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Tribological Considerations of Recycled Aluminum Chips in Strain-Gradient Solid-State Consolidations

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Abstract

Solid-state recycling has emerged as an energy-efficient alternative to conventional remelting for aluminum scrap; however, its effectiveness depends on achieving sufficient metallurgical bonding between oxide-covered aluminum chips during consolidation. In this study, AA6063 aluminum chips were consolidated using a multi-stage billet packing technique followed by hot extrusion through a modular die system incorporating normal and strain gradient feeder geometries. The consolidated products were evaluated by optical microscopy and tensile testing to investigate the influence of material flow on consolidation behavior. Microstructural observations showed that hot extrusion effectively eliminated most of the large packing voids, although localized oxide-rich interfaces and residual chip boundaries remained within the recycled material. Tensile testing demonstrated that the recycled chip billet achieved an ultimate tensile strength comparable to that of a conventional cast billet while exhibiting a higher yield strength, indicating effective solid-state bonding during extrusion. The observed microstructural evolution and mechanical response were interpreted from a tribological perspective, highlighting the role of friction and interfacial shear in oxide fragmentation and chip-to-chip bonding. The proposed strain-gradient feeder provides a practical approach for enhancing localized deformation and offers a promising die-design strategy for improving the consolidation efficiency and performance of solid-state recycled aluminum.

1 Introduction

Aluminum alloys are among the most widely used engineering materials owing to their low density, excellent corrosion resistance, and high specific strength, making them indispensable in the automotive, aerospace, transportation, and construction industries. The continuous growth in aluminum consumption has consequently resulted in increasing quantities of post-industrial machining waste and end-of-life scrap, emphasizing the need for efficient and sustainable recycling technologies. Conventional secondary aluminum recycling through remelting requires only a fraction of the energy consumed during primary aluminum production from bauxite; however, the process still involves significant energy consumption, oxidation losses, and dross formation, leading to reduced material recovery and additional environmental impacts (Boin & Bertram, 2005; Duflou et al., 2015). To address these limitations, solid-state recycling has emerged as a promising alternative by eliminating the melting stage and directly consolidating aluminum chips into dense bulk materials through plastic deformation at elevated temperatures below the melting point. This approach not only improves material recovery but also reduces energy consumption while preserving the intrinsic properties of the aluminum alloy (Wan et al., 2017a).

Despite these advantages, successful solid-state recycling remains fundamentally dependent on achieving effective metallurgical bonding between individual aluminum chips. Freshly machined aluminum surfaces rapidly develop a thin but stable oxide layer, which acts as a physical barrier that prevents direct metallic contact during consolidation. Consequently, simply applying compressive loading is insufficient to produce fully consolidated products. Instead, the recycling process must generate adequate plastic deformation to fracture the surface oxide films, expose fresh aluminum surfaces, and establish intimate metal-to-metal contact under elevated temperature and pressure. (J. Z. Gronostajski et al., 1997; Laurent-Brocq et al., 2023; Shamsudin et al., 2016) Therefore, controlling the deformation behavior during consolidation is one of the most critical factors governing the quality of solid-state recycled aluminum products.

Numerous studies have demonstrated that increasing extrusion ratio or imposing severe plastic deformation can significantly improve chip bonding by promoting oxide fragmentation and pore closure while simultaneously refining the microstructure of recycled aluminum (Abd El Aal et al., 2018; Wan et al., 2017b). However, most previous investigations have primarily focused on processing parameters such as extrusion ratio, temperature, and ram speed, whereas comparatively limited attention has been devoted to tailoring the material flow through extrusion tool design. Introducing localized strain gradients within the feeder region provides an alternative approach for enhancing chip consolidation by increasing interfacial shear deformation before the material enters the extrusion die. From a tribological perspective, friction and interfacial shear developed at both chip to chip and chip to die interfaces play a fundamental role in disrupting oxide layers, promoting fresh surface exposure, and facilitating solid-state bonding. Consequently, the tribological conditions generated during extrusion directly influence the evolution of residual interfaces, defect distribution, and the resulting mechanical performance of the consolidated material (Su et al., 2023).

