Outlining the Limits of Friction Stir Consolidation as Used as an Aluminum Alloys Recycling Approach

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Abstract. Friction stir consolidation (FSC) is a solid-state process that recycles metal scraps economically and eco-friendly compared to the conventional melting method. The process parameters especially processing time and rotational speed, have a crucial role in achieving a sound disc during FSC. The current study answers the research question of how far these process parameters can be effective when the mass of chips to be recycled increases. In specific, an experimental setup was analyzed that was previously identified as challenging for recycling 20 g chips of aluminum alloy AA 2024-O. Rotational speed was set doubled, and processing time was increased up to 1.5 times of their initial values. The results were found opposing to the reported one. It was noticed that raising the processing time and rotational speed are not always promising to achieve a quality consolidated disc with better mechanical properties. In contrast, they can lead to unconsolidated discs with more non-homogeneous mechanical properties. Thus, this research work highlights the hidden challenges in producing a sound disc during friction stir consolidation.

Keywords: Friction stir consolidation · Recycling aluminum chips · Process parameters

1 Introduction

Aluminium production has increased rapidly over the last decades due to an increasing consumer population and new application areas of this versatile metal [1]. According to Hydro Annual Report, 2010 [2], the global aluminium consumption in 2019 was 89.9 million tonnes. In which the share for transport was 26%, 24% for construction, 11% for each of the categories electrical goods and machinery, 8% for each of the packaging and foil stock applications, and 6% for consumer durables.

However, the production of virgin aluminum from bauxite ore is a complicated process. It is costly, energy-intensive, and responsible for approximately 20% loss of pure aluminum. Besides, large amounts of waste slag are generated, which takes up considerable land resources and pollutes the environment [3]. Modern industrial societies and environmental policy efforts strongly encourage the processes that reduce primary resource use, pollution prevention, waste management, and sustainable products.

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Therefore, metals can be melted down, reformed, and reused without losing any of their beneficial qualities rather than mining for new ore. Such practices can meet much of the demand for new metals by simply recycling metals that are already in circulation. According to the European Aluminium Association (EAA, 2003), about 32% of European aluminium demand is satisfied by recycled material [4]. The quantities of recycled aluminium in Europe were estimated on 2.3 million tonnes approximately [5].

Usually, aluminum is recycled through the conventional melting method. However, this route has severe implications, especially during recycling aluminum scraps. It caused the adverse environmental impact, high cost, and significant material loss. Therefore, the research attempted solid-state recycling techniques [6–9]. These new methods can save up to 95% of energy, 59% of the cost, and 46% of material compared to the conventional melting process [10].

Duflou et al. [11] performed an environmental assessment of three different solid-state recycling methods comparing with the melting process as a reference. They concluded that solid-state recycling methods are more effective for machining scraps recycling. The kind of scraps, due to their high surface-to-volume ratio are prone to oxidation causing permanent material loss during the melting process.

Friction stir extrusion (FSE) is one of the solid-state methods used to convert metal scraps into the final product [12]. First, a rotating die plunges into a cylindrical chamber containing the metal scraps during FSE. Next, the stirring action of the tool plastically deforms the materials and forces them into the extrusion chamber. Finally, after densifying and heating, fully dense rods are extruded.

Many researchers have worked on the environmental assessment and finding the critical process parameters for FSE. Baffari et al. [13] analyzed the energy demand for 2050 aluminum alloy wire production through friction stir extrusion. They reported that FSE allows a reduction in energy demand up to 74% and 63% compared to the conventional and the equal channel angular process methods, respectively. Be-sides, growing extrusion rate or decreasing processing time led to reducing significant power demand was one of their critical findings.

Baffari et al. [14] investigated the effect of process parameters on friction stir extrusion of 2050 aluminum alloy. They found that high rotational speed and extrusion force caused significant grain growth and cracks due to high thermal input. Similarly, Tahmasbi et al. [15] analyzed the influence of rotational speed during friction stir extrusion of 7022 aluminum alloy. The study suggested that a rise in rotational speed decreased hardness and dislocation density and increased average grain size.

