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A new sustainable direct solid state recycling of AA1090 aluminum alloy chips by means of friction stir back extrusion process

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Abstract

Friction stir extrusion is an innovative process designed to recycle metal chips from various machining operations. In this research, the feasibility of solid-state recycling of pure aluminum AA1090 machining chips using FSE process is investigated. In the early stage, a FE simulation was conducted in order to optimize the die design (spiral scroll of the plunge, hole size and bearing distance) and the process parameters in terms of plunge rotational speed and extrusion rate. The AA1090 aluminum chips were produced by turning off an as-received bar without lubrication. The chips were compacted on a MTS machine up to 150KN of load. The resulting chip-billets had a diameter of 40mm and 30mm high. The chip-based billet was FS Extruded at 1000rpm rotational speed and 0.8mm/s of plunge displacement. The extruded samples were analyzed by optical microscope in order to see the material flow and to characterize the microstructure. Finally, micro-hardness Vickers profiles were carried out, in both longitudinal and transversal direction, in order to investigate the homogeneity of the mechanical properties of the extrudate.

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Keywords: Friction stir extrusion; Aluminium recycle; FEM simulation; Microhardness; Microstructure

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1. Introduction

At present, machining operations are required for the production of most mechanical components. Traditional cutting processes involve a high removal of material that is lost as a production waste [1]. The recovery of these materials today is taking on a particularly important role, especially when it comes to aluminum for the transport and building sectors, thanks to its high strength/weight ratio and good workability [2, 3].

Unfortunately, aluminum processing waste, including swarf and small chips, is one of the most difficult types of waste to be processed due to some critical features such as the high ratio of surface/volume, irregular geometry, presence of contaminants and usually made of different alloys. These scraps are sold to buyers of scrap and to recycling smelters at a price equal to about 30% of the purchase price of the second commercial fusion raw aluminum [4].

Aluminum recovery processes involve two methods, conventional and unconventional. The first (CRP) provides a phase of fusion that is considered fundamental. During this phase an oxide layer is created, which, added to the layer already present on the whole surface of the chips, greatly influences the amount of metal lost. The skim formed during the melting phase can contain up to 95% of metallic material that must be recovered with a particular process after casting.

To facilitate handling and to reduce metal losses during the melting process, the density of the chip mass should be increased to 1 kg/dm3. Conventional aluminum recovery methods for which a recasting phase is also envisaged are characterized by high energy consumption, numerous operations and high costs per individual operation [5, 6]. It is estimated that about 20% of metallic material is lost during the

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remelting phase, without considering the subsequent operations, such as casting, cutting or extrusion [7]. In recent years, the recycling by melting aluminum and magnesium alloys has been studied extensively by many scholars [8, 9] showing that most of the times the total recovery rate hardly reaches 60%.

Recent literature has revealed some potential variants to the aluminum recycling process compared to the conventional method, therefore without going through the recasting phase, where aluminum alloys are subjected to significant plastic deformations at temperatures below solidus. In 1945 Stern [10] proposed and patented hot extrusion as a way to recycle processing waste without melting the material and, in 1993, TWI patented a new recycling process to be applied to metal shavings, named Friction Stir Extrusion (FSE). This technique belongs to the same family as the Friction Stir Welding technique (FSW) and follows the same principles. It uses the heat generated by friction, between a rotating head and the chips to be recycled, contained within a cylindrical container where the head is inserted; the plastic deformation generated by the heat relative to the friction of rotation and the progress of the head involves the mixing, the compaction and the extrusion of the chips. In this way the FSE process makes it possible to transform the aluminum chips into an extruded product, with high savings in terms of energy, work and economy in relation to the conventional direct extrusion recycling method. This technique therefore seems to be quite interesting for the chip recycling industry. The process is currently in an initial development phase and only a few articles in the literature can be found regarding this application to aluminum alloys. In particular, Tang et al. produced detectable wires of AA2050 and AA2195 alloys from machining chips by analyzing the amount of heat generated when the head rotation speed varies [11]. R.A. Behnagh et al. have shown how the rotation speed influences the quality of the wires produced in AA7277; high rotational speeds involve hot cracking formation, while low velocity results in cold tearing [12]. Baffari et al. have done a campaign on FSE of AA2024 aluminum alloy chips, aimed at the production of MMC within the recycling process by adding SiC powder to the aluminum chips [13]. Some of the authors of this paper have studied how the tool rotation speed affects the extrusion temperature thus influencing the plasticity of the chips [14]. Other researchers direct studies on the recycling of pure magnesium chips and AZ31 alloys through the FSE process [15-19].

