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Energy Demand Reduction Of Aluminum Alloys Recycling Through Friction Stir Extrusion Processes Implementation

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Abstract

Aluminum alloys are characterized by high-energy demands for primary production. Recycling is a well-documented strategy to lower the environmental impact of light alloys production. Despite that, conventional recycling processes are still energy-intensive with a low energy efficiency. Also, permanent material losses occur during remelting because of oxidation. Recently, several solid-state recycling approaches have been analyzed; in fact, by avoiding the remelting step both energy and material can be saved and, therefore, the embodied energy of secondary production can be substantially reduced. In this paper, the solid-state approach Friction Stir Extrusion (FSE) is analyzed for aluminum alloys recycling, the primary energy demand of such recycling strategy is quantified. Comparative analyses with both conventional and direct extrusion based processes are developed.

Keywords: Solid state recycling, FSE, aluminum alloys, comparative analysis

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1. Introduction

A relevant share of global CO_2 emissions is caused by raw material production. Worrell et al. [1] state that material production activities cause about 25% of global CO2 emissions. What is more, such environmental burden is dominated by only five materials: steel, cement, paper, aluminum alloys, and aggregated plastics. To be more specific, metals, steel and aluminum alloys are responsible for about 25% and 3% of CO_2 emissions for material production,

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respectively [2]. Gutowski et al. [2] state that, from 2005 to 2050, the demand for aluminum is expected to grow by a factor of between 2.6 and 3.5, while the demand for steel between 1.8 and 2.2. In order to limit and reverse such phenomenon, putting in place strategies to keep the material in the circle over multiple life-cycles is mandatory. Actually, the concept of circular economy is gathering more and more pace, and there is a global need to move towards a closed-loop society [3]. Longer life, more intense use, repair, product upgrades, modularity, remanufacturing, component re-use and open/closed loop recycling are some of the strategies to put in place to reduce the environmental impact of raw material production.

At present, conventional recycling is the most applied strategy for metals as it offers many advantages in terms of technical, economic and environmental concerns. Concerning light-weight alloys, primary energy savings as high as about 90% can be obtained for aluminum, magnesium and titanium alloys [4]. As far as aluminum alloys are concerned, conventional (remelting based) recycling route is still an energy-intensive one and there is still room to make the recycling process more efficient. As a matter of facts, the overall energy efficiency is quite low and, more importantly, permanent material losses occur during remelting because of oxidation. This aspect is particularly relevant for light-gauge scraps like chips, material losses as high as 15-20% [5] may occur. In order to overcome such issue, researches have been turned to several Solid State Recycling (SSR) approaches; in fact, by avoiding the remelting step, both energy and material can be saved.

Solid state activation depends on pressure, temperature and contact time among surfaces to be joined and several strategies have been already successfully applied. Haasse et al. [6] used the ECAP (Equal Channel Angular Pressing) integrated extrusion processes to consolidate aluminum chips into a billet. A variant of this process was presented by Widerøe et al. [7], they applied a direct screw extrusion method, to compact scraps and extrude profiles in one single step. Kamilah et al. [8] used hot forging processes as a sustainable direct recycling technique of aluminum. Other authors [9] used Friction Stir Extrusion (FSE) to fully consolidated wires from aluminum alloys chips; Li et al. [10] proposed the friction consolidation process to turn chips into a billet.

Paraskevas et al. [11], instead of using severe plastic deformation to get solid bonding conditions, applied sintering based processes propose the use of Spark Plasma Sintering (SPS) as a novel solid-state recycling technique for aluminum alloys. A comprehensive summary of solid-state recycling processes of aluminum chips has been recently developed [12].

It is worth pointing out that environmental impact characterization of the direct recycling processes is yet to be well evaluated and standardized. The only available quantitative, as well as comparative analysis, was proposed by Duflou et al. [13]. In this research, the environmental impact of ECAP extrusion, screw extrusion, and SPS is analyzed and compared with the traditional remelting based recycling route.

In the present paper, a new solid-state recycling process, based on the Friction Stir Extrusion (FSE) step, is analyzed for aluminum alloys recycling. The primary energy demand characterization of such recycling strategy is quantified and compared to ECAP based as well as to conventional recycling processes.

