 mm in diameter and 90 mm in length (Fig. 1(b)). The second type was prepared by selecting the two mm-thick chips from the previous lathe-turning process and compressing them (100-ton pressure) with heat (200°C) to have 42 mm in diameter and 30 mm in length (Fig. 1(c)) [11]. Three pieces of chip billets were used in the experiments to obtain the same billet length (90 mm) as that of the first type. The densities of the cast billet and chip billet were 2.700 g/cm3 and 2.607 g/cm3, respectively. Two die designs were considered: solid die (Fig. 1(d)) and pseudo porthole die (Fig. 1(e)). The main difference between these two designs was adding a port section in the pseudo-porthole die. The extrusion profile was rectangular (1.5 mm x 18.6 mm), giving an extrusion ratio of 49. The material of the toolset was SKD61, which was surface-treated with nitriding. Before the extrusion experiments, the billets were cleaned with acetone and then pre-heated to 500°C, and the die temperature was set to 500°C. All the extrusion tests were carried out at 0.5 mm/s ram speed, and the extruded profiles were cooled by air.

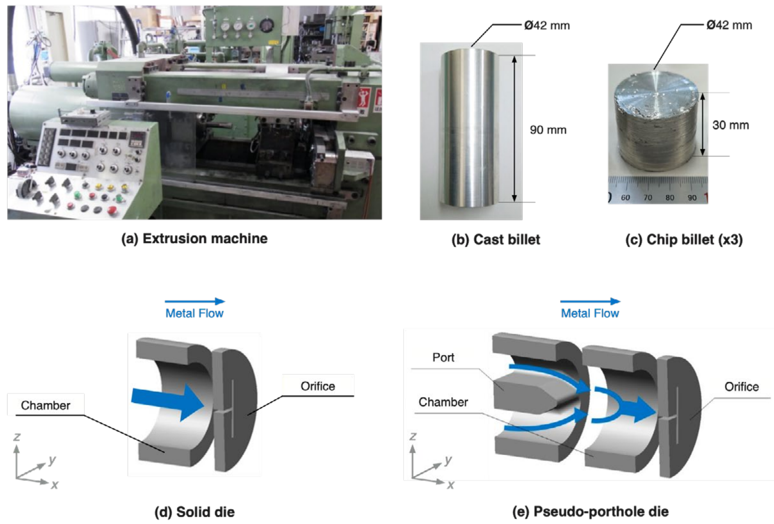

Figure 1 – Hot extrusion experimental setup.

Table 1 shows the considered extrusion tests. Three repeated tests were carried out for each condition.

Table 1 – Considered extrusion conditions.

Conditions	Die Type	Billet Type
A	Solid Die	Cast Billet
B	Solid Die	Chip Billet
C	Pseudo-Porthole Die	Cast Billet
D	Pseudo-Porthole Die	Chip Billet

The extruded profiles were investigated at three locations of interest (Fig. 2): Head (I), Middle (II), and Tail (III). The optical microscope (Nikon ECLIPSE LV150N) was used to investigate the surface of these areas. The mechanical properties of the extruded profiles at these locations were analyzed using the tensile test according to the Japanese Industrial Standard (JIS Z 2241). From Fig.3 (b) The tensile test specimens from the middle zone of extruded product were prepared by wire cutting and tested using the 10-kN universal testing machine (SHIMADZU, Autograph AGS-X Series) at 1.0 mm/min at room temperature (25°C). The fractured specimens' cross sections (SEC A-A) were also investigated using the optical microscope in the three areas of interest (left, central, and right zones).

