Uncovering technological and environmental potentials of Aluminum Alloy scraps recycling through Friction Stir Consolidation

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Abstract

Conventional metal chips recycling processes are energy-intensive with low efficiency and permanent material losses during re-melting. Solid state recycling allows direct recycling of metal scraps into semi-finished products. It is expected that this process category would lower the environmental performance of metals recycling. Friction Stir Consolidation is a new solid-state technique taking advantage of friction heat generation and severe plastic deformation to consolidate chips into billets. In this research, the feasibility of Friction Stir Consolidation as aluminum chips recycling process is analyzed. Specifically, an experimental campaign has been carried out with varying main process parameters. Three main aspects have been evaluated in order to highlight products quality and environmental impact of the process: i) metallurgical and mechanical properties of the consolidated products; ii) primary energy demand, as compared to conventional processes; iii) forgeability of the consolidated products, as compared to parent material. Results revealed that a proper process parameters selection results in fully consolidated aluminum disk with satisfactory mechanical properties. Also, the new recycling strategy allows substantial energy savings with respect the conventional (remelting based) route.

Keywords: Recycling, Aluminum, Solid bonding, Friction stir consolidation, Sustainable manufacturing

1. Introduction

Production of materials is responsible for a significant share, larger than 25%, of global CO_2 emissions [1]. Metals play a key role as steel and aluminum account for about 30% of the emissions due to the raw materials production. Although at present the impact of steel is larger than the one of aluminum, demand previsions for the latter material during the next 30 years estimate a grow factor which is double with respect to the one of steel [2]. It arises that action must be taken with the aim to limit the raw material production by significantly reducing material usage and enhancing the capacity to keep the produced material in the “circle”. Possible strategies appear to be the introduction of new technologies enabling material saving at the design stage, repair, modularity, remanufacturing, re-use and recycling both in open and closed loops [3, 4].

At the moment, recycling is the most used approach for metals because of the well-established advantages from the economic and environmental points of view. In particular, concerning light alloys, it is possible to reach energy savings of about 90% [5, 6]. However, looking at traditional melting-based recycling processes, it arises that the energy efficiency can be significantly improved. As a matter of fact, although the theoretical energy needed to melt and cast aluminum alloy scraps is only 1.14 MJ/Kg, the actual average energy used in the EU for the recycling of these light materials is 5.59 MJ/Kg [7]. This is also due to the significant losses caused by material oxidation and it becomes particularly significant when high surface to volume parts, as chips, have to be recycled.

Solid State Recycling (SSR) techniques have been developed with the aim to overcome the above cited drawbacks [8]. To be more specific, according to the review paper published by Wan et al., two main SSR approaches have been investigated so far: techniques based on severe plastic deformation and SSR techniques based on powder metallurgy [9]. It is worth mentioning that most of the already published strategies rely on superimposing severe plastic deformation, in fact most of SSR practitioners focused on extrusion-based recycling approach.

Chiba et al. used a recycling route made of degreasing, cold compaction, annealing, cold extrusion and cold rolling in order to recycle AC4CH aluminum cast alloy machining swarf [10]. The mechanical properties of the recycled objects were tested after extrusion and after rolling, finding that the last stage is needed in order to eliminate residual voids present after extrusion and to increase the yield and ultimate tensile strength. It is worth noticing that after extrusion, although voids are found in the profile, the mechanical properties are higher than the ones of the as cast material. Misiolek et al. presented a comprehensive study on recycling by hot extrusion of AA6060 chips [11]. Different approaches were followed for the chips' compaction, i.e. single layer and multi-layer, and three different extrusion processes, i.e. flat face, porthole and ECAP (Equal Channel Angular Extrusion) were compared. It was found that the three processes result in true stress at necking similar to the one of cast billet extruded by flat face die, while ductility was significantly increased using ECAP. Some of the same authors have also pointed out that the overall quality of the extruded part is dependent on the breaking of the oxide layers between the chips, which occurs when proper shear stress is reached, and on the exceeding of a threshold value for the cumulative value of the ratio between the mean stress and flow stress [12]. Behrens et al. used hot back extrusion to recycle AA2007-T6 and AA7075-T6 aluminum alloys [13]. Both the alloys showed, after extrusion, 100% density and reduced hardness, ductility and ultimate tensile strength. The latter result was expected due to the loss of the thermal treatment of the parent material.

As alternative processes are concerned, Widerøe et al. developed in 2013 continuous screw extrusion for aluminum alloys [14]. The authors studied the material flow occurring during the process in order to optimize the design of the extruding machine. Paraskevas at al. presented in 2014 a novel process for aluminum chips called Spark Plasma Sintering (SPS) [15]. Two different aluminum alloys were tested and the recycled billet mechanical properties were compared to the ones of base material. Sound billets with fine equiaxed grains and no significant porosities were produced, characterized by higher elastic properties, due to the presence of dispersed oxides and similar plastic properties, depending on the temper status. Finally, Li et al. recently proposed a Friction Stir Welding based process, called Friction Stir Consolidation (FSC), to produce AA6061 aluminum alloy disks from machining chips [16]. This process needs no pre-compaction stage as the tool itself compacts the chips in the first stage of the process. Preliminary study on the process mechanics with varying process parameters revealed that the process has the potential to produce full dense disks/billets once tool force exceeds a threshold value.