Although the importance of severe plastic deformation in solid-state recycling has been widely recognized, comparatively few studies have investigated how feeder-induced gradients influence chip consolidation while simultaneously considering the tribological mechanisms governing oxide fragmentation and interfacial bonding. Especially the role of feeder geometry in controlling localized deformation and material flow remains relatively unexplored.

To address these gaps, this study proposes an integrated solid-state recycling approach consisting of a multi-stage billet packing technique followed by hot extrusion using a modular die system equipped with interchangeable normal and strain-gradient feeders. The modular design enables direct comparison between different material flow conditions while providing a practical platform for future optimization of extrusion geometry. Recycled AA6063 aluminum chips and cast billets were processed under comparable conditions and characterized through optical microscopy and tensile testing to evaluate consolidation quality and mechanical performance. Rather than evaluating the process solely from a deformation perspective, the observed microstructural evolution and mechanical response are further interpreted through the underlying tribological mechanisms governing friction, interfacial shear, oxide fragmentation, and chip-to-chip bonding during solid-state consolidation. The outcomes of this work provide insight into the relationship between strain-gradient deformation, consolidation behavior, and the tribological phenomena that ultimately govern the structural integrity of recycled aluminum products.

2 Experimental Section

2.1 Aluminum Chip Preparation

Figure 1: AA6063 Aluminum Chips

Post-industrial AA6063 aluminum alloy scrap, including extrusion cut-offs, rejected products, trimming residues, and machining waste, was used as the feedstock for billet preparation. The scrap was mechanically ground using a bench grinder to produce irregular aluminum chips representative of industrial recycling waste. Prior to consolidation, the chips were cleaned with a soap-based detergent solution to remove residual lubricants and contaminants, then rinsed and dried under ambient conditions while preserving the naturally formed oxide layer.

The resulting feedstock consisted of mixed chip morphologies, including long curled, short fragmented, thick, and thin chips, representative of practical recycling conditions (Latif et al., 2022; Wang et al., 2024). Different chip geometries influence packing behavior and deformation during consolidation, where long curled chips tend to reduce packing efficiency, while shorter and fragmented chips rearrange more readily to promote denser packing and improved mechanical interlocking. This heterogeneous morphology provides a realistic precursor for subsequent hot extrusion and tribological evaluation.

2.2 Billet Packing Procedure

A custom packing apparatus as per figure 2 was designed and fabricated to produce packed aluminum billets the packing system was mounted on an INSTRON 1000HDX universal testing machine, which provided controlled compressive loading throughout the packing process. The apparatus was designed to maintain constant billet geometry while allowing the packing parameters to be precisely controlled and reproduced.

Preliminary trials were conducted to optimize the packing procedure by investigating the effects of compaction load and holding time on billet integrity. It was observed that insufficient compaction pressure or inadequate holding time resulted in significant elastic recovery after unloading, causing chip relaxation, poor particle interlocking, and the formation of loosely consolidated billets. Conversely, excessively long holding times promoted over-consolidation between successive chip layers, reducing the integrity of the layered structure and making the billet more susceptible to internal defects during subsequent processing. These observations highlight the importance of balancing particle rearrangement and stress relaxation to achieve a stable green compact.

Based on the optimization study, the final packing procedure consisted of five sequential filling and compaction stages. In each stage, aluminum chips were added to the die cavity and compressed under a load of 7.5–10 tones, followed by a holding period of 5 min to facilitate particle rearrangement, stress relaxation, and mechanical interlocking. After the fifth and final compaction stage, the billet was maintained under the applied load for an additional 15 min to enhance consolidation stability before unloading. This multi-stage packing strategy produced cylindrical billets with an average diameter of 15 mm and an average green density of approximately 2.4 g/cm³, providing sufficient structural integrity for handling and subsequent hot extrusion.