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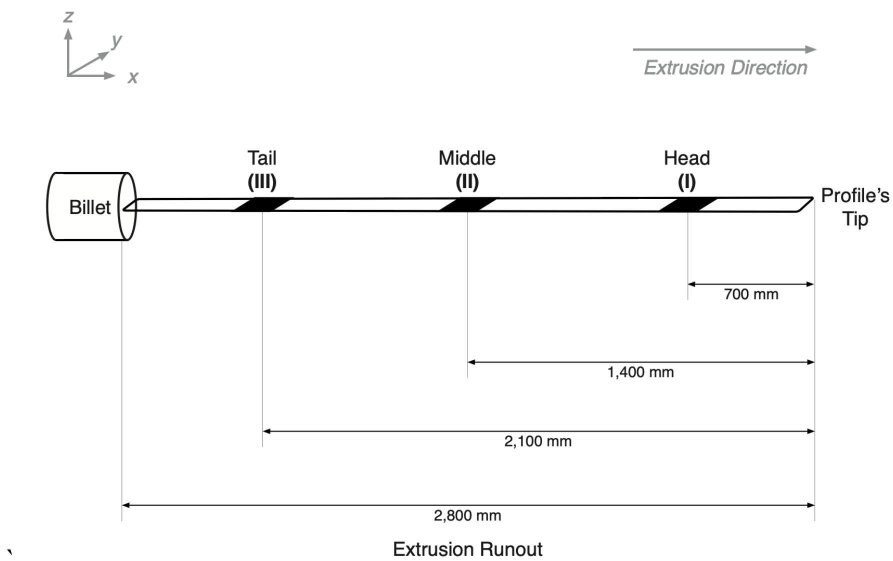

Figure 2 – Measurement locations of the extruded profiles

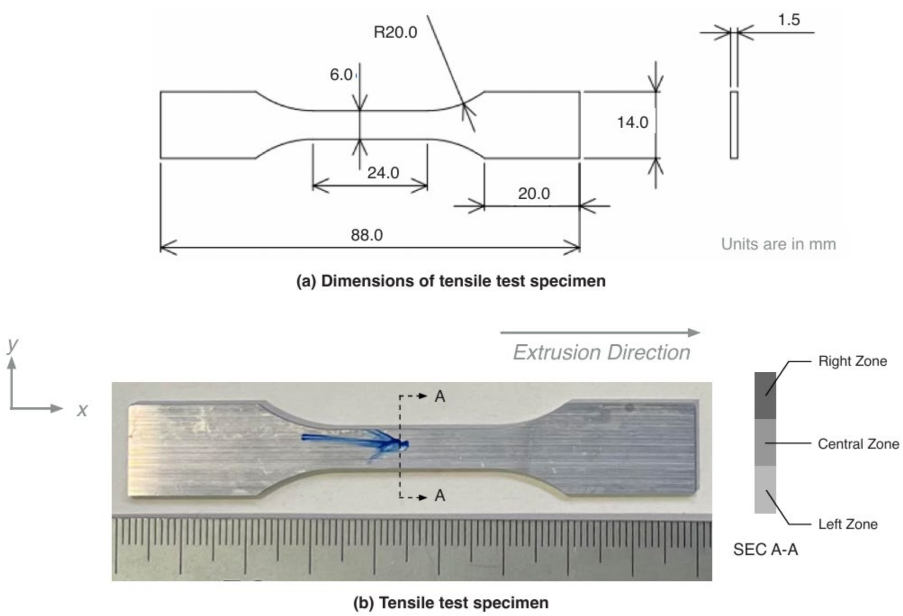

Figure 3 – Tensile test specimen

Results and discussions

The average extrusion test results (from three repeated tests for each condition) are displayed in Fig. 4. The maximum extrusion forces of the pseudo-porthole die (C and D) were approximately 1.5 to 2.0 times higher than those of the solid die (A and B). In the pseudo-porthole die conditions, the billet materials were broken into two equal parts in the z-direction of the port section. This led to increased material flow resistance before entering the chamber section. The resistance was further increased when the material was forced to exit the orifice from the chamber section, giving the two-step increased loads. The first step was from 0.0 to 15.0 mm strokes, and the second was after the 15.0 mm strokes. On the contrary, the solid die had no material flow barrier (port), resulting in only a one-step load with less extrusion forces.