The analysis of the literature reveals that over the last years several SSR technologies have been proposed. Different academic labs across the world have proved the technical feasibility of such processes. Nevertheless, the way to a full understanding of the actual potential of such process category is still long. In fact, three different research gaps can be identified: 1/mechanical and microstructural analysis of all the proposed processes is still incomplete; in-fact most of the studies focus on extrusion-based approach; 2/ the environmental sustainability with respect to the conventional (remelting based) route is still to be deeply understood. In this respect, only two researches were presented: Duflou et al. [17] applied a full LCA approach to compare three different SSR processes (ECAP, screw extrusion based and SPS) with the remelting route. Stotz at al. analyzed the aluminum can recycling case study. They considered a scenario including a SSR strategy (sintering based) implementation. It was concluded that SSR showed some potential improvements with respect conventional remelting based approach [18]. 3/ The workability of the consolidated samples has been barely analyzed. To the authors knowledge, only two researches dealt with this topic. Paraskevas et al. [15] carried out upsetting tests on spark plasma sintered samples and Kore et al. [19] developed cup drawing test on hot rolled consolidated aluminum sheets.

The present paper aims at contributing to fill the mentioned research gaps. To be more specific, a comprehensive analysis on FSC process is presented. Due to the asymmetric nature of FCS, microhardness and grain size analyses are performed in order to specifically evaluate the recycled disks homogeneity. A primary energy demand characterization is provided and a comparative analysis including remelting, ECAP and SPS approach is presented. Finally, the consolidated billets were further processed through closed die forging in order to have a first insight into the workability of SSR samples. The paper thus deals with the full recycling route, from chips up to final component obtainment.

2. Experimental procedure

2.1. The FSC process for chips recycling

Friction Stir Consolidation is a novel process developed to recycle metal chips by producing disks and small billets. In the process, a cylindrical rotating tool, controlled with constant force, is pushed into the billet chamber where the specific amount of chips has been previously placed. The combined action of tool force, tool rotation and process time determine an intimate contact between the chips which undergo significant strain. At the same time, temperature increases because of the friction between the bottom surface of the tool and the top layer of the chips inside the billet chamber. In this way, solid state welding can take place, starting from the top of the billet chamber towards its bottom, while the oxides on the chips surface can be finely dispersed into the compacted final product [16]. Although discontinues, the whole process can be considered a single-step operation, as pre-compaction is not needed, making worth of attention the study of its energy efficiency. Figure 1a shows a sketch of the process, together with the chips loaded in the billet chamber before the process (Figure 1b) and the final consolidated billet at the end of the process (Figure 1c).

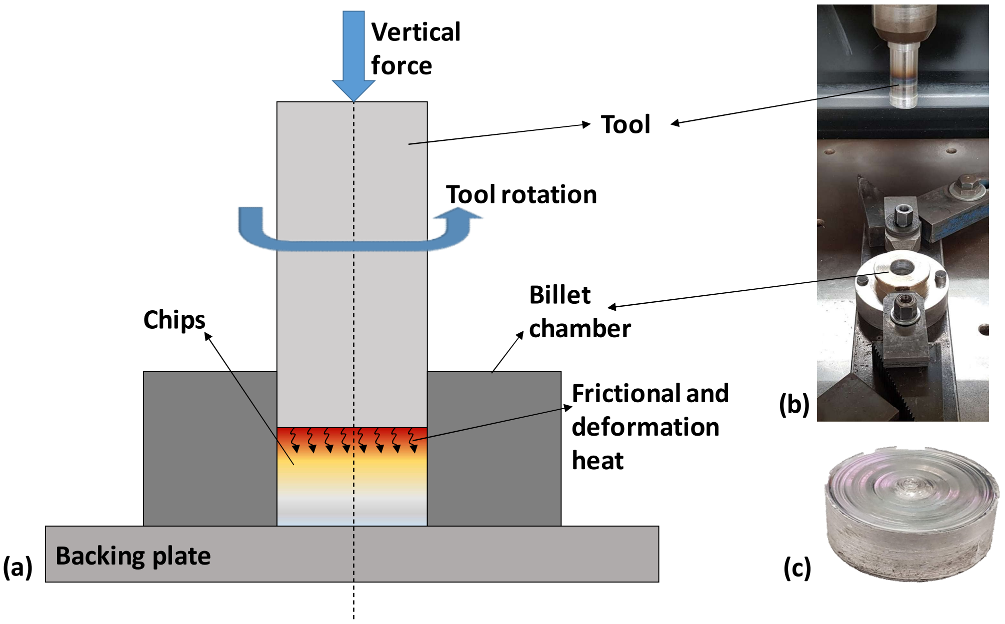

Fig. 1 (a) sketch of the process, (b) utilized fixture and (c) consolidated billet

2.2. Materials and process parameters

A 30 mm diameter round bar made of AA2024-0 aluminum alloy, characterized by Vickers microhardness of 47 and average grain size of 38 μm, was used for the experiments. Chips were created by dry turning in order to avoid the cleaning and decreasing steps. An H13 cylindrical tool with flat surface, 25mm in diameter, was used. Billet chamber was also made of H13 steel and is characterized by nominal diameter of 25 mm (tolerance 0.1-0.2 mm) and height of 40 mm. Among the main technological parameters there are tool rotation, tool force and process time. Previous studies on AA6061 aluminum alloys have highlighted that a threshold value of tool force must be reached in order to activate the process and produce consolidated billets [16]. In this study, constant tool force equal to 20KN, variable tool rotation, i.e. 500rpm, 1000rpm and 1500rpm, and variable process time, i.e. 10s, 30s and 40s, were used. It is worth noting that previous research showed that increasing tool force is the most influential factor for improving fraction of consolidation [16]. Hence, in this research, we decided to select a fixed force value equal to the maximum tool force exerted by the used machine. Finally, three different values of chips mass were used, i.e. 10g, 15g and 20g. In this way, a complete experimental plan of 27 different process conditions was carried out. The mass of chips in the billet chamber determines the final height and diameter of the consolidated disks. In order to increase each of the two parameters (or both) still obtaining a sound consolidation process an increase of the tool force is needed. As stated, in this study the maximum force available in the used machine was selected. In this way, the value of m=20g is an upper bound for the considered process conditions. ESAB Legio-3ST machine, specifically designed for Friction Stir Welding, was used for its capability to control the tool with constant force during the tests. Each experiment was repeated three times.

