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Aluminium sheet metal scrap recycling through friction consolidation

Dario Baffari*, Gianluca Buffa, Giuseppe Ingarao, Attilio Masnata and Livan Fratini

Department of Industrial and Digital Innovation (DIID) - Chemical, Management, Computer, Mechanical Engineering, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy

Abstract

In the last decades, several direct-recycling techniques have been developed and investigated in order to avoid material remelting, typical of the conventional aluminum alloys recycling processes. Moreover, the remelting step for aluminum recycling is affected by permanent material losses. Solid-state recycling processes have proven to be a suitable strategy to face such issues. Friction Consolidation is an innovative solid state-recycling technology developed for metal chips. During the process, a rotating die is plunged into a hollow chamber containing the material to be processed. The work of friction forces decaying into heat soften the material and, together with the stirring action of the die, enable solid bonding phenomena producing a consolidated metal disc. This technology has been successively applied to metal chips; in this paper, the feasibility of the process to recycle sheet metal scrap is investigated. The quality of the obtained billets is evaluated through morphological observation and hardness measurements.

Keywords: Aluminum Alloys; Scrap Recycling; Friction Consolidation

* Corresponding author. Tel.: +39 091 238961832; fax: +39 091 23860840.
E-mail address: dario.baffari@unipa.it

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1. Introduction

In the last decades, the use of lightweight alloys has been spreading in almost any industrial field thanks to the relevant weight reduction enabled by the use of such materials. On the other hand, aluminum alloys are characterized by high-energy demands primary production cycles that are responsible for a relevant share of the global CO_2 emissions [1]. In particular, the raw materials production cause one-quarter of the annual CO_2 emissions, with steel and aluminum causing 25% and 3% of the global emissions, 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 since energy savings as high as 90% can be achieved with the secondary production of lightweight alloys [3].

Nevertheless, metal scraps are often composed of chips resulting from machining operations and sheet metal coming from trimming after forming processes. This kind of wastes is among the most difficult to be recycled as they are characterized by high surface/volume ratio and they are usually covered by oxides formations or other contaminants. In the last years, recycling by remelting of aluminum and magnesium alloys has been deeply investigated by many researchers [4,5]. From these studies, it arises that 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, where material losses as high as 15-20% [6] may occur. Moreover, the whole conventional process requires several intermediate operations: cleaning, dying, compacting, as well as high-energy demand. In order to overcome such issue, researchers started investigating Solid State Recycling (SSR) approaches; in fact, by avoiding the remelting step, both energy and material can be saved.

In 1999, Gronostajski and Matuszak [7] first introduced the direct conversion method. The metal scraps were segregated according to the composition, cleaned, chopped, compacted and hot extruded between 500°C and 550°C. These approaches are relatively simple and are characterized by lower environmental impact compared to the conventional methods, as shown by Duflou et al. [8]. However, the irregular swirly geometry of the chips causes a "chopping stage" to be undertaken in order to obtain proper compaction before the extrusion and, consequently, good quality recycled material. Haasse et al. [9] used the ECAP (Equal Channel Angular Pressing) integrated extrusion processes to consolidate aluminum chips into a billet while a variant of this technique, including direct screw extrusion, was proposed by Widerøe et al. [10]. Paraskevas et al. [11], instead of using severe plastic deformation to get solid bonding conditions, applied a sintering based processes named 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].

In 1975 Andrew and Gilpin [12] developed the first friction based forging process that leads to the development of the Friction Stir Extrusion process that was patented by The Welding Institute of Cambridge in 1991. A rotating tool is used to produce heat and plastic deformation through friction between the tool itself and the chips to be recycled (into a hollow cylindrical matrix) by compacting, stirring and extruding the material. In this way, the recycling process takes place in a unique operation, resulting in significant cost, energy, and labor-saving with respect to both the conventional method and the direct method. This technology laid dormant for more than a decade before starting being investigated again after the TWI patent expiration due to failure to pay maintenance fee in 2002. FSE has been proved an effective process for producing high-quality wires and rods from the direct recycling of metal scrap or primary manufacturing from metal powders or billets for aluminum [13] and magnesium alloys [14].

Friction Stir Consolidation is a technology similar to FSE but developed to obtain bulk material from the processing of an incoherent material [15]. The equipment to be used in this process is the same as FSE, whit the only exception of the die that does not present any extrusion channel. The action of that rotating tool causes the generation of heat by friction and plastic deformation of the material in the chamber that is hence softened. Under the forging and stirring action of the die, the oxide layer on the particle is broken and they can bond together. A sketch of the process is presented in Fig. 1a. Low porosity and a fine recrystallized grain structure were obtained through FSC to produce Metal Matrix Composites [16] and thermoelectric material [17].