In the solid die tests, the extrusion force of the cast billet (A) was 26.0% higher than that of the chip billet (B). The chip billet's density was 9.3% less than the cast billet's, requiring less extrusion force. However, the pseudo-porthole die increased the billet's density to that of the cast billet, leading to similar extrusion force values (C and D). Thus, the port section's compression mechanism effectively made the chip billets more dense.

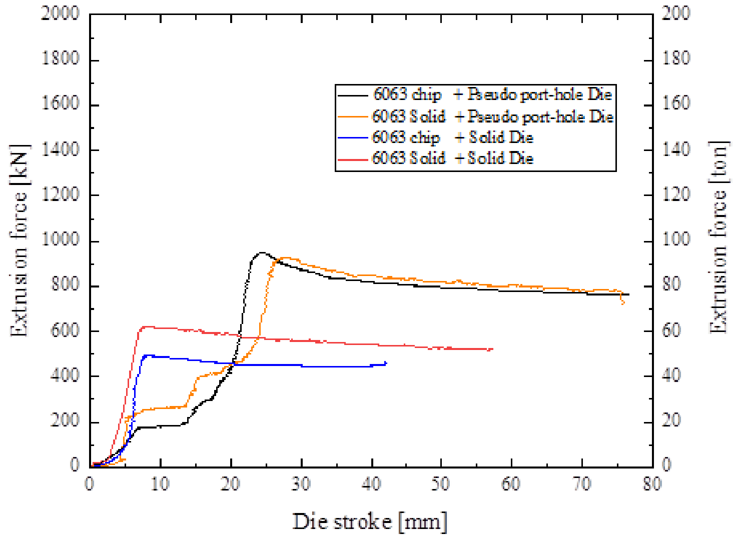

Figure 4 – Extrusion force vs. stroke curves

Fig. 5 shows the surface characteristics of the extruded profiles. Surface defects (lumps or pickups) could be observed in the solid die testing chip billets (B). The chip billets' porosity (voids) and non-smooth surfaces (saw-like features) significantly influenced such defects (Fig. 6). This indicated that the bonding of the chip billets was not poorly bonded throughout. Nevertheless, no surface defects were observed using cast billets and pseudo-porthole die (A, C, and D). The pseudo-porthole die's compression mechanism assisted in bonding the chip billets, reducing the porosity and increasing the density close to the cast billets.