In this research, the feasibility of solid-state recycling of pure aluminum AA1090 machining chips using FSE process is investigated. Initially, a finite element simulation was performed to analyze and obtain information on the geometry of the instruments (spiral scroll of the plunge, hole size, and bearing distance) and process variables, such as feed rate and extrusion ratio. Aluminum chips AA1090 were obtained by turning a bar without lubrication and then compacted by an MTS machine. Cylindrical billets were obtained and extruded through the FSE process at constant rotation and feed rates. Fig.1c shows an example of the FS Extruded billet. The extruded samples were analyzed by optical microscopy. Finally, hardness tests were carried out in both longitudinal and transverse directions to obtain the microhardness Vickers profiles in order to study the homogeneity of the mechanical properties of the extruded product.

2. Materials and experimental procedures

2.1. Material

The aluminum chips used for the FSE extrusion test were obtained by working on the lathe with a bar of AA1090 without any type of lubricating or cutting fluids. This material is a pure aluminum at 99.9 (wt.%) Characterized by an Ultimate Tensile Strength (UTS) equal to 80MPa, 38% relative elongation and a Vickers microhardness of 22.

Differently, the material of the main and supporting components, that are the dies, the inserted rotational punch head, the container and the rotating plunger, is a K720 tool steel.

2.2. Experimental procedures

Once the shavings are obtained by turning the bar, they are they were compacted by a universal MTS hydraulic machine at a load of 150KN of force (Fig. 1a). Cylindrical billets of 40mm diameter and 30mm in height were then obtained (Fig. 1b) which were then extruded through the FSE process at a head rotation speed of 1000rpm with a feed rate of 0.8mm/s.

The shape of the main components used in the process greatly influences the flow of the plasticized material and the final properties of the product. For this reason and, therefore, in order to define the design of these components, in particular the dies and the inserted rotational punch head, finite element simulations have been performed. The numerical simulations have been implemented on the commercial FEM code "SFTC DEFORM 3D", characterized by a Lagrangian implicit solver.

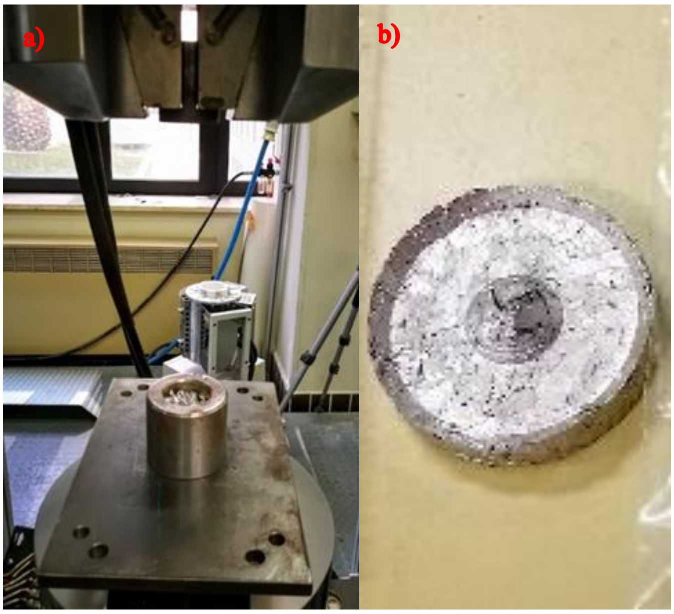

Fig. 1: a) chip compaction process with the MTS machine; b) pre-compacted AA1090 aluminum billet.