In this paper, the feasibility of the process to recycle sheet metal scrap is investigated since the direct recycling of the sheet metal instead of the chip can reduce the overall processing time [18]. The quality of the obtained billets is evaluated through morphological observation and hardness measurements.

Nomenclature

FSC Friction Stir Consolidation
R die rotational speed
T process time
F processing force
BM base material

2. Materials and Methods

The sheet metal scrap used for the experimental campaign consisted of 1 mm thick AA1050 aluminum alloy sheet chopped into irregular pieces (see Fig. 2) with sizes ranging from 5 mm to 10 mm.

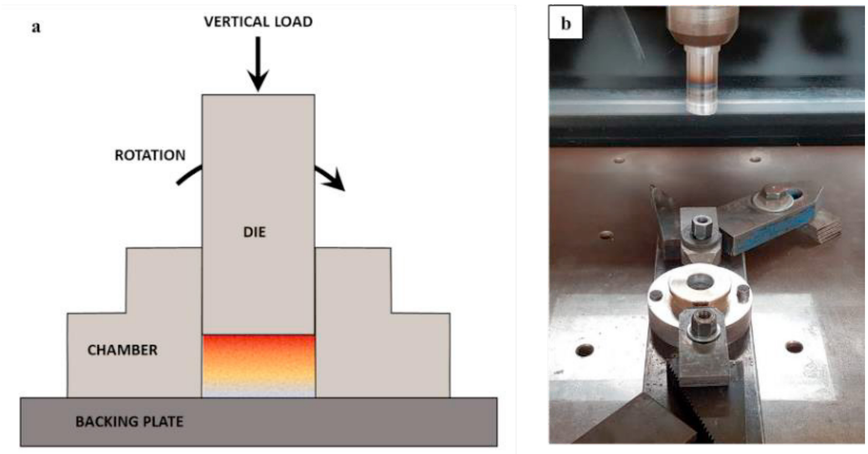

Fig. 1. (a) Process sketch; (b) experimental fixture.

Table 1. Case studies.

ID	R [rpm]	F [kN]	T [s]
ID1	1000	20	30
ID2	1000	20	60
ID3	1500	20	30
ID4	1500	20	60

A dedicated fixture was designed and built for the experiments. In particular, the rotating die and the chamber were manufactured in AISI H13 steel quenched at 1020°C and characterized by 52 HRc hardness. The chamber was hence mounted on a steel backing plate to ease consolidated billets extraction. The die presented a flat surface without any ridges. The experimental fixture is presented in Fig. 1b. Friction Stir Welding machine ESAB LEGIO was used for the experiments. This machine allows the control of the applied load on the vertical axis resulting in a force-controlled consolidation process. The rotation speed, die position, and Z-force were recorded during the consolidation by the ESAB control computer with 1 Hz sampling rate. 15 g of the scrap to be processed were loaded into the chamber and pre-compacted with a load of 5 kN without rotating the die. This stage was aimed at obtaining a more effective filling of the chamber. The spindle rotation was hence started and the vertical force was gradually increased to the desired value. This transient was necessary in order to reduce any initial torque peak that could be overcome machine limits. The trend against time of the main process variables during the transient and consolidation phases are shown in Fig. 3a. The FSC process was analyzed with varying die rotation speed "R" and process time "t" while the vertical force was kept constant and equal to 20 kN. The case investigated case studies were summarized in Table 1.

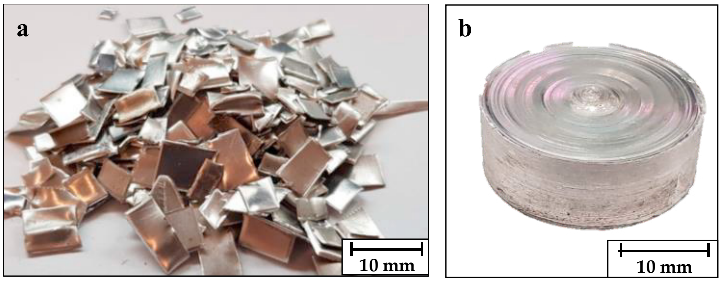

Fig. 2. (a) sheet metal scraps to be recycled; (b) Friction Stir Consolidated billet.