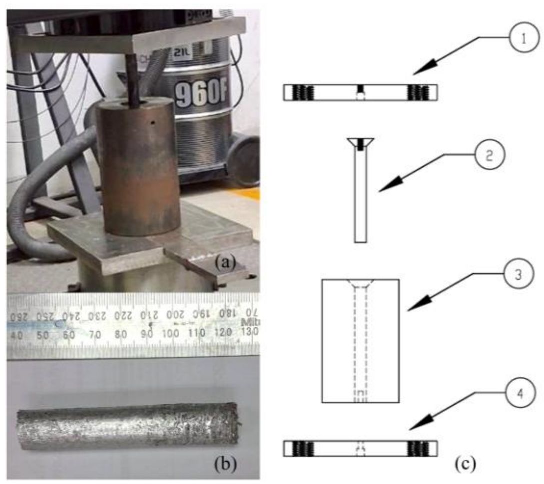


Figure 2: (a) Packing System Unit (b) Aluminum packed billet (c) Packing Apparatus Drawing [(1) Upper Plate (2) Ramp (3) Packing Die (4) Lower Plate]

2.3 Extrusion Die Design

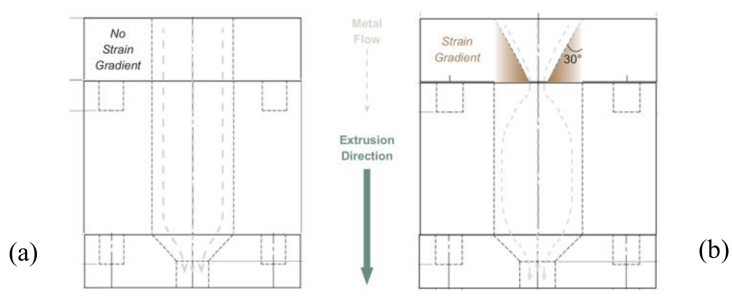
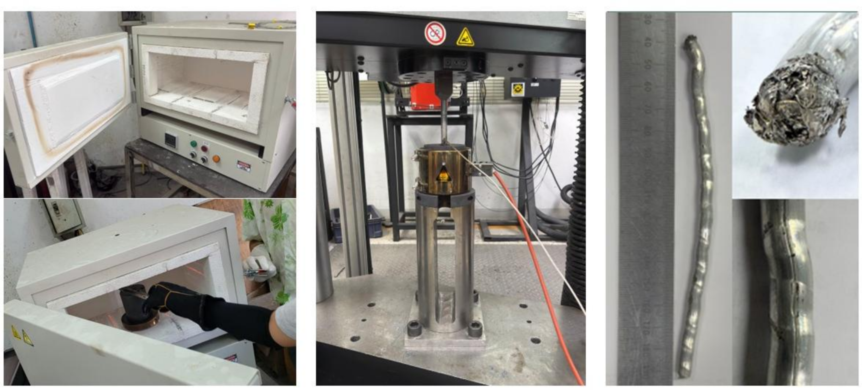


Figure 3: Extrusion Die Designs (a) Normal Feeder (b) Strain-gradient Feeder

Two feeder geometries were developed within a modular die system to investigate the influence of strain distribution on the consolidation of AA6063 chips: a normal feeder and a strain-gradient feeder as illustrated in Figure 3. Normal Feeder: Features a straight, symmetrical flow channel that promotes uniform material velocity and deformation across the billet cross-section, ensuring stable extrusion behavior. Strain-Gradient Feeder: Incorporates a 30° wedge-shaped restriction at the entrance region. This geometry acts as a localized constraint, forcing the material to undergo inward bending and lateral redirection. The primary objective of the strain-gradient design is to generate higher localized plastic deformation and interfacial shear. The strain-gradient deformation promotes fragmentation of surface oxide films, grain refinement, and the formation of gradient microstructures, thereby improving the conditions required for solid-state bonding (Peng et al., 2023; Roghani et al., 2022; Xie et al., 2025) The modularity of this system allows for a direct comparison of these two distinct flow conditions under identical processing parameters.