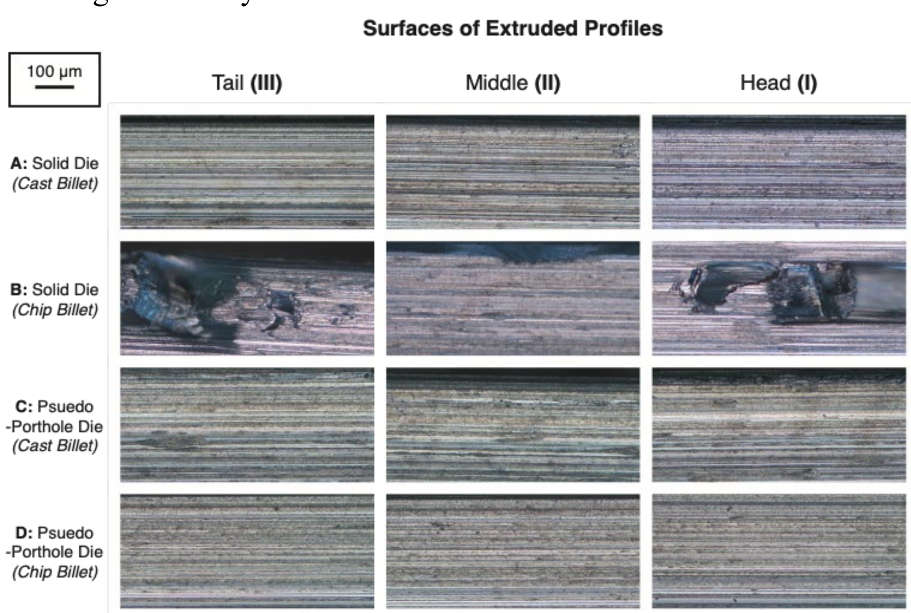

Figure 5 – Surface characteristics of the extruded profiles

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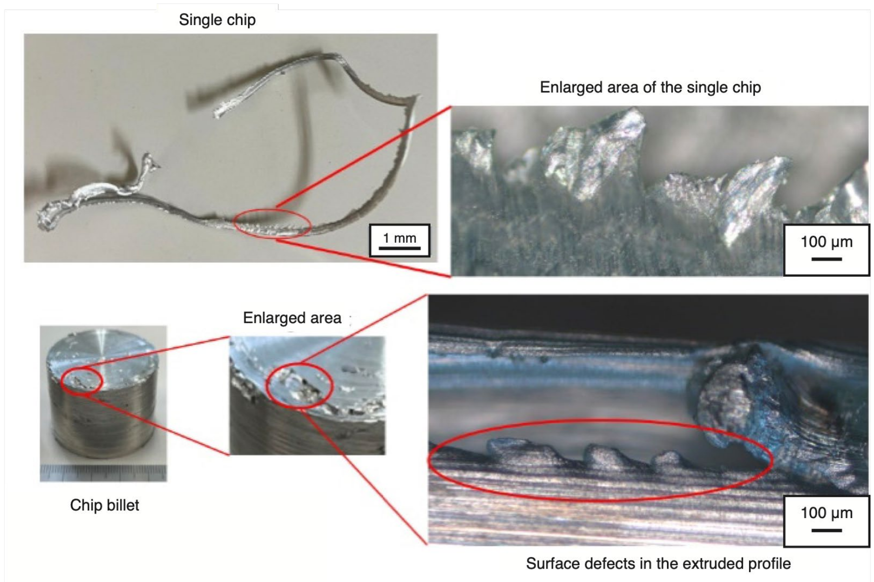

Figure 6 – Influence of chip billet's porosity on the surface defects of the extruded profiles

Fig. 7 shows the mechanical properties of the extruded profiles. It presents the average values of the stress-strain curves from three repeated tests of each condition. Cast billets (A and C) provided approximately 8-15% higher strengths and 3-7% strains than chip billets (B and D). The pseudo-porthole die (C) increased by approximately 4% in strengths and 10% strains compared to using the solid die (A) for cast billets. The tensile strength was highest when the pseudo porthole die was used with the solid material, followed by the solid die with the solid material, and the chip material tended to be lower than the solid material for each die. This shows that the tensile strength tends to be higher in extrusion products using solid material, and that the effect of differences in die structure is small, however, the pseudo-porthole die (D) had approximately 2% lower strengths but 13% higher strains than the solid die (B) for chip billets. Furthermore from Fig. 7 the breaking elongation was highest when the solid material and the pseudo porthole die were used, The next highest score was achieved by using a pseudo porthole die with chip material, and the lowest was achieved by using a solid die with chip material. In this case we are using welded of three small chip billets, there may be deviations in terms of some mechanical properties.

Fig. 8 shows the cross-sections of the tensile test specimens at their fractured locations. Under these conditions, a typical ductile fracture was observed. Using a solid die and chip billets (B), noticeable voids and dimples appeared. The pseudo-porthole die (D) minimized the chip billets ' internal voids (porosity).

The pseudo-porthole die could minimize surface defects (lumps or pickups) and internal defects (voids). Although the port section increased the extrusion forces, the compression mechanism helped fuse chip billets' bonds and reduce porosity. The pseudo-porthole die increased the chip billet's density and effectively improved its mechanical properties (higher elongation) and surface quality (reduced pickups).