After each consolidation experiment, the obtained billet was removed from the chamber, sectioned, ground, polished, and etched using Keller's etchant (190 ml water, 2 ml HF, 3 ml HCl, and 5 ml HNO3) to reveal the macrostructure and the material flow. Optical microscopy was used to show the morphological variation along the radial and vertical directions of the specimens. Microhardness tests were carried out on the cross-section of the consolidated billets along two perpendicular lines as shown in Fig. 3b. The spacing between the indents was 1 mm for both measurement lines.

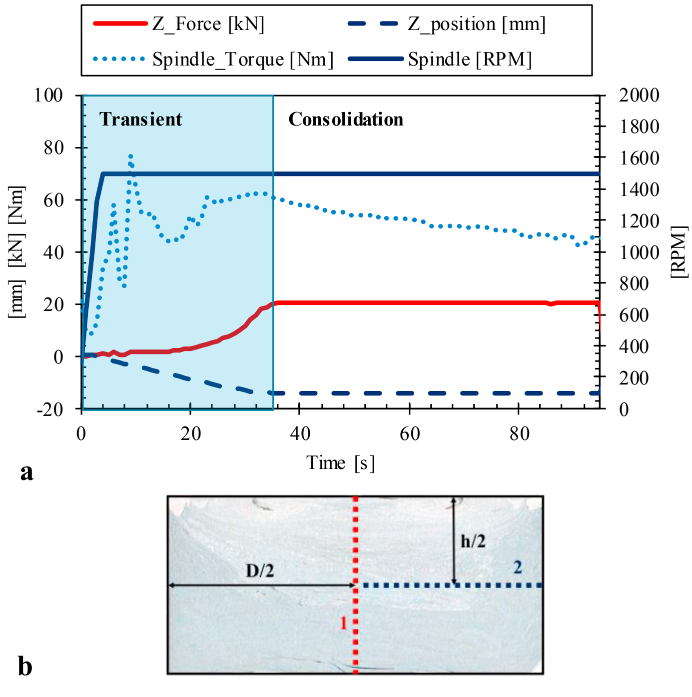

Fig. 3. (a) Process variable against time for the ID4 case study; (b) Micro hardness measurement lines.

3. Results

The results of the microhardness tests along the two measurements line (see Fig. 3b) for case studies ID3 and ID4 are presented in Fig. 4. The material in the upper area of the chamber (i.e. the material closer to the tool) is characterized by HV values equal to the base material while the mechanical property decays significantly moving toward the bottom of the chamber. This effect is more relevant in the case study ID3 characterized by a minor processing time where the area of uniform and high hardness is smaller. No significant gradient is observed along the second measuring line (see Fig. 4b) where the hardness values match the corresponding one on the billet center.

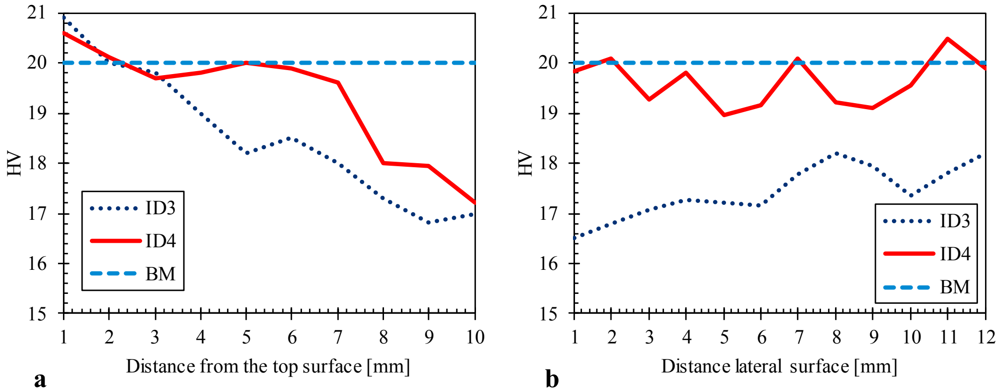

Fig. 4. Microhardness measurements on the cross section for the ID3 and ID4 against distance from the top (a) and lateral (b) surface compared to the base material (BM).