2.4 Hot Extrusion Procedure

A modular extrusion system was designed and fabricated in-house to investigate the influence of material feed conditions. Two feeder geometries were developed: a normal feeder with a constant flow channel and a strain-gradient feeder incorporating a reduced cross-sectional region to impose higher localized plastic deformation during extrusion. In addition, interchangeable bearing configurations were incorporated into the die assembly to facilitate future investigations on bearing geometry and material flow characteristics. The entire die set was designed using a bolted locking mechanism, allowing rapid assembly and disassembly within the extrusion chamber while maintaining accurate alignment of all components.



(a) (b) (c)

Figure 4: (a) Preheating in Furnace [500 °C] (b) Hot Extrusion Setup (c) Extruded Profile

Prior to extrusion, the die assembly, extrusion chamber, and ram were preheated in a furnace to 500 °C to minimize thermal gradients during processing. The packed and cast billets were separately heated to the same temperature before being transferred into the preheated extrusion chamber. Hot extrusion was then performed at a constant ram speed of 1 mm/s. Successful extrusion was readily achieved using the normal feeder for both the packed recycled-chip billet and the cast billet, producing fully extruded specimens for comparison. In contrast, the strain-gradient feeder generated substantially higher extrusion loads because of the severe reduction in flow area, making it difficult to achieve stable extrusion when processing cast billets during the initial experimental stage. Therefore, three extruded specimens were selected for subsequent characterization and discussion: (i) cast billet extruded through the normal feeder, (ii) packed recycled-chip billet extruded through the normal feeder, and (iii) packed recycled-chip billet extruded through the strain-gradient feeder.

2.5 Microstructural Characterization

The specimen which performs for microstructural analysis is conducted on mounted, ground, and polished using standard metallographic techniques. Keller's reagent was applied to reveal grain boundaries and secondary phases. Microstructural observations were conducted with optical microscopy, focusing on grain morphology, void formation, etc. (Gzbyk, n.d.)

2.6 Mechanical Characterization

Mechanical Characterization. The mechanical properties of the extruded profiles were evaluated by uniaxial tensile testing using an Instron 68TM-100 universal testing machine, equipped with a 100 kN load cell. Tensile testing was performed in accordance with the principles of ASTM E8/E8M for metallic materials. Test specimens were machined from the extruded products to identical dimensions, with a gauge diameter of 6 mm and an initial gauge length of 25.4 mm, to ensure consistent comparison between the cast billet and packed billet extrusions. Each specimen was securely clamped in the testing machine and subjected to a continuously increasing tensile load until fracture.

2.7 Proposed Tribological Evaluation

Figure 5: Proposed Pin-on-Disk tribological evaluation in Bruker TriboLab test setup

The tribological performance of the consolidated aluminum materials will be evaluated in future work using a Pin-on-Disk configuration on a Bruker TriboLab tribometer. The test is designed to investigate the influence of chip consolidation quality and interfacial bonding on friction and wear behavior under sliding conditions representative of hot metal forming applications. Extruded AA6063 specimens will be machined into cylindrical pins and tested against hardened SKD61 hot-work tool steel disks, which are widely employed as die materials in aluminum hot extrusion and forging owing to their high-temperature strength, wear resistance, and thermal stability. The SKD61 counterface therefore provides a practical representation of the tool–workpiece interface encountered during industrial forming operations.