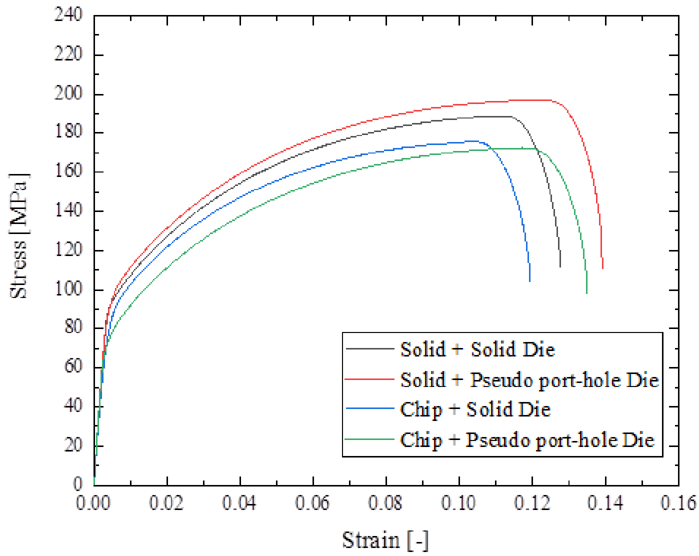

Figure 7 Stress-strain curves of the tested conditions

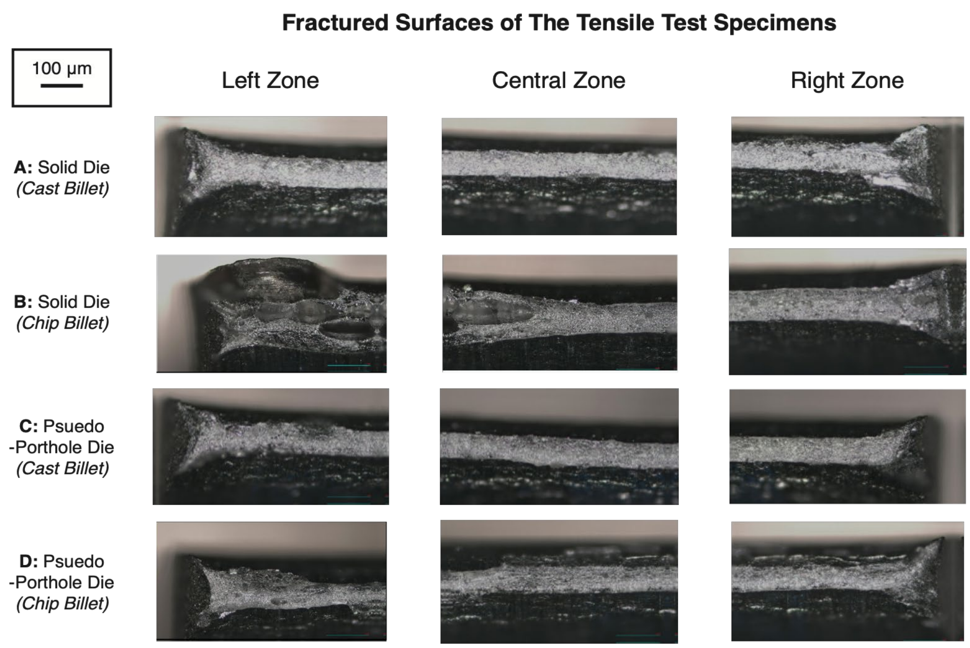

Figure 8 – Cross-sections of the tensile test specimens at their fractured locations

Conclusions

The hot extrusion experiments of cast and chip billets using solid and pseudo-porthole dies were investigated. The surface characteristics and mechanical properties of the extruded profiles were examined. The results showed that the pseudo-porthole die improved the chip billet's density by reducing the porosity through the compression mechanism. This type of die design also reduced the surface defects (lumps or pickups) and internal defects (voids). High elongations of the extruded profiles could also be achieved by using the pseudo-porthole die.

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