This hardness distribution can be explained analyzing the material morphology on the cross-section of the consolidated billet. Fig. 5 shows two partial views of the section from case studies characterized with different process time. Observing the etched surfaces, three different morphologies can be identified: starting from the top of the billet (Fig. 5c, i.e. the area closer to the die) the material appears to be highly deformed and none of the initial scraps can be observed, possibly thanks to the recrystallization happening in the area due to the die stirring action. Moving along the billet height, after a transition zone (Fig. 5d); the material appears to be composed of the initial sheet metal pieces welded together thanks to solid bonding phenomena (Fig. 5e). The boundaries between the particles are clearly visible and the oxides have not been dispersed since the stirring action of the tool has not reached that area.

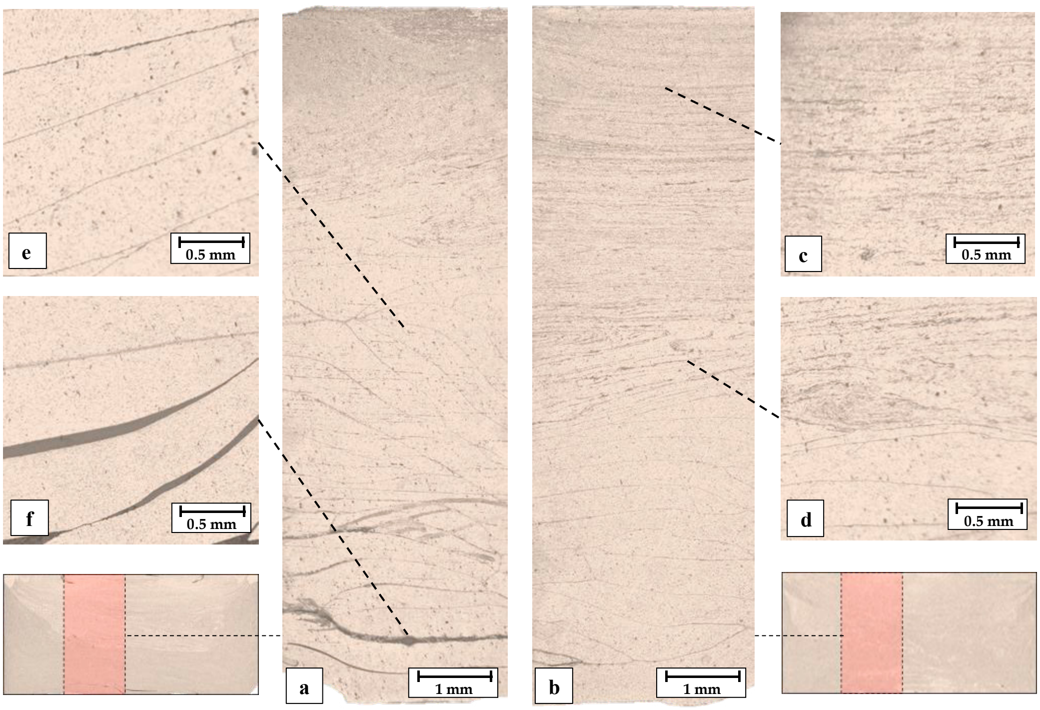

Fig. 5. Macro and micro observation of the cross-section for the ID3 (a) and the ID4 (b) case studies; (c) stirred material; (d) transition zone; (e) bounded material; (f) unbounded material.

Finally, at the very bottom of the billet (Fig. 5f) the scraps are merely compacted, without any proper bound between each other. Is it worth noticing that a longer processing time (Fig. 5b) allows the front of stirred material to advance more in deep in the chamber resulting in a wider effectively processed. This part of the billet is characterized by uniform mechanical properties comparable to the parent material while the rest of it has certainly lower mechanical strength due to the progressively less effective bonding.

The other case studies investigated during the campaign (characterized by lower spindle speed) presented an analogous morphology and mechanical resistance, with a slightly less extended area of properly consolidated materials.

4. Conclusions

In this paper the FSC process has been used to direct recycle sheet metal scrap; the obtained billets presented a non-uniform morphology and mechanical resistance due to the slow advancing of the stirred front in the chamber. The extent of the material being effectively processed increases with time but hardly reaches the bottom of the billet that is hence constituted of bonded sheet metal pieces. Nevertheless, the material being properly consolidated presents mechanical properties comparable to the parent material being recycled.

In order to increase the process effectiveness, strategies to reduce the process time and widen the processed area have to be implemented. Future experiments may include the usage of a non-flat die in order to increase the stirring action and the area of the influence of the die itself. Furthermore, a proper assessment of the process environmental impact in comparison with conventional and non-conventional recycling routes has to be carried out.

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