2. The FSE as solid-state recycling process

Friction Stir Extrusion (FSE) is an innovative solid-state technology that allows the production of wires and rods from metal chips or solid billet. This technique belongs to the Friction Stir Processing (FSP) technologies, developed following up the “Friction Stir Welding” (FSW). During the process, a rotating die is plunged into a hollow chamber containing a billet of the material to be extruded. The work of the friction forces between the die and the billet decaying into heat causes the metal to soften, producing a plastic flow through the extrusion channel on the rotation axis of the die itself. FSE was developed in 1993 by The Welding Institute in Cambridge, UK and underwent very little evolution until the patent was allowed to lapse in 2002. Fig. 1 shows a sketch of the process. The chip closer to the tool, i.e. closer to the heat source, rotates together with the tool and plasticizes due to the combined effect of high temperature and stirring. Moving far from the tool interface, a transition layer is encountered, in which the chip is heated but has not been homogenized as a continuum material. The extrusion starts from the rotating plasticized layer and is influenced by the combined action of tool rotation and force on the tool. At the end of the process, the extruded material returns to room temperature by calm air cooling. Similarly, to the conventional extrusion processes, the main geometrical parameter of the FSE process is the extrusion ratio, namely the ration between the extrudate and the chamber diameters. Choosing a high extrusion ratio may prevent the reaching of critical bonding at the center of the produced wire, leading to defect formations [14]. On the other hand, the main technological parameters affecting the process are the tool rotational speed and the extrusion force. Applying a constant extrusion force allows the plunge velocity to adapt to the local flow stress of the material. In this way, the extrusion occurs only when the raw material reaches proper levels of temperature and strain.

For the present research, the parameters used during the experimental campaign have been selected from the effective parameter engineered on previous work on aluminum alloy by some of the authors of this paper [15]. Specifically, 2 mm diameter wire was extruded and an extrusion ratio as high as 156.

In the present research an ESAB LEGIO 3ST, a dedicated FSW machine with force controlled vertical axis (maximum load 25 kN), was used. Figure 2 depicts the used machine alongside an example of the extruded wire.

It is worth pointing out that although the used machine was not specifically designed for FSE processes, it is a quite dedicated machine as both FSE and FSW processes use the same main friction based principle enabled by a tool rotating. The dedicated tool set was manufactured out of AISI H13 steel and it consists of a hollow matrix and a rotating die characterized by a 2 mm extrusion channel with an external diameter equal to 25 mm. The process parameters selected for the experiments were 700 rpm for tool rotation and 22 kN for the extrusion force.

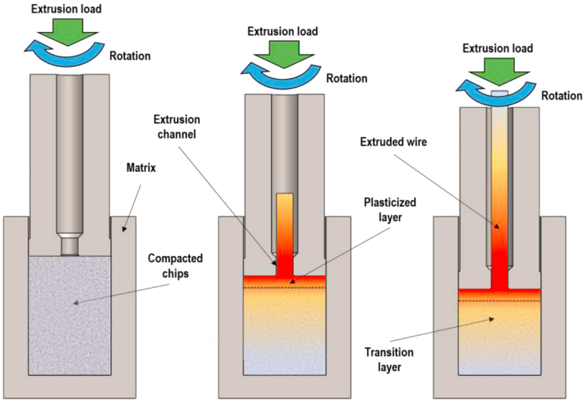

Fig. 1 Sketch of the Friction Stir Extrusion process.

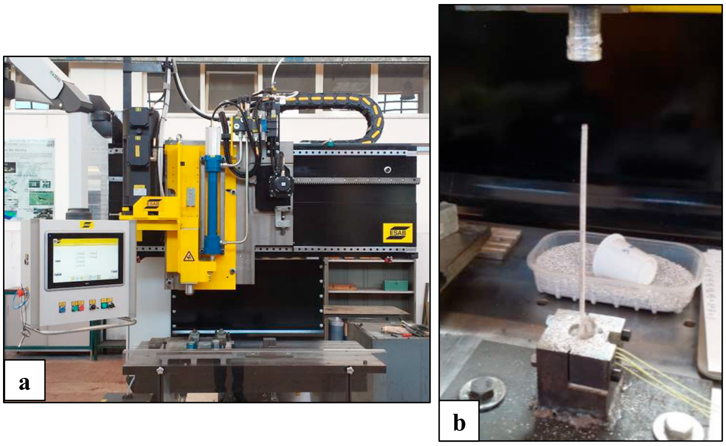

Fig. 2 (a) The used machine and (b) an example of the obtained wire.