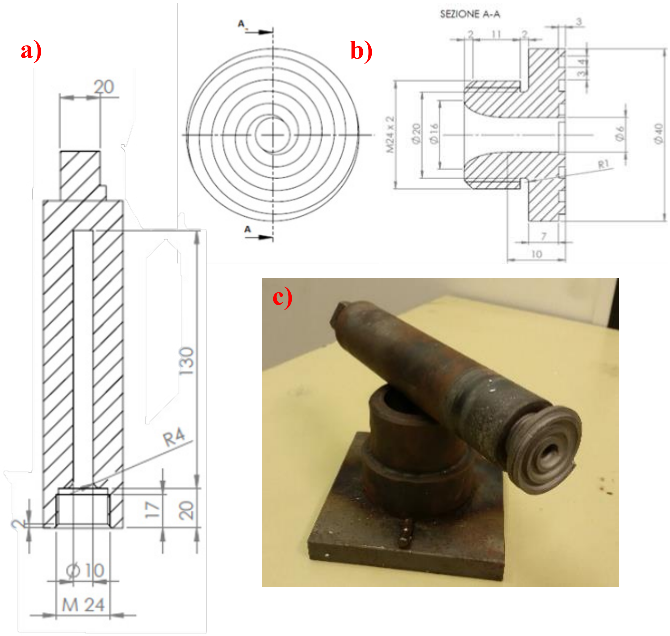

Fig. 2: a) Section of the rotating plunger; b) front view and section of the inserted rotational punch head; c) Complete set of components for FSE tests.

The diameter of the container cavity is 41mm, with a height of 70mm. The rotating plunge die is 40mm wide with a central hole that determines the size of the extruded wire diameter. It is also characterized by two different movements, one rotating clockwise and one advancing towards the container cavity, in which the pre-compacted aluminum billet is inserted. The rotational movement of the die relative to the container causes the mixing and the stirring of the aluminum chips, during which the pressure generated by the contact between the rotary dip mold and the Al chips involves the conversion of the mechanical energy into thermal energy. The length of the wire that will be generated for the extrusion will be determined by the size of the container. The chip-based billet was FS Extruded at 1000rpm rotational speed and 0.8mm/s of plunge displacement and two thermocouples were inserted to monitor the process temperatures during the test.

The microstructures of the samples obtained from the tests were studied by means of an optical microscope (OM) from transversal sections of extruded wires cutting perpendicular to the extrusion direction. The samples were grinded with a 1000 grit paper and then with a 1µm diamond paste. After polishing, the surfaces were electrochemically etched for a few seconds using a 5% solution of fluoroboric acid (HBF_4) in ethanol at room temperature at 18V.

Finally, through a Remet® HX1000 micro-hardness tester, the tests were carried out of micro-hardness with a load of 100g for 15s. The micro-hardness values were averaged over at least three individual measurements, the profiles were measured in the longitudinal and transverse directions, in order to study the homogeneity of the extruded mechanical properties.

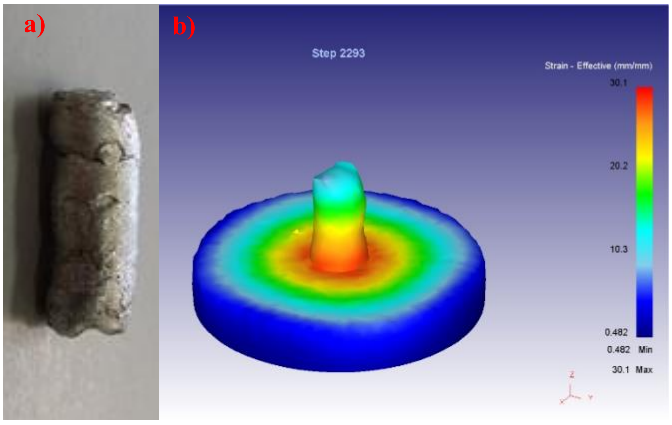

Fig. 3: a) stretch of the wire produced by test; b) strain effective result of FEM simulation.