2.3. Analyzed Output

For each test, the electrical energy demand was acquired by a Fluke 435 power quality analyzer able to measure voltage, current, and power over process time. For each process condition, the cross section of the recycled disks was embedded, polished and etched with Keller reagent in order to highlight the microstructure. Vickers microhardness was measured in the cross section along three vertical lines, with vertical pitch of 0.25mm, at radius equal to 0 (the center of the disk), 6.25mm (corresponding to) R/2 and 12.25 (close to the outer surface, i.e. R). Finally, average grain size was measured along the same vertical lines used for the microhardness with vertical pitch equal to 1mm according to the standard test method for determining average grain size ASTM E112-13. It is worth mentioning that hardness and grain size measurements allows mechanical properties of the obtained disk to be analyzed and compared to the one of the parent material.

3. Results and discussion

3.1. Metallurgical and mechanical properties of consolidated billets

Disks, 25mm in diameter, were produced. Based on the starting chip mass, different heights, i.e. 6 mm, 10 mm and 15 mm, were obtained. As a matter of fact, FSC is a non-symmetrical process as the source of heat and plastic deformation, i.e. the bottom surface of the tool, acts on the top surface of the chips agglomerate to be recycled. In this way, the consolidation of the material starts close to the tool and “propagates” to the bottom of the disk. In case of wrong choice of the process parameters, typical unconsolidated material will be at the bottom of the disk. Figure 2 shows the typical conditions that may occur at the end of the process. Only partial consolidation occurred for the specimen produced with process time of 10s and rotation of 500rpm, for which the base of the disk was not formed (Figure 2a). As process time increases to 30s and rotation increases to 1500rpm, the disk is formed, but at the bottom several voids and only partially consolidated areas can be found (Figure 2b). In particular, four different zones can be identified as better visible in the magnified micrographs shown in figure 3: zone A, with fully recrystallized grain, characterized by larger dimensions in correspondence of the two "bowl" shaped areas. In these areas, the heat input is higher because of the rotation of the tool, which has a lower effect at the center of the disk; zone B, in which recrystallization is taking place and equiaxed recrystallized grains (B1 in figure 3) can be found together with deeply elongated grains (B2 in figure 3); zone C, in which the chips are welded but interfaces are still visible; zone D, characterized by unconsolidated material and visible pores and voids. Finally, figure 2c shows a fully consolidated disk for which only zones A and B are observed.

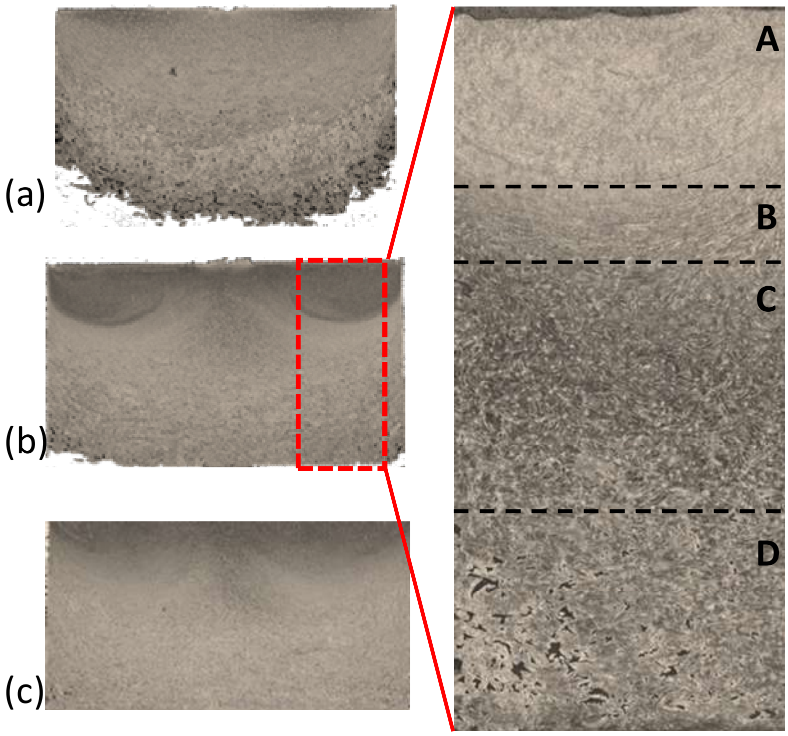

Fig. 2 Macrographs and microstructure of disks produced with mass of 20g: (a)R=500rpm, t=10s, (b)R=1500rpm, t=30s, (c)R=1500rpm, t=40s