3. System boundary and major assumptions

Three different recycling routes are considered for comparison, namely: conventional (remelting based), ECAP based and FSE based. Since FSE is particularly suitable for wire production, the production of 1 kg of AA 6060 aluminum alloy was selected as a functional unit. In the ECAP based route, chips cleaning and compaction steps are considered prior the actual ECAP extrusion step. The severe deformation characterizing the process, enable oxides layers breaking and solid bonding activation. Concerning the remelting approach, the chips are collected and melted together to get the desired alloy, extrusion, and wire drawing steps are envisaged to get the proper workpiece.

A closed AA6060 recycling loop was considered for all the routes, avoiding down-cycling or compositional corrections during melting. The selected system boundary is depicted in figure 3 where all the process steps accounted for as well as the material flows are highlighted. It can be noticed that process scraps were taken into account and were considered as part of a new recycling phase. The impact of permanent material losses occurring during remelting was considered by adding the same amount of primary aluminum in the model. The primary energy was considered as a metric to compare the different process routes. The processes 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.

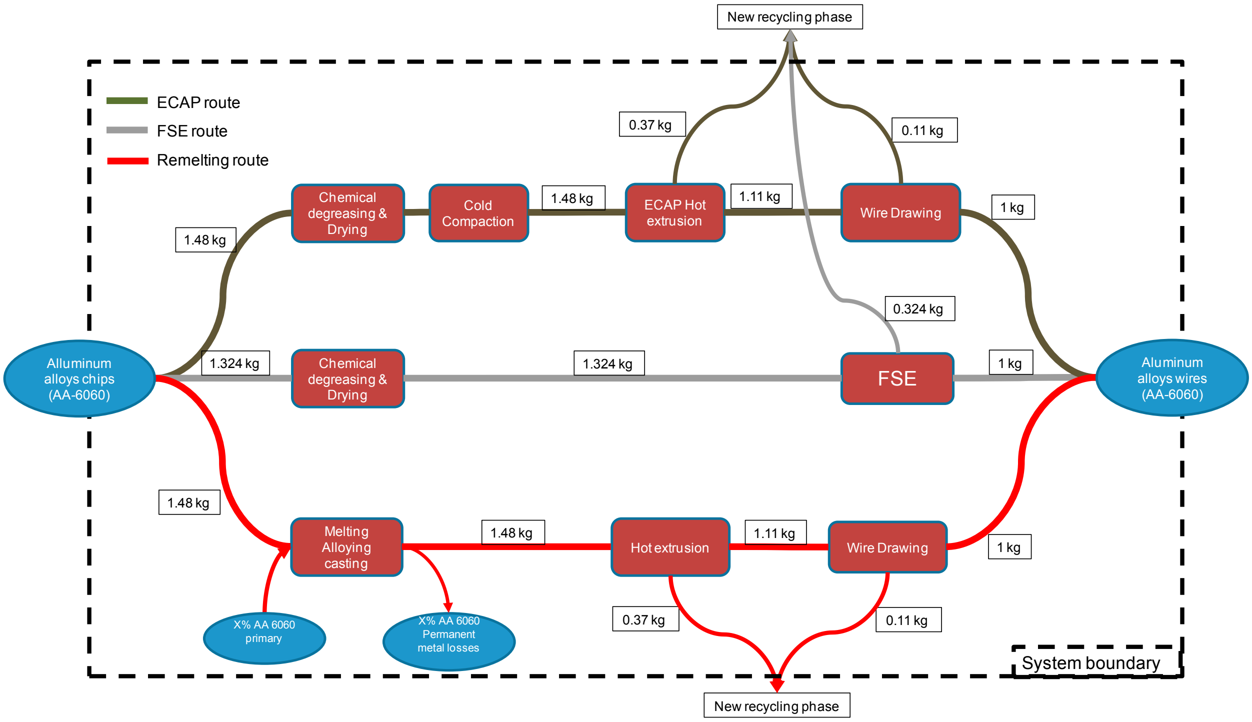

Fig. 3 System boundary with considered processes and material flows highlighted.