3. Results and discussion

The tests carried out in the laboratory produced the stretch of wire shown in Fig. 3a).

To perform the test, the same parameters of the simulations were used and, therefore, both the simulations and the experimental tests were carried out with the control in speed of rotation (1000rpm) and advancement (0.8mm/s), kept constant throughout the test. Strain effective result of the FEM simulation is reported in Fig. 3b). Thanks to the simulations, it was also possible to evaluate the load trend that the CNC machine maintains during the process.

The graph in figure 4 shows that during the transitional phase lasting about 2s, a sudden increase in the load up to values higher than 90kN occurs and then an immediate lowering to constant values around 40kN until, evidently linked to the first contact between the rotating head and the billet, where the first chip remeshing takes place. Then, for the seconds part of the test and after the transitional phase, the load is increasing again until a value over 80kN because of the

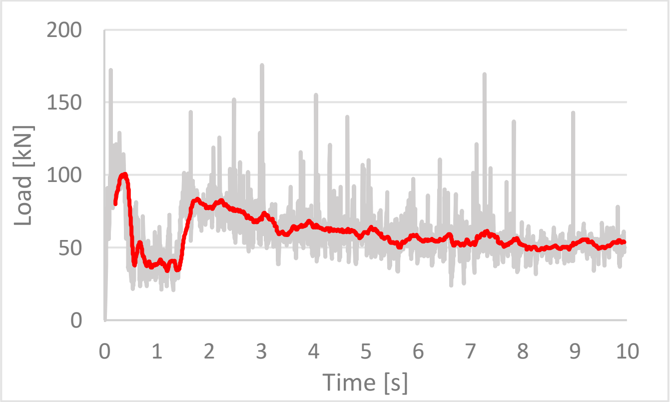

Fig. 4: Load prediction for the CNC machine during the process.

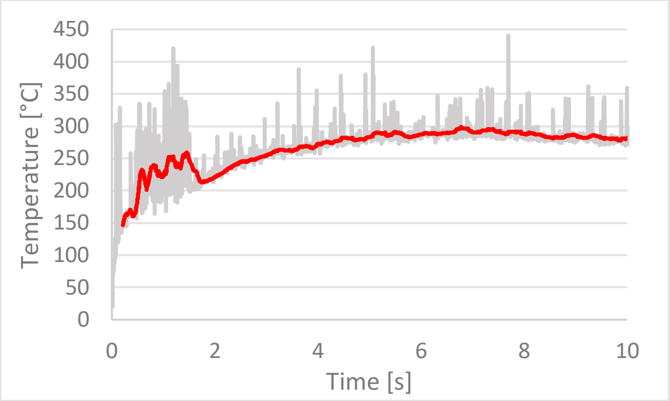

Fig. 5: Max temperature reached during the process.

temperature of the system still too low to facilitate extrusion. In the second phase it is possible to notice that there is a progressive lowering of the load of the machine, linked to the increasing temperature of the aluminum as showed in fig5, until a constant value around 50kN.

From the graphs of Fig. 4 and Fig. 5 it is possible to see the correlation related to the second phase, following the transitional one, between the raising of the system temperature and the gradual lowering of the machine load level.

The analysis carried out subsequently took place through the OM In particular, the specimen was observed on the section of the obtained wire and on the section along the vertical plane. In Fig. 6 it is possible to observe the plans that have been analyzed in the OM.

Fig. 6: plane section for the following observation through OM

Fig. 7: metallography of the vertical section of the extruded wire.