The Pin-on-Disk configuration was selected because it provides stable and repeatable sliding contact under controlled normal load and sliding velocity while enabling continuous monitoring of the coefficient of friction (COF). Compared with reciprocating sliding configurations, continuous circular sliding generates a steady-state contact condition that facilitates evaluation of adhesive wear, abrasive wear, oxide-film stability, and transfer-layer formation. Following tribological testing, the wear tracks formed on both the aluminum pin and SKD61 disk will be examined using optical microscopy to characterize wear morphology, including ploughing grooves, adhesive transfer, oxide films, and surface damage. Wear volume or mass loss will also be quantified to determine the wear rate of each material condition. Similar experimental approaches have been widely employed to investigate the tribological behavior of aluminum alloys under dry sliding conditions and to establish relationships between microstructure, oxide films, friction coefficient, and wear mechanisms (*Engineering Tribology*, 2013; Hutchings & Shipway, 2017).

3 Results and Discussion

3.1 Cross Sectional microstructure of the extruded Packed Billet (Normal Feeder)

The cross-sectional micrographs shown in Figure 6(a) reveal a relatively dense aluminum matrix, indicating that hot extrusion successfully eliminated most of the large packing voids. However, several dark, irregular, and locally elongated features remain visible, which may correspond to residual micro voids, incompletely closed pores, oxide-rich regions originating from the original chip surfaces, incompletely bonded chip-to-chip interfaces, or polishing artefacts. These features cannot be definitively identified using optical microscopy alone and therefore should not be conclusively interpreted as cracks or oxide films. Consequently, the dark discontinuities are tentatively attributed to residual oxide-rich interfaces, incompletely closed pores, or polishing artefacts, while definitive identification requires SEM coupled with EDS analysis (Carta et al., 2024; Koch & Walther, 2025; Kościelniak et al., 2024; Krolo et al., 2025).

3.2 Extrusion direction microstructure of the extruded Packed Billet (Normal Feeder)

Figure 6(c) shows stronger evidence of incomplete chip consolidation in the longitudinal section, where a long, wavy, semi-continuous dark feature is aligned approximately parallel to the extrusion direction. This feature is likely associated with a prior chip boundary elongated during extrusion. During solid-state recycling, sufficient plastic deformation is required to fracture the oxide films surrounding the chips and promote fresh metal-to-metal contact. When oxide fragmentation and interfacial bonding are incomplete, residual oxide-rich interfaces and micro voids may remain after extrusion, as reported in previous studies (Yu et al., 2025; Zhang et al., 2023). The alignment of these residual interfaces along the material flow direction suggests that extrusion stretched the original chip boundaries rather than eliminating them, which may contribute to anisotropic mechanical behavior by reducing transverse ductility and providing preferential paths for crack initiation and propagation.

3.3 Microstructure of the Extruded Cast Billet (Normal Feeder)

Both cross-sectional and longitudinal micrographs of the extruded as-cast billet appear more homogeneous than those of the chip billet. No comparable continuous dark interface is clearly visible as shown in Figure 6(b) and Figure 6(d). The as-cast billet does not contain the large internal surface area and oxide-covered interfaces associated with individual machining chips. Therefore, its extrusion primarily involves plastic flow and microstructural deformation of a continuous metallic body rather than simultaneous pore closure and chip-to-chip welding. Some isolated rounded or irregular particles are visible at higher magnification. These could be intermetallic particles, inclusions, small pores, etching pits, or polishing artefacts. (Perrin et al., 2026a, 2026b; Zhang et al., 2023) However, they are more isolated and are not connected to the long boundary-like networks observed in the chip billet.