Friction stir consolidation (FSC) is a new solid-state process, similar to friction stir extrusion, differing for the absence of an extrusion channel within the tool. Further, a semi-product is developed in the form of a billet or disc shape that can be used for many applications. FSC process consists of two main steps: compaction and consolidation [16]. Compaction refers to the initial pressing of aluminum chips or powder in a hollow die chamber by applying a specific load through a cylindrical tool. The materials are then further pressed and stirred through the tool's downward force and rotational speed during consolidation.

Li et al. [17] revealed critical process parameters during FSC of AA 6061 aluminum alloy. They determined that increasing processing time, rotational speed, or consolidation force led to improved mechanical and metallurgical properties of the consolidated disc. Buffa et al. [18] examined the effect of processing time, rotational speed, and quantity of chips on the AA 2024 consolidated disc. The report suggested that increasing processing time and speed or lowering mass resulted in a better-quality consolidated disc.

In the current study, we extended our work on critical process parameters of FSC. Specifically, the mass of the chip was increased to 20 g, and the effectiveness of processing time and rotational speed were analyzed by using the experimental setup of the previous researcher [17, 18]. The aim was to analyze if, for challenging input chip masses (higher than 20 g), sound, as well as high quality, recycled samples can be obtained. The analyses were developed by increasing the main process parameters: the rotation speed and the consolidation time. The grain size, as well as hardness, were considered as the main output metrics. The study aims at improving the industrial applicability of the FSC process; as a matter of fact, bigger recycled samples would be beneficial both for FSC process productivity and for its environmental sustainability.

2 Materials and Methods

A cylindrical rod of 2024-O aluminum alloy was reduced to chips through turning operation (parameters listed in Table 1). The diameter of rod was 30 mm and chemical composition by mass percentage was 94.1Al-0.003-Cr-4.26Cu-0.57Fe-0.004Mg-0.01Mn-0.129Si-0.003Ti-0.008Zn-0.5Pb-0.12Sn. The chips were clean through acetone and then dried. Then a fixed mass of 20 g was charged in a die of 26 mm diameter (Fig. 1a). ESAB LEGIO, a dedicated friction welding machine and a cylindrical tool of 25 mm diameter (shown in Fig. 1b and c), were adopted to perform the experiments. A 5kN pre-load was applied to compact the charge, then followed by a consolidation force of 20 kN under the experimental conditions listed in Table 2 and Table 3.

Table 1. Detailed information of chips preparation

Machine	Process	Rotational speed (rev/min)	Depth of cut (mm)	Feed (mm/rev)	Cutting angle (degree)
COMEV 180	Finishing	460	1.5	2	15º

The consolidated disc was cut into two halves along the cylindrical axis. The disc section was well polished with water as a coolant and 0.05 μm alumina as a lubricant using a series of abrasive papers. Vickers hardness test was performed by applying a 49 N (5 kg) load for 15 s over the four lines along the cylindrical axis. The lines were at radius, r = 0 (central line), 6.50, 9.00, and 12.25 mm (near the external surface). The pitch of the load points was 0.50 mm, as shown in Fig. 2a. Specimens' microstructure was revealed through Keller reagent and then analyzed under the OLYMPUS GX51F microscope at a magnification lens of 5×, 20×, 40×, and 100×. On each line, grains were examined on three different zones (top, mid, and bottom), as shown in Fig. 2b.

Fig. 1. (a) Tool, (b) die & (c) ESAB LEGIO

Table 2. Experimental conditions

Constant parameter	Value of fixed parameter	Variable parameter	Level and value of variable parameter
Mass of charge (g)	20	Rotation speed (rev/min)	1000; 2000
Compaction force (kN)	5	Consolidation time (sec)	40; 60
Consolidation force (kN)	20		

Table 3. Experimental plan

Experiment no	Rotational speed (rev/min)-time (seconds)-mass (g)
Exp 1	1000-40-20
Exp 2	1000-60-20
Exp 3	2000-40-20
Exp 4	2000-60-20

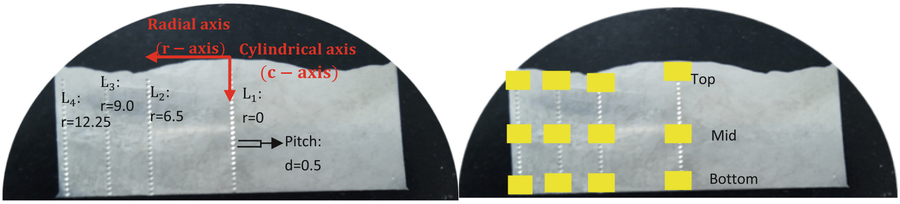
3 Analysis of Results

3.1 Grain Analysis

In this section, grains size has been analyzed along cylindrical and radial axes and its trend with processing time and rotational speed.