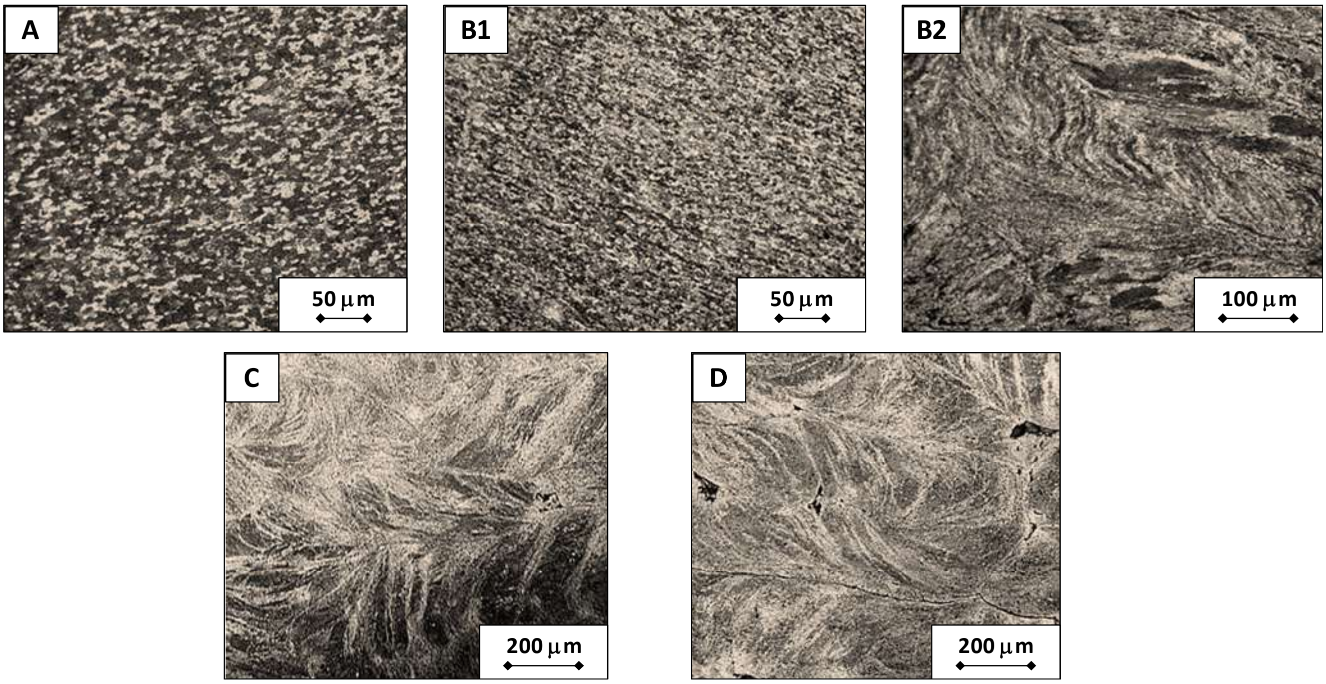

Fig. 3 Micrographs of the different disk zones shown in figure 2b.

Table 1 shows, for each case study, the average values of HV and average grain size, calculated taking into account all the measurements in the same specimen. In the table, the energy demand to carry out the process and the disk status (fully consolidated or not) are also reported. It is noted that only one specimen is not fully consolidated when m=10g is used, while 3 and 6 unconsolidated specimens are obtained when m=15g and m=20g are used, respectively. Low rotation, i.e. 500 rpm and short process time, i.e. 10s, always result in not fully consolidated disks due to the low heat input into the chips. Energy for these process conditions increases with process time and tool rotation. Slightly higher values are observed with larger mass to heat transfer phenomena inside the disk. As far as grain size is concerned, quite homogeneous conditions are found as it varies in a range of 10-18μm, with larger grains measured for "hotter" process conditions, i.e. longer time or higher rotation. The standard deviation of average grain size was also calculated, and similar low values were obtained for all the case studies. However, this parameter cannot be considered as a valid indicator of homogeneous conditions through the disk as, for not fully consolidated disks, grain size cannot be measured in zones C and D (see Figure 3). In other words, where grain can be identified, it has a fine equiaxed shape and quite regular dimension.

Looking at disks' homogeneity, more interesting information can be acquired from the standard deviation of microhardness (Figure 4). It is noted that a significant difference exists between the considered case studies. Overall, a decreasing trend is observed from the top surface of the consolidated billets to the bottom surface. In particular, high quality specimens show only a minimal decrease in microhardness (e.g. lower than 4HV) while low quality specimens show more significant drops. In order to quantitatively take into account this aspect and to evaluate the consolidation, standard deviation of microhardness was also analyzed. It was observed that HV standard deviation increases with increasing mass. The observation of micrographs and Figure 4 allows the determination of a threshold value, equal to 10, to identify fully consolidated disks. Specimens with values higher than the threshold are the not fully consolidated ones (see table 1). As heterogeneity risk increases as the sample height (i.e. mass of the disk) increases, higher tool rotation and process time have to be used. Finally, the average HV value of fully consolidated disks ranges between 70 and 80, which is larger than the 47HV of base material. Reasons for this behavior are: (i) the material during the process undergo a sort of heat treatment due the thermal history [20], the hardening effect of recrystallized grains and the dispersion of oxides originally present on the surface of chips [21].