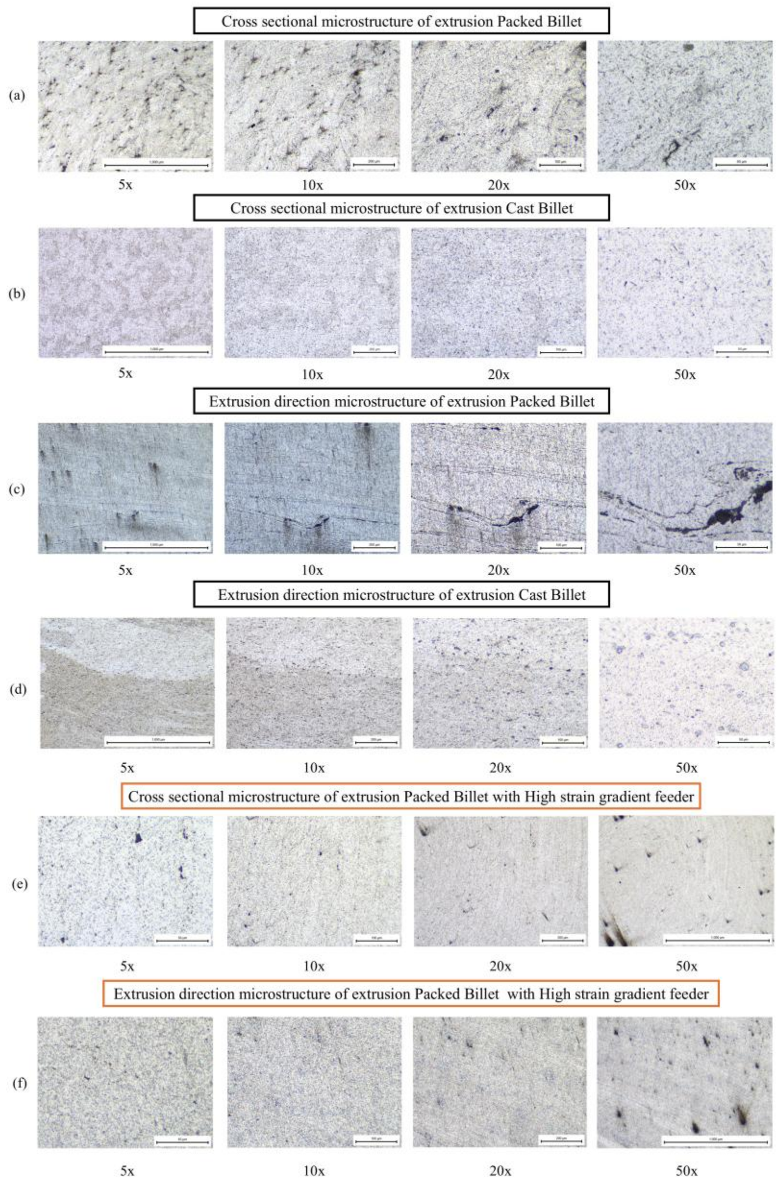


Figure 6: Microstructure of extruded billets and feeder conditions

3.4 Extruded Billets from Strain-gradient feeder

Microstructure of the packed billet extruded using the strain-gradient feeder as shown in Figure 6(e) and Figure 6(f) show a more homogeneous aluminum matrix than the billet extruded with the normal feeder. This specimen contains fewer long, continuous dark interfaces, with most remaining defects appearing as isolated dark particles or short discontinuous features. The most notable improvement is observed in the extrusion direction section, where the continuous chip-boundary-like feature visible in the normal feeder specimen is largely absent. These observations suggest that the strain-gradient feeder promoted more effective disruption and redistribution of the original chip interfaces during extrusion. The wedge-shaped feeder geometry increases interfacial shear and non-uniform strain, enhancing void closure and promoting fragmentation of the surface oxide films covering the aluminum chips. This facilitates greater fresh metal-to-metal contact and improves solid-state bonding between adjacent chips. Overall, the strain-gradient feeder produced a microstructure that is more homogeneous than that obtained using the normal feeder and more closely resembles the extruded cast billet, although complete elimination of interfacial defects was not achieved. The summary as shown in Table 1.