Grain Size Distribution Along Cylindrical Direction

A disc was developed at a rotational speed of 1000 revolutions per minute (rpm) and a processing time of 40 s during the first experiment (Exp 1). The disc section was examined



(a) (b)

Fig. 2. Schematic diagram for (a) Vickers hardness test (b) microstructure analysis **Note:** All dimensions are in mm for Vickers hardness test.

at the top, mid, and bottom zones to analyze grain size trends in the cylindrical axis. A zone of very refined grains was found at the top of the central line (Fig. 3a). Then, 1–2 mm below this zone, a grain growth occurred (Fig. 3b) until the mid of the disc section, where the grain size started to reduce (Fig. 3c). Finally, grains disappeared, and various defects originated at the bottom zone (Fig. 3d).

Grain Size Distribution Along Radial Direction

The other three lines at r = 6.50, 9.00, and 12.25 mm were also examined to analyze grain size trends in the radial direction. The zone near the top surface was characterized by coarse grains of the same size regardless of their distance from the central line (Fig. 4). At the middle of the disc, grains of larger size were observed on the central line. However, their size decreased continuously in the radial direction. In the bottom of the disc section, grains were not visible. Besides, the region with no visible grains expanded, and the number of defects increased from the central line towards the external surface.

Modelling of Grain and Defective Areas

Figure 5a depicts grain evolution during Exp 1. Based on the grain size distribution, the disc section has four major regions. In each region, the alignment of the grains is symmetrical along the cylindrical axis (central line).

The first zone represents an oval shape region at the top of the central line and is characterized by very refined grains. Then the second zone exists below zone 1. It is a rectangular-shaped area and composed of very coarse grains. In the third zone, grain size decreases continuously from top to bottom of the disc. Together zone 2 and zone 3 constitute a significant portion of the disc. Two triangular areas at the bottom represent the final zone. In this zone, grains started to disappear, and several defects emerged in the radial direction. Based on this model, roughly 25% sectional area of the disc was found defective (Fig. 5b).

Trend With Processing Time and Rotational Speed

For achieving a fully consolidated disc with uniform grain size, the consolidation time was increased from 40 to 60 s during Exp 2 while other parameters were kept constant. Nevertheless, the trend of grain size variation of Exp 2 was found similar to Exp 1, showing further grain growth in zone 2 due to the increased processing time (Fig. 6b).