Table 1

Mechanical, microstructural and energetical properties of the considered case studies

Case study (rotation-time-mass)	Avg grain size [μm]	Avg HV	Energy [kWs]	Fully consolidated
500-10-10	12.0	74	40	N
500-30-10	11.6	71	120	Y
500-40-10	11.7	72	160	Y
1000-10-10	12.0	78	42	Y
1000-30-10	13.0	73	135	Y
1000-40-10	14.0	79	170	Y
1500-10-10	16.6	86	45	Y
1500-30-10	15.5	83	135	Y
1500-40-10	18.0	82	180	Y
500-10-15	9.6	70	45	N
500-30-15	14.8	70	135	N
500-40-15	16.9	70	170	Y
1000-10-15	14.9	71	43	N
1000-30-15	16.4	70	135	Y
1000-40-15	13.9	72	180	Y
1500-10-15	16.0	76	50	Y
1500-30-15	15.1	73	150	Y
1500-40-15	15.7	76	190	Y
500-10-20	10.2	60	32	N
500-30-20	10.6	68	150	N
500-40-20	15.7	65	195	N
1000-10-20	14.6	77	45	N
1000-30-20	12.8	80	150	N
1000-40-20	13.0	75	200	Y
1500-10-20	13.2	80	47	N
1500-30-20	12.1	77	150	N
1500-40-20	15.9	79	220	Y

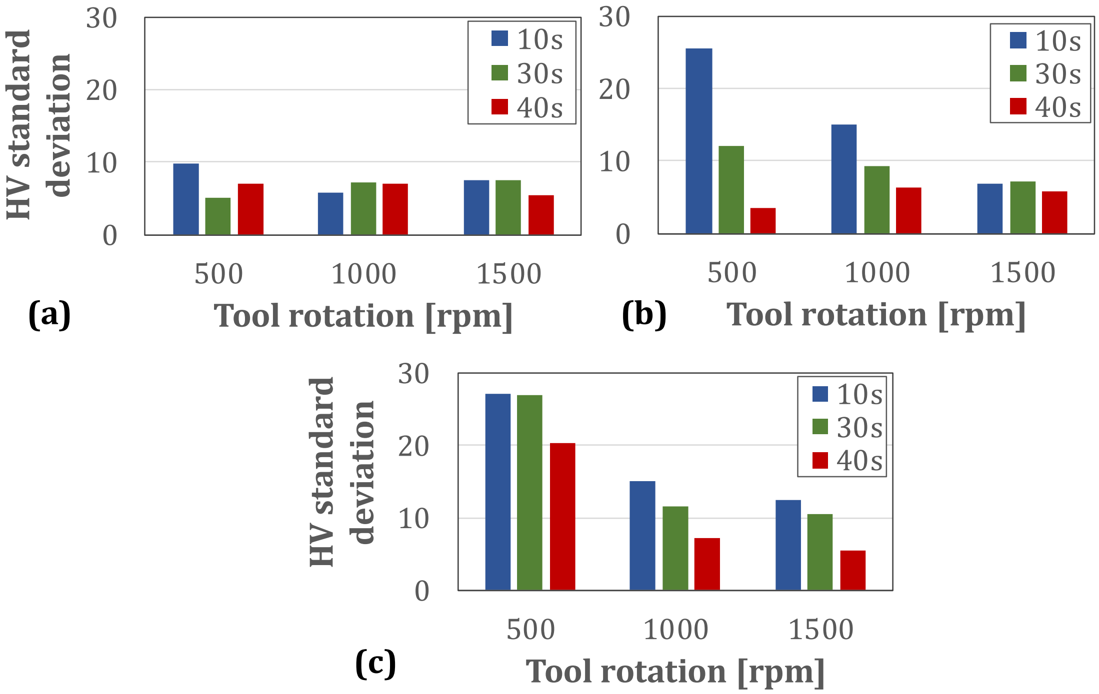

Fig. 4 Standard deviation of the microhardness for the considered case studies: (a) m=10g, (b) m=15g, (c) m=20g

3.2. Primary energy demand characterization

In order to properly characterize the energy efficiency of FSC processes as recycling method, a comparative analysis with both conventional (remelting based) and SSR routes (SPS and ECAP) recycling approaches is presented in this section.

The functional unit selected to develop the analysis is the production of 0.01 kg of aluminum alloys billet starting form chips. For each process route, all the energy and resource flows to consolidate scraps into billet were included in the analysis. The primary energy demand (or cumulated energy demand) was selected as metric to compare the energy efficiencies of the considered recycling routes. Electric energy demand was converted into primary energy source consumption by considering an average efficiency of 34% to account for the energy generation and the transmission losses.

As first step, a drying process is envisaged for each process route. Although, normally, chips undergo both chemical degreasing and drying, in this research only drying is considered as the only relevant in terms of primary energy demand indicator [22]. After drying, the FSC can be directly applied to obtain a recycled billet, while, for the SPS and ECAP routes, a compaction step is considered before the actual consolidation step. Concerning the remelting route, besides the melting step, which includes also casting and alloying, hot extrusion and sawing were considered to obtain the desired billet. Sawing was considered as final step also for the ECAP route. As mentioned in introduction, permanent material losses occur while remelting due to oxidation. In this research it is assumed that the amount of material losses is as high as 16%; this amount is the most likely scenario to happen during chips melting as suggested by Duflou et al. [17]. The impact of permanent material losses was considered by adding the same amount of primary aluminum in the model. An embodied primary energy equal to 206 MJ/KG [23] was used for the AA2024.

All the material yields for each considered process were taken into due account. Permanent material losses occurring while remelting aside, the others process scraps are basically homes scraps (high quality with high level of purity), therefore they can be easily recycled. It is assumed that such scraps leave the system without any environmental cost. Since the Mg content of the scrap is expected to become half or less after remelting, such loss was compensated by adding 0.75% wt of pure Mg. The main Life Cycle Inventory (LCI) data are reported in Table 2. The results of the comparative analyses are reported in Figure 5. For each analyzed recycling route, the contribution of each process step/factor towards the total primary demand is reported. Overall, it is possible to notice that SSR approaches enable substantial energy savings with respect to the remelting based approach. ECAP requires the lowest amount energy enabling 56% of primary energy saving.