Characteristic	**Normal Feeder (Packed Billet)**	**Strain-Gradient Feeder (Packed Billet)**	**As-cast Billet**
Large packing voids	Mostly eliminated	Mostly eliminated	Not applicable
Longitudinal interfaces	Continuous chip-boundary features	Mostly short and discontinuous features	Not observed
Microstructural homogeneity	Moderate	Improved	Highest
Chip boundary continuity	Relatively high	Reduced	Not applicable
Bonding quality	Local incomplete bonding	Improved inter-chip bonding	Continuous parent material
Remaining defects	Oxide-rich interfaces and voids	Isolated oxide fragments/voids	Minor inclusions or casting defects

Table 1: Comparison of the three extrusion conditions

3.5 Mechanical Properties

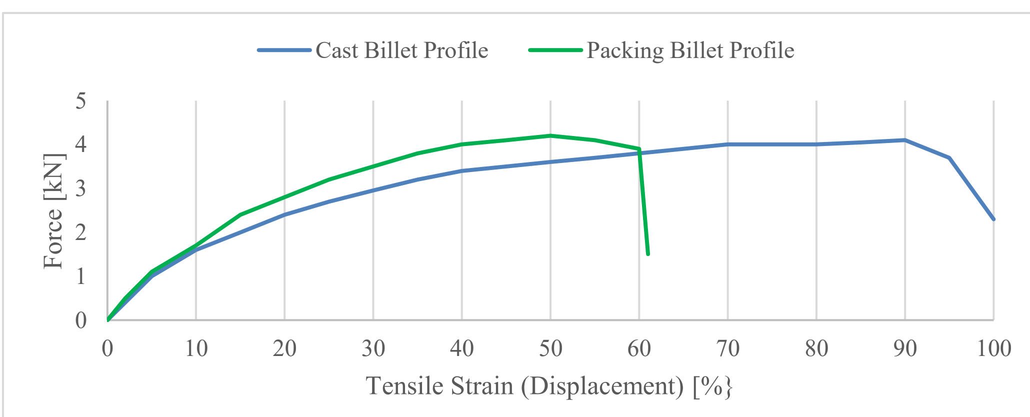
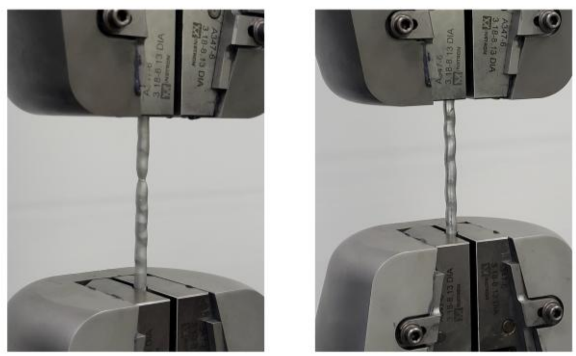


Figure 7: Tensile testing results between cast billet and packing billet extruded from normal feeder

Property	**Cast Billet**	**Packed Billet**	**AA6063 (Typical) Ref**	**Difference between Cast and Packed**
Yield Load (kN)	2.60	4.06		+56.2%
Tensile Load (kN)	4.10	4.25		+3.7%
Yield Strength (MPa)	91.80	143.53	~ 60-90	+56.3%
Ultimate Tensile Strength (MPa)	144.97	150.39	~ 130-170	+3.7%

Table 2: Mechanical Properties of Extruded Parts



(a) (b)

Figure 8: Extruded parts under tensile testing (a) Casted Billet (b) Packed Billet

Table 2 compares the tensile properties of extruded profiles produced from the cast billet and the packed aluminum chip billet. Both specimens had identical gauge dimensions (6 mm diameter and 28.27 mm² cross-sectional area), allowing a direct comparison of their mechanical performance.

The relatively small difference in ultimate tensile strength indicates that the extrusion process successfully consolidated the packed aluminum chips into a structurally sound product capable of carrying loads comparable to those of conventionally cast material. The mechanism where plastic deformation disrupts oxide layers and exposes fresh metallic surfaces that bond under compressive loading (Lilensten et al., 2025).