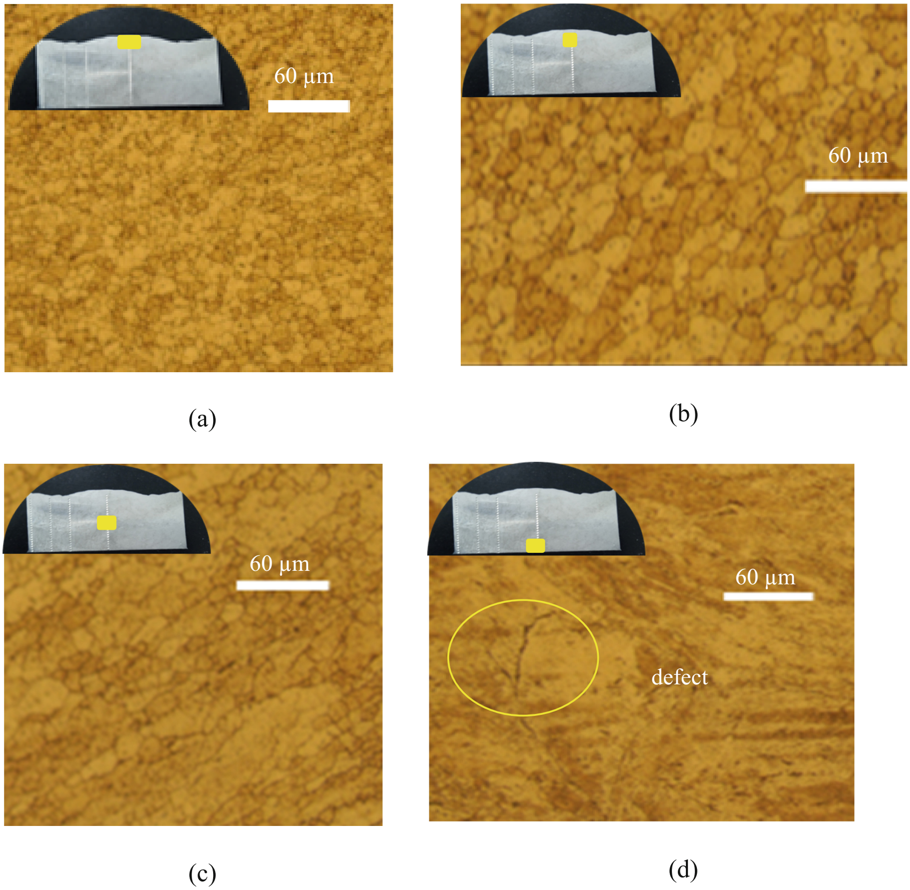


Fig. 3. Exp 1 central line at 20× (a) very top zone (c) zone near the top (c) mid zone and (d) bottom zone

Then in Exp 3, the rotational speed was doubled (from 1000 to 2000 rev/min). Once again, it caused grain growth in zone 2 (Fig. 6c) with no notable improvement in the quality of the disc. Finally, raising both processing time and rotational speed during Exp 4 caused no significant improvement in overall grain size distribution. However, it caused further grain growth in zone 2 (Fig. 6d).

Even with 1.5 times rise in processing time and doubling rotational speed could not achieve a fully consolidated disc (Fig. 7). Both process parameters, though, lead to an increase in the average grain size. However, the increase in average grain size occurred mainly due to the grain growth at zone 2, while the grain size pattern at other zones remained unchanged. Thus, the standard deviation rose and intensified the non-uniform grain distribution across the disc section (Fig. 8).