Table 2.
Life cycle inventory data.

Process	Primary energy [MJ/kg]	Material Yeld (**%**)	Reference
Drying	3.4	100	[22]
Cold compaction	8.8	100	[21]
FSC	41	100	100-30-10
Hot extrusion	11.5	75	[7]
ECAP Hot extrusion	13.5	75	[7], [21]
Melting and casting	6.4	16% of permanent losses	[7][21]
SPS	31.3	100	[21]
Sawing	0.4	90	[24]

Also, results reveal that FSC and SPS energy demands are very close each other and their implementation would allow a reduction in energy demand as high as about 43% with respect to the conventional recycling route.

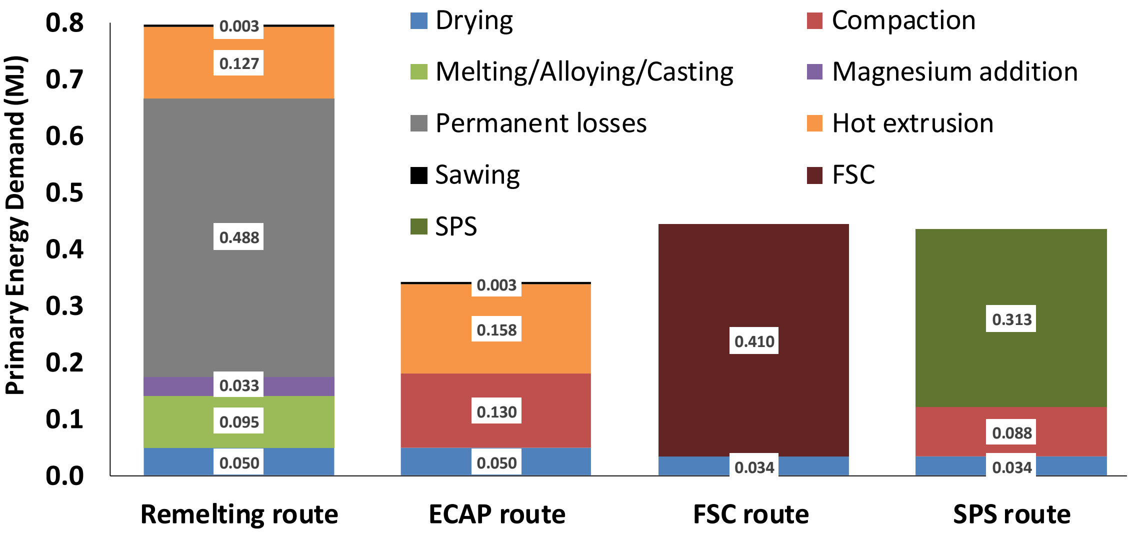

Fig. 5 Primary energy demand of different recycling routes

Permanent material losses significantly affect the bad performance of the conventional route. In fact, material losses account for 63% of the energy demand trough remelting. As a matter of facts, in terms of pure processing energy, the conventional route would demand even less energy with respect to SSR processes. Finally, it is worth mentioning that SPS and FSC energies are based on not fully dedicated machine working in lab environment. Fully dedicated machine coupled with industrial practices would further improve the energy efficiency of these processes.

4. Processability evaluation

In order to further explore the suitability of FSC as recycling process, forging operations were performed on the consolidated disk to turn the semi-finished workpieces into near net shape parts.

Cold forging was considered by using a simple axisymmetric geometry, thus allowing a first insight into the processability of the consolidated billets. A 450 tons screw-press, with energy set at 55%, was used to test both the fully consolidated specimens obtained with m=15g and parent material.

Figure 5 shows the cross section of the forged parent material (PM-F) and the one of the 1500-30 case study. Satisfying die filling is obtained with both disks. However, as expected, microstructure is significantly different: the PM-F forged part (Figure 6a) shows a homogeneous microstructure with typical flow lines, while in the forged consolidated specimen (Figure 6b) the two distinct zones observed after FSC, i.e. zone A and B, are still visible. No cracks were observed.

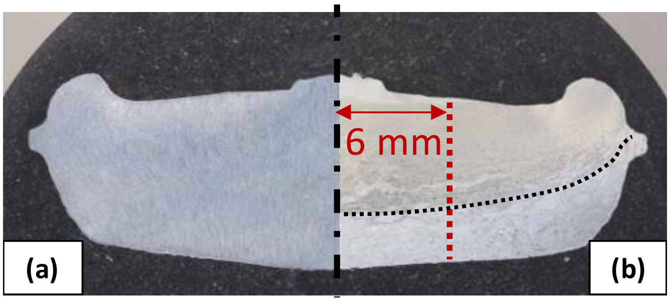

Fig. 6 Etched cross section of forget parts: (a) parent material (PM-F and (b) 1500-30 case study

With the aim to evaluate the local mechanical properties of the forged parts, microhardness has been measured along the dotted red line shown in Figure 6. Figure 7 shows the results obtained for the PM-F, 1500-30 and 1000-30 case studies, as compared to parent material (PM) and average hardness of consolidated disks (FSC).