Interestingly, the packed billet exhibited a substantially higher yield strength than the cast billet. Improvements in yield strength following solid-state recycling have been attributed to grain refinement, work hardening, and elimination of casting defects resulting from severe plastic deformation (Paraskevas et al., 2014; Wan et al., 2017a). In contrast, cast billets generally contain coarser grains and casting defects such as dendritic segregation and micro-porosity, which reduce resistance to plastic deformation. Similar improvements in yield strength following solid-state recycling have been reported by researchers including(J. Gronostajski et al., 2000), who attributed enhanced strength to severe plastic deformation, refined microstructures, and the elimination of casting-related defects.

Figure 8 compares the fracture morphology of the tensile specimens after failure. The cast billet exhibited pronounced necking prior to fracture, indicating greater ductility, whereas the packed billet fractured with a relatively flat surface and limited necking. This behavior suggests that residual oxide-rich interfaces or incompletely bonded chip boundaries acted as preferential crack initiation sites, despite effective solid-state bonding during hot extrusion. Similar observations have been reported in previous studies, where the strength of solid-state recycled aluminum approaches that of cast material, while ductility remains more sensitive to bonding quality. Nevertheless, the packed billet achieved an ultimate tensile strength comparable to the cast billet and a significantly higher yield strength, demonstrating that the proposed packing method produced mechanically sound extruded products with effective inter-chip bonding.

3.6 Discussion of Tribological Implications

The microstructural and mechanical results suggest that tribological interactions during hot extrusion play a key role in the consolidation of recycled aluminum chips. Friction and interfacial shear promote fragmentation of the surface oxide films, exposing fresh aluminum surfaces that enable solid-state bonding under elevated temperature and compressive loading. Although extrusion eliminated most of the large packing voids, localized dark discontinuities remained, which are likely associated with residual oxide-rich interfaces, incompletely bonded chip boundaries, or microvoids. Similar observations have been reported in previous studies on solid-state recycled aluminum (Laurent-Brocq et al., 2023; Yu et al., 2025; Zhang et al., 2023).

The tensile results support these observations, with the packed billet achieving an ultimate tensile strength comparable to the cast billet while exhibiting reduced necking before fracture. This suggests that residual chip interfaces may act as localized stress concentrators, reducing ductility despite effective load-bearing capacity (Lilensten et al., 2025; Perrin et al., 2026a). The strain-gradient feeder further reduced the continuity of these interfaces, indicating enhanced oxide fragmentation and inter-chip bonding. Future Pin-on-Disk testing using a Bruker TriboLab with an SKD61 steel counterface will validate these proposed tribological mechanisms by correlating friction and wear behavior with the observed microstructure and mechanical properties.

4 Conclusions

This study investigated the solid-state recycling of AA6063 aluminum chips through a multi-stage billet packing technique followed by hot extrusion using a modular die system incorporating normal and strain-gradient feeder geometries. The proposed processing route successfully produced consolidated recycled aluminum profiles with sufficient integrity for subsequent microstructural and mechanical characterization. Optical microscopy revealed that hot extrusion effectively eliminated most of the large packing voids within the recycled billets, although localized dark discontinuities associated with residual chip interfaces or oxide-rich regions remained. Compared with the cast billet, the recycled chip billet exhibited a comparable ultimate tensile strength while achieving a higher yield strength, demonstrating that effective metallurgical bonding was established during solid-state consolidation. However, the reduced neck observed during tensile fracture suggests that residual interfacial defects continue to influence ductility and fractured behavior.

From a tribological perspective, the results indicate that friction and interfacial shear generated during hot extrusion play a critical role in promoting oxide fragmentation, fresh metal exposure, and chip-to-chip bonding. The proposed strain-gradient feeder is expected to further enhance these mechanisms by increasing localized plastic deformation prior to extrusion, thereby improving consolidation efficiency through die design rather than relying solely on higher extrusion ratios or processing temperatures.

Future work will experimentally validate these tribological mechanisms using Pin-on-Disk testing on a Bruker TriboLab system with an SKD61 tool steel counterface. The findings presented in this work provide a foundation for the development of tribology-informed die designs that enhance the performance and sustainability of solid-state recycled aluminum components.

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