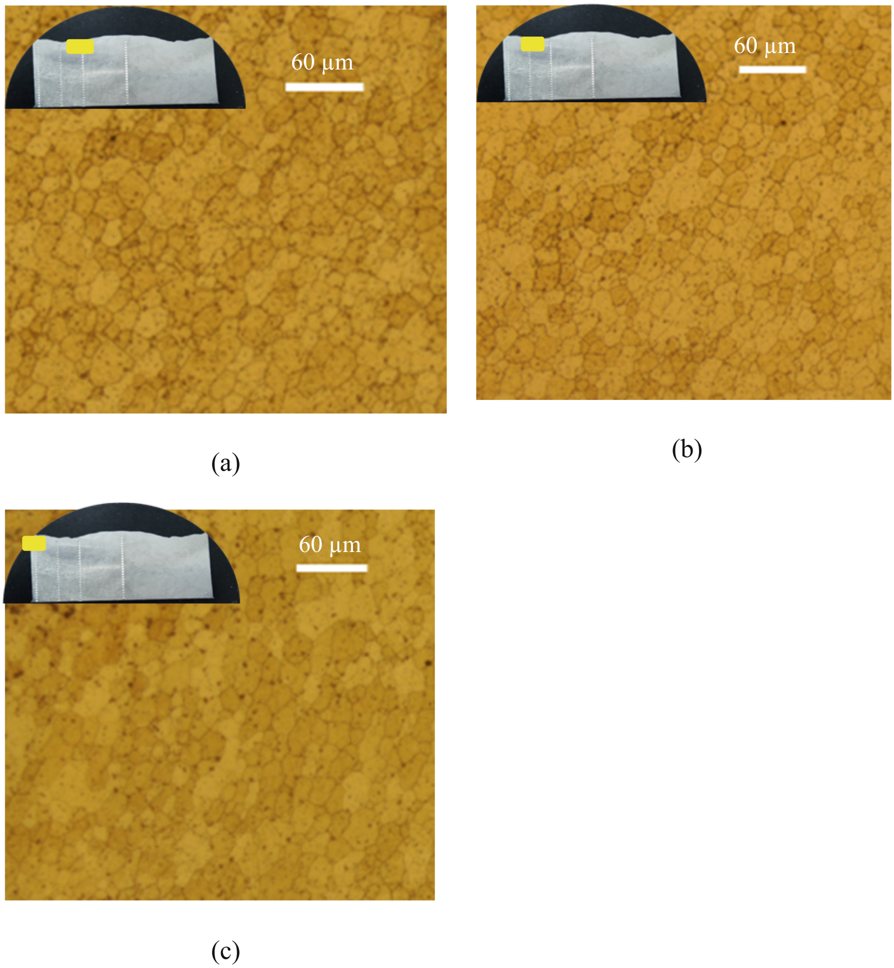


Fig. 4. Exp 1 top surface at 20× at lines (a) r = 6.5 mm (b) r = 9.0 mm and (c) r = 12.25 mm

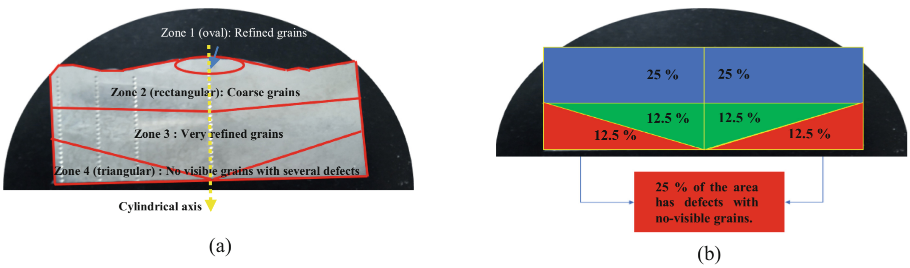


Fig. 5. Scematic presentation of (a) grain evolution (b) area of visible grain

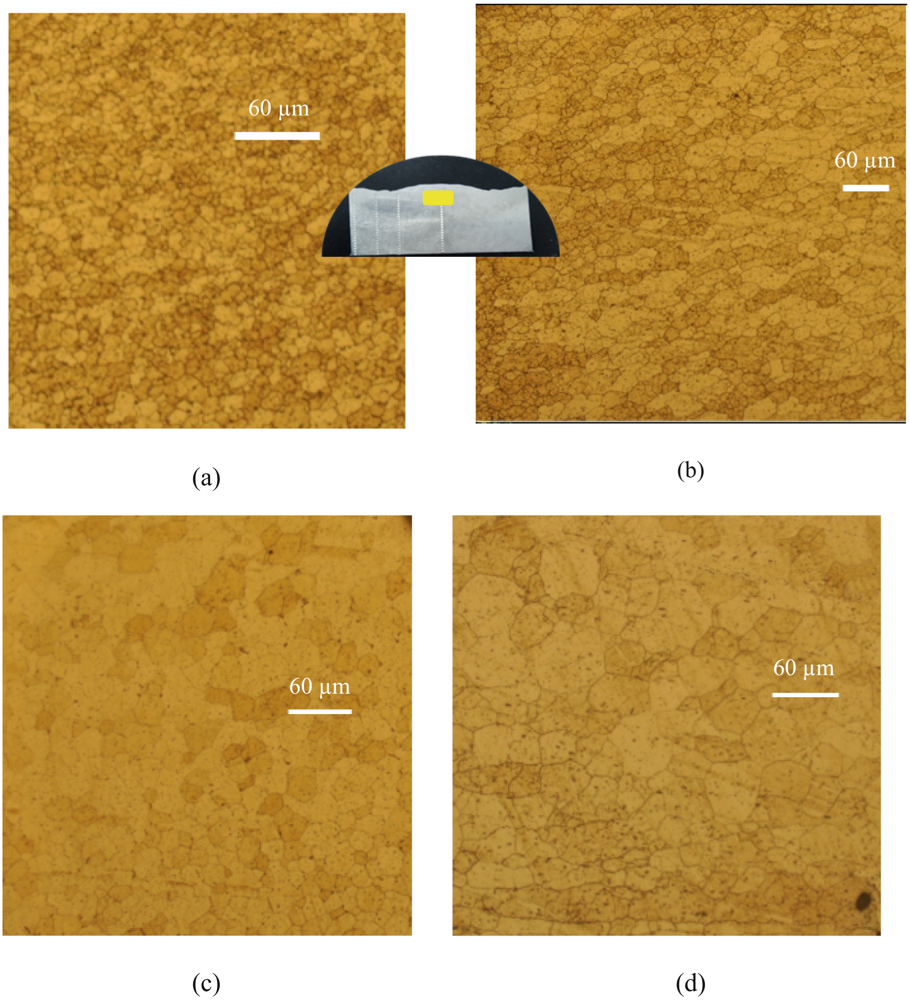


Fig. 6. Near the top surface of central line at 20× for (a) Exp 1, (b) Exp 2, (c) Exp 3, and (d) Exp 4