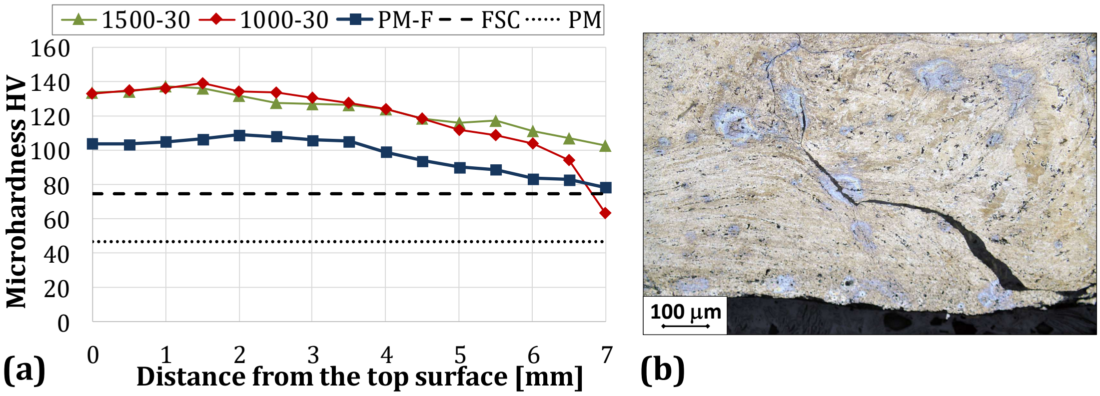

Fig. 7 (a) Microhardness of the forged parts and (b) micrograph of the center bottom of the 1000-30 case study

A slight decrease is observed for the 1500-30 case study getting close to the bottom of the forged part, due to the change of microstructure, from fully recrystallized (zone A) to partially recrystallized (zone B). The PM-F specimen shows less significative variations along the measurement line. Additionally, average larger values are found for the consolidated forged specimen, being the hardness values of the latter larger, consistently with the average values measured in the starting disks and reported in the figure. Finally, a peculiar condition is found for the 1000-30 case study. The HV measured is similar to the one of the 1500-30 specimen in the top half of the specimen, while decreases sharply close to the bottom. Looking at the center of the specimen, close to the bottom, a fracture can be observed (Figure 7b) in correspondence with the grain boundaries. Although the disk was considered sound after FSC, it can be noted that a value of HV standard deviation equal to 9.2, close to the threshold value of 10 identified for fully consolidated disks, was obtained. In this way, it can be inferred that ineffective solid bonding have been achieved during FSC, and the threshold value of HV standard deviation for sound disks should be lowered, for the process parameters considered in this study, to 7.2, i.e. the second highest value of the "fully consolidated" disks, which corresponds to the 1500-30 case study.

5. Conclusions

The paper presents an insight into a novel solid-state recycling process. Performances of FSC for consolidating aluminum chips into billet are analyzed. In order to uncover the actual potential of this recycling process, FCS has been studied under three different perspectives.

1/Since FCS is an asymmetric process, metallurgical and mechanical properties homogeneity of the consolidated billet with varying process parameters have been first analyzed. Results revealed that a strict correlation exists between the mass of chips to be consolidated and the heat that must be input by increasing tool rotation and process time. An inadequate combination of these parameters results in voids at the bottom of the billets. Process parameters configuration leading to satisfactory results were identified. In fact, fully consolidated billet characterized by both suitable grain size distribution (as it varies in a range of 10-18μm with low standard deviation) and hardness values (higher than that of the parent material) were obtained.

2/Second, in order to characterize the energy efficiency of the process, a comparative primary energy demand analysis is presented. FCS allows substantial energy saving (a reduction as high as 43% was quantified) with respect conventional remelting based route and its energy demand is similar to those of other SSR routes. It is worth mentioning industrial implementation of FSC by means of dedicated machine would further improve the energy efficiency of these recycling approach.

3/Finally, the forgeability of the consolidated billets is tested. The shapes and hardness measured in the forged parts proved that FS consolidated parts can be directly used as input workpiece for net shape processes. In fact, forged components characterized by no material flow defects and with proper harness distribution were obtained.

It is worth mentioning that SSR techniques allows only closed-loop recycling strategies implementation. In fact, these recycling approaches do not allow composition changes (either alloying elements or primary aluminum addition) as remelting based route does. In consequence, at present, the big variety characterizing the aluminum demand cannot be met by SSR. On the other hand, SSR approaches are particularly suitable for in-house recycling and the supply chain could be significantly compressed enabling further energy savings.

Also, dynamic material flows of aluminum demand show that improving sorting techniques is mandatory regardless of the SSR implementation; in fact, as stated by Hanno Buchner et al. “if current recycling practice is retained, a surplus of mixed Al scrap over final cast Al demand is expected around 2045” [25]. A better sorting approach would enable a better wrought alloy recycling efficiency. Summing up, SSR processes still represent part of the solution and there is a pressing research need to uncover their actual potential in being applied as environmentally friendly aluminum recycling strategy.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Worrell, E., Allwood, J.M., Gutowski, T. (2016). The Role of Material Efficiency in Environmental Stewardship. *Ssrn* 41, 575–598. https://doi.org/10.1146/annurev-environ-110615-085737
2. Gutowski, T.G., Sahni, S., Allwood, J.M., et al (2013). The energy required to produce materials: Constraints on energy-intensity improvements, parameters of demand. *Philos Trans R Soc A Math Phys Eng Sci* 371,. https://doi.org/10.1098/rsta.2012.0003
3. Tolio, T., Bernard, A., Colledani, M., et al (2017). Design, management and control of demanufacturing and remanufacturing systems. *CIRP Ann - Manuf Technol* 66, 585–609. https://doi.org/10.1016/j.cirp.2017.05.001
4. Lee, C.-M., Woo, W.-S., Roh, Y.-H. (2017). Remanufacturing: Trends and issues. *Int J Precis Eng Manuf - Green Technol* 4, 113–125. https://doi.org/10.1007/s40684-017-0015-0
5. Ingarao, G. (2017). Manufacturing strategies for efficiency in energy and resources use: The role of metal shaping processes. J. Clean. Prod. 142:2872–2886
6. Kim, D.-H., Kim, J.-H., Kim, Y.-G., et al (2018). Evaluation of Microstructure and Mechanical Properties on Solution Heat Treatment of Recycled A319 Cutting Chip. *Int J Precis Eng Manuf - Green Technol* 5, 427–433. https://doi.org/10.1007/s40684-018-0018-5
7. EAA (2013). Environmental Profile Report for the European Aluminium Industry April 2013- Data for the year 2010 Life Cycle Inventory data for aluminium production and transformation processes in Europe
8. Lee, C.-M., Choi, Y.-H., Ha, J.-H., Woo, W.-S. (2017). Eco-friendly technology for recycling of cutting fluids and metal chips: A review. *Int J Precis Eng Manuf - Green Technol* 4, 457–468. https://doi.org/10.1007/s40684-017-0051-9