4. Life cycle inventory

Apart from the electrical energy of the FSE process, which was experimentally quantified, the other inventory data were selected from both scientific papers and dedicated databases. The EAA environmental report [16], as well as the paper from Duflou et al. [13], were used as primary LCI sources. The process material yields were found in the EAA report and in CES Edupack [17] for the hot extrusion and the wire drawing processes, respectively. As far as the FSE is concerned, there are no available industrial data about material yield; considering the straightforward similarity with conventional extrusion processes, the same material yield was assumed in the present study.

Since the Mg content of the scrap is expected to become half or less after remelting, such loss was compensated by adding 0.3% wt of pure Mg [14]. The main LCI values alongside the consulted references are reported in table1.

Table 1. Main LCI data and sources

	Primary specific energy (MJ/kg)	Reference
Cleaning	8.1	[18]
Cold Compaction	8.8	[13]
ECAP hot extrusion	12.8	[13][16]
FSE	23.5	Experimentally measured
Hot extrusion	10.7	[16]
Primary Production AA-6060	210	[17]
Wire drawing (AA-6060)	17	[17]
Melting and casting	7.6	[16]

Concerning the electric energy characterization of FSE, the Fluke 435 power quality analyzer was used to measure tension, current, and power over process time. The Power profile of the whole working to produce 0.03 kg of aluminum alloy wire depicted in figure 4.

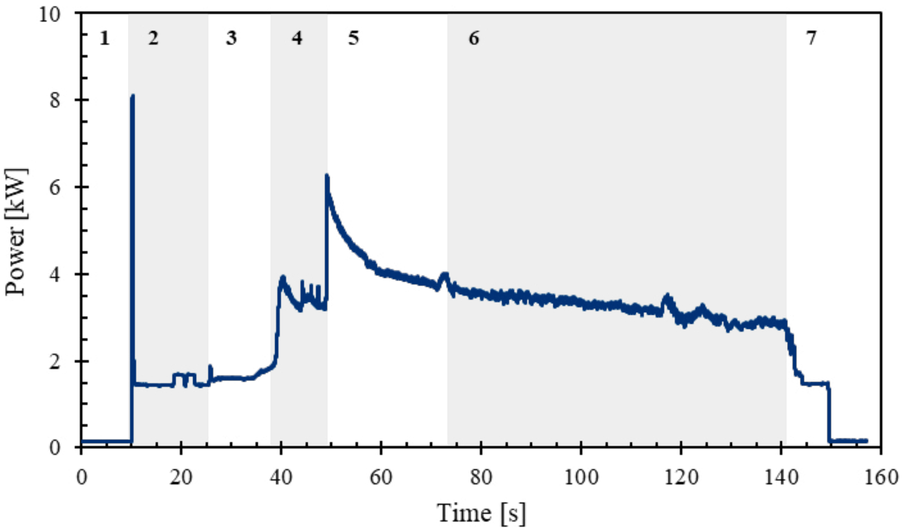

Fig. 4 Power trend for FSE recycling.

Four different power levels can be noticed, corresponding to different production phases. In figure 4 seven different production phases are highlighted, an explanation of these phases follows:

1. Machine switch/on
2. Hydraulics on/ Stand-by mode
3. Spindle on and first plunging phase (0.5 mm/s, position control)
4. Switch to force control (5 kN)
5. Force increase to extrusion value (18 kN)
6. Extrusion phase
7. Spindle stop and hydraulic off

For the present study only phase 4, 5 and 6 have been considered for quantifying the electric energy demand of wire production, other non-productive production modes were left out for lack of industrial time studies.

5. Discussion of the results

The results of the developed comparative analysis are reported in figure 6. For each analyzed recycling route the contribution of each process step/factor, towards the total demand, is highlighted. An intermediate scenario with 15% material losses is reported, to get this share of permanent losses a briquetting step to compact scraps is to be implemented [18]. It is possible to see that both SSR processes outperform conventional remelting based route. This is mainly due to the avoided permanent material losses. In fact, in terms of pure processing energy, the conventional route would demand less energy with respect to SSR processes. It is worth pointing out that FSE based route is the most energy efficient for the analyzed case study; as a matter of facts, FSE enables the primary energy demand to be reduced by 53% and by 33% with respect the remelting and the ECAP route, respectively. The energy reduction, characterizing the FSE process is due to the absence of the wire drawing step which is an energy-intensive one. In fact, if the drawing process is left out of the comparative analysis, FSE as ECAP route primary energy demands are very close to each other. In addition, the variability of the data characterizing the eco-properties (Embodied energies for material production as well as processing energies values) of materials and processes [19], does not allow a more general and clear identification of the most efficient SSR process.