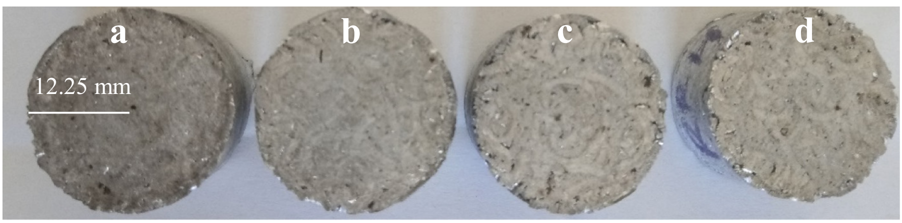


Fig. 7. Unconsolidated chips at the bottom of the disc (a) Exp 1, (b) Exp 2, (c) Exp 3, and (d) Exp 4

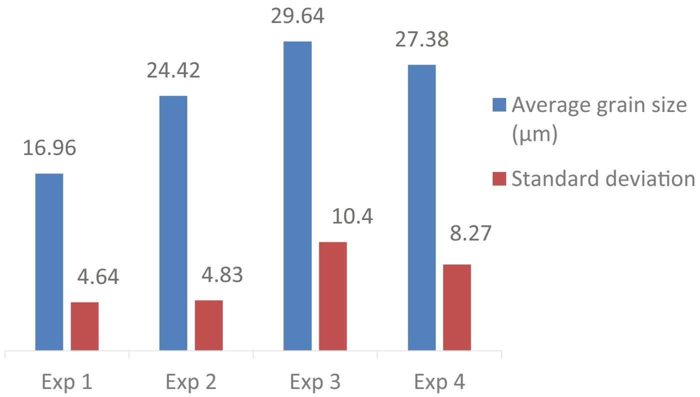


Fig. 8. Average grain size and standard deviation for all experiments

3.2 Hardness Analysis

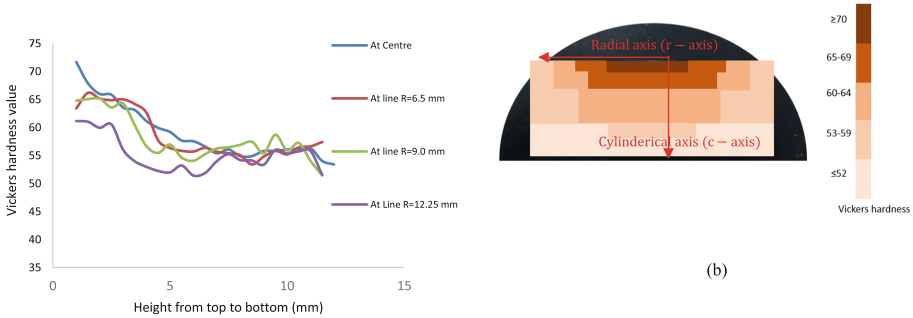
This section provides a complete discussion about the trend of hardness along cylindrical and radial axes and influence of processing time and rotational speed.

Hardness Analysis Along Cylindrical Axis
The hardness value continuously decreases from top to bottom of the disc during Exp 1 (Fig. 9a) along the cylindrical axis. The maximum and minimum hardness values were existed at the top and bottom, respectively. The Vickers hardness value (HV) at the midsection was HV 58, almost equal to the average value. Besides, the lowest hardness values were observed near the surface at a line $r = 12.25$ mm.

Hardness Analysis Along Radial Axis
The hardness also follows a decreasing trend along the radial direction. It decreased from the central line to the line near the external surface. Although a uniform hardness of HV 50 was found at the bottom of the disc, this value is remarkably lower than the average hardness value (HV 58). Figure 9b provides a schematic presentation of hardness across the section of the disc during Exp1. Besides, symmetry also exits for hardness along the cylindrical axis (central line).