9. Wan, B., Chen, W., Lu, T., et al (2017). Review of solid state recycling of aluminum chips. *Resour Conserv Recycl* 125, 37–47. https://doi.org/10.1016/j.resconrec.2017.06.004
10. Chiba, R., Nakamura, T., Kuroda, M. (2011). Solid-state recycling of aluminium alloy swarf through cold profile extrusion and cold rolling. *J Mater Process Technol* 211, 1878–1887. https://doi.org/10.1016/j.jmatprotec.2011.06.010
11. Misiolek, W.Z., Haase, M., Ben Khalifa, N., et al (2012). High quality extrudates from aluminum chips by new billet compaction and deformation routes. *CIRP Ann - Manuf Technol* 61, 239–242. https://doi.org/10.1016/j.cirp.2012.03.113
12. Güley, V., Güzel, A., Jäger, A., et al (2013). Effect of die design on the welding quality during solid state recycling of AA6060 chips by hot extrusion. *Mater Sci Eng A* 574, 163–175. https://doi.org/10.1016/j.msea.2013.03.010
13. Behrens, B.A., Bouguecha, A., Brunotte, K., et al (2016). Reprocessing of aluminum chips by hot backward extrusion. *Prod Eng* 10, 375–382. https://doi.org/10.1007/s11740-016-0682-7
14. Widerøe, F., Welo, T. (2013). Using contrast material techniques to determine metal flow in screw extrusion of aluminium. *J Mater Process Technol* 213, 1007–1018. https://doi.org/10.1016/j.jmatprotec.2012.11.013
15. Paraskevas, D., Vanmeensel, K., Vleugels, J., et al (2014). Spark plasma sintering as a solid-state recycling technique: The case of aluminum alloy scrap consolidation. *Materials (Basel)* 7, 5664–5687. https://doi.org/10.3390/ma7085664
16. Li, X., Baffari, D., Reynolds, A.P. (2018). Friction stir consolidation of aluminum machining chips. *Int J Adv Manuf Technol* 94, 2031–2042. https://doi.org/10.1007/s00170-017-1016-4
17. Duflou, J.R., Tekkaya, A.E., Haase, M., et al (2015). Environmental assessment of solid state recycling routes for aluminium alloys: Can solid state processes significantly reduce the environmental impact of aluminium recycling? *CIRP Ann - Manuf Technol* 64, 37–40. https://doi.org/10.1016/j.cirp.2015.04.051
18. Stotz, P.M., Niero, M., Bey, N., Paraskevas, D. (2017). Environmental screening of novel technologies to increase material circularity: A case study on aluminium cans. *Resour Conserv Recycl* 127, 96–106. https://doi.org/10.1016/j.resconrec.2017.07.013
19. Kore, A.S., Nayak, K.C., Date, P.P. (2017). Formability of aluminium sheets manufactured by solid state recycling. In: Journal of Physics: Conference Series
20. Baffari, D., Reynolds, A.P., Li, X., Fratini, L. (2017). Influence of processing parameters and initial temper on Friction Stir Extrusion of 2050 aluminum alloy. *J Manuf Process* 28, 319–325. https://doi.org/10.1016/j.jmapro.2017.06.013
21. Duflou, J.R., Tekkaya, A.E., Haase, M., et al (2015). Environmental assessment of solid state recycling routes for aluminium alloys: Can solid state processes significantly reduce the environmental impact of aluminium recycling? *CIRP Ann - Manuf Technol* 64, 37–40. https://doi.org/10.1016/j.cirp.2015.04.051
22. Cooper, D.R., Song, J., Gerard, R. (2018). Metal recovery during melting of extruded machining chips. *J Clean Prod* 200, 282–292. https://doi.org/10.1016/j.jclepro.2018.07.246
23. (2017). Granta Design Limited. CES Selector
24. Milford, R.L., Allwood, J.M., Cullen, J.M. (2011). Assessing the potential of yield improvements, through process scrap reduction, for energy and CO2 abatement in the steel and aluminium sectors. *Resour Conserv Recycl* 55, 1185–1195. https://doi.org/10.1016/j.resconrec.2011.05.021
25. Buchner, H., Laner, D., Rechberger, H., Fellner, J. (2017). Potential recycling constraints due to future supply and demand of wrought and cast Al scrap—A closed system perspective on Austria. *Resour Conserv Recycl* 122, 135–142. https://doi.org/10.1016/j.resconrec.2017.01.014