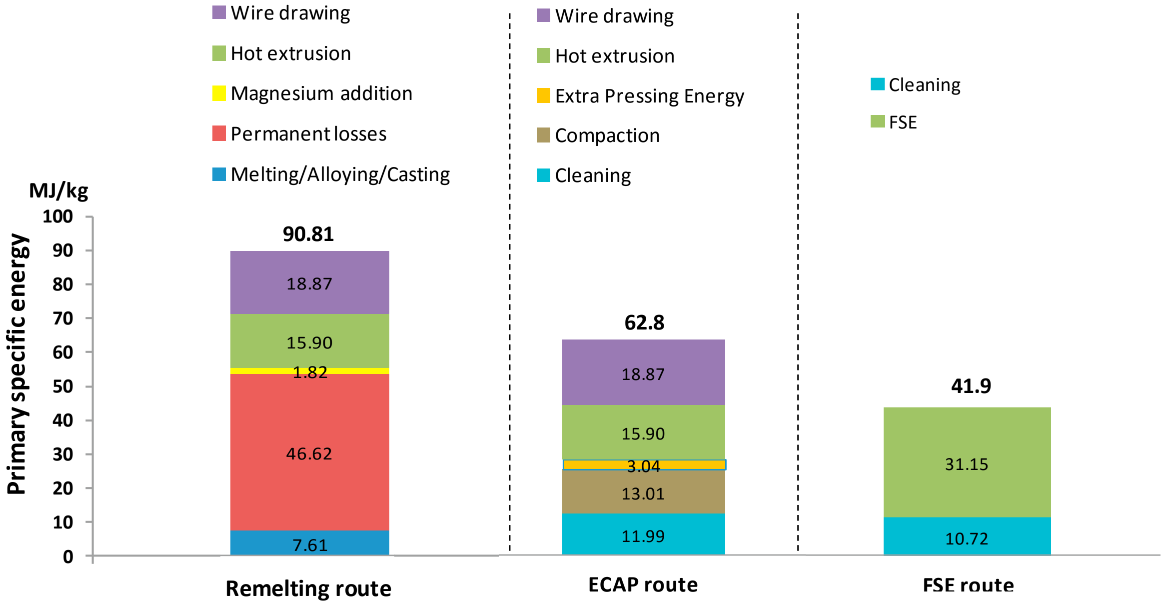

Fig.5 Primary specific energy demands of the analyzed recycling routes.

6. Conclusions and further developments

In this research, a comparative analysis of three aluminum recycling routes is developed. The aim was to characterize the energy efficiency of FSE as a new variant of SSR processes. According to what reported by Duflou et al. [13], the advantages of SSR processes with respect to the remelting route was proved. In case of wire production, the FSE enables a further primary energy demand reduction with respect to ECAP based route. Results do not allow the authors to generalize such results for other output shapes/semi-finished products (billet, profiles, etc.). It is worth pointing out that FSE process is still a discontinuous process and cannot provide the same productivity of extrusion-based processes, some authors of the present paper are focusing their research effort in making FSE recycling process a continuous one. A further development of the present research will concern the quantification of energy efficiency of FSE processes to recycle magnesium chips, in fact, some of the authors of the present paper have already successfully recycled magnesium alloy chips into wire [14].

It is worth pointing out that, at present, SSR might represent a part of the solution; in fact, such techniques do not allow composition changes (either alloying elements or primary aluminum addition) as remelting based route does.

In consequence, only closed-loop recycling strategies can be applied and 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, cost comparison among the available recycling routes it not available in literature yet, such further analysis could provide more clarity in suitable recycling option identification.

In conclusion, researchers should focus on identifying the suitable applications for SSR and, more importantly, should identify the best matching between SSR processes and the shape of the obtained semi-finished product (slab, billet, profiles, wires, etc.).

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