Effect of Processing Time and Rotational Speed on Hardness
The influence of processing time and rotational speed was analyzed by comparing the hardness of the central line. The trend of hardness was similar for all four experiments (Fig. 10). It was a decreasing trend both in the cylindrical and radial directions.

However, the processing time and rotational speed have no significant effect on the average hardness value, as shown in Fig. 11a. The average hardness was around HV 58. In comparison, the standard deviation of hardness values increased (Fig. 11b). This fact illustrates that increasing rotational speed and processing time result in more non-uniform hardness across the disc section.



(a)

Fig. 9. (a) Hardness for Exp 1 over four lines and (b) schematic presentation for hardness profile

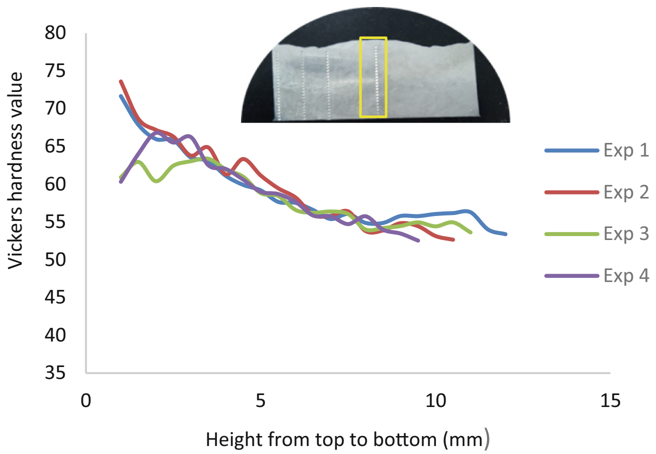
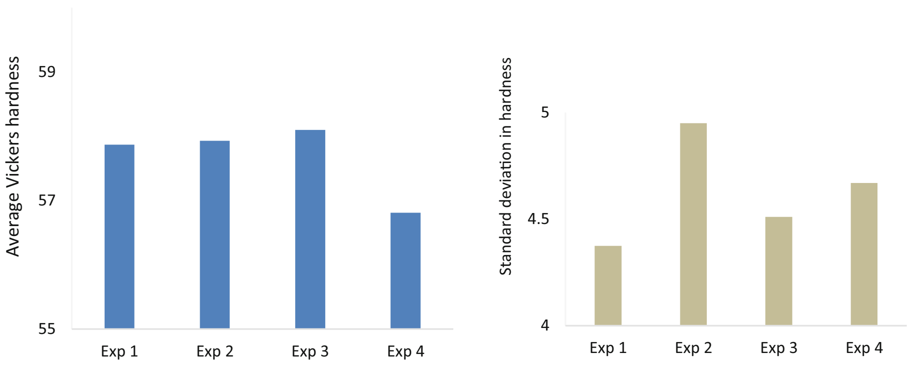


Fig. 10. Hardness over the central line for all four experiments



(a) (b)

Fig. 11. (a) Average Vickers hardness and (b) standard deviation in Vickers hardness

4 Conclusion and Further Development

The rotational speed and processing time are the process parameters reported to improve the mechanical properties. Under the experimental setup of the current study, this fact is valid for recycling up to 15 g chips. However, when mass surpasses this threshold, these parameters become less effective to achieve a fully consolidated disc. In contrast, they intensify non-homogenous hardness value and grain size across the section of the disc. Based on the current study, the following main conclusions can be drawn.

1. Grain size distribution and hardness were found symmetrical along the cylindrical axis of the disc.
2. The processing time and rotational speed increased the average grain size, standard deviation and caused grain growth in the area closest to the top surface. On the other hand, the mid and bottom zones turned out to be unaffected and thus non-homogeneous grain size distribution intensified with increase in processing time and rotational speed.
3. Even 1.5 times rise in processing time, and double increment in rotational speed could not achieve a fully consolidated disc. Furthermore, defects like voids and cracks did not eliminate in the bottom zone.
4. Hardness value decreased both in the direction of cylindrical and radial axes across the section of the disc.
5. Average hardness value remained unchanged with increasing processing time and rotational speed. The standard deviation increased slightly and thus resulted in more non-homogeneous hardness across the disc section.

The study suggests that regulating mechanical properties by only varying process parameters is not adequate when recycling scrap mass exceeds 15 g for the experimental setup used in the current study. Therefore, strategies are to be identified to get a consistent grain structure and hardness value throughout the cross-section.

References

1. Gökelma, M., Vallejo-Olivares, A., Tranell, G.: Characteristic properties and recyclability of the aluminium fraction of MSWI bottom ash. Waste Manage. **130**, 65–73 (2021)
2. Hydro Annual Report: https://www.hydro.com/Document/Index?name=Annual%20report%202019%20web.pdf&id=506433 (2019)
3. Li, Q., et al.: Aluminum material flow analysis for production, consumption, and trade in China from 2008 to 2017. J. Clean. Prod. **296**, 126444 (2021)
4. European Aluminium Association (EAA): http://www.eaa.net (2003)
5. Organization of European Aluminium (OEA) Refiners and Remelters: http://www.oea-alurecycling.org (2004)
6. Wan, B., Chen, W., Lu, T., Liu, F., Jiang, Z., Mao, M.: Review of solid state recycling of aluminum chips. Resour. Conserv. Recycl. **125**, 37–47 (2017)
7. Haase, M., Tekkaya, A.E.: Recycling of aluminum chips by hot extrusion with subsequent cold extrusion. Procedia Eng. **81**, 652–657 (2014)

8. Behnagh, R.A., Fathi, F., Yeganeh, M., Paydar, M., Mohammad, M.A., Liao, Y.: Production of seamless tube from aluminum machining chips via double-step friction stir consolidation. Int. J. Adv. Manuf. Technol. **104**(9–12), 4769–4777 (2019). https://doi.org/10.1007/s00170-019-04326-5
9. Jordon, J.B., et al.: Direct recycling of machine chips through a novel solid-state additive manufacturing process. Mater. Des. **193**, 108850 (2020)
10. Samuel, M.: A new technique for recycling aluminium scrap. J. Mater. Process. Technol. **135**, 117–124 (2003)
11. Duflou, J.R., et al.: Environmental assessment of solid state recycling routes for aluminium alloys: can solid state processes significantly reduce the environmental impact of aluminium recycling? CIRP Ann. **64**(1), 37–40 (2015)
12. Behnagh, R.A., Mahdavinejad, R., Yavari, A., Abdollahi, M., Narvan, M.: Production of wire from AA7277 aluminum chips via friction-stir extrusion (FSE). Metall. Mater. Trans. B **45**(4), 1484–1489 (2014)
13. Baffari, D., Reynolds, A.P., Masnata, A., Fratini, L., Ingarao, G.: Friction stir extrusion to recycle aluminum alloys scraps: energy efficiency characterization. J. Manuf. Process. **43**, 63–69 (2019)
14. Baffari, D., Reynolds, A.P., Li, X., Fratini, L.: Influence of processing parameters and initial temper on friction stir extrusion of 2050 aluminum alloy. J. Manuf. Process. **28**, 319–325 (2017)
15. Tahmasbi, K., Mahmoodi, M.: Evaluation of microstructure and mechanical properties of aluminum AA7022 produced by friction stir extrusion. J. Manuf. Process. **32**, 151–159 (2018)
16. Baffari, D., Reynolds, A.P., Li, X., Fratini, L.: Bonding prediction in friction stir consolidation of aluminum alloys: a preliminary study. In: Fratini, L., Lorenzo, R.D., Buffa, G., Ingarao, G. (eds.) AIP Conference Proceedings 21st International ESAFORM Conference, vol. 1960, pp. 050002–050006. AIP Publishing LLC (2018)
17. Li, X., Baffari, D., Reynolds, A.P.: Friction stir consolidation of aluminum machining chips. Int. J. Adv. Manuf. Technol. **94**(5–8), 2031–2042 (2017). https://doi.org/10.1007/s00170-017-1016-4
18. Buffa, G., Baffari, D., Ingarao, G., Fratini, L.: Uncovering technological and environmental potentials of aluminum alloy scraps recycling through friction stir consolidation. Int. J. Precision Eng. Manuf. Green Technol. **7**(5), 955–964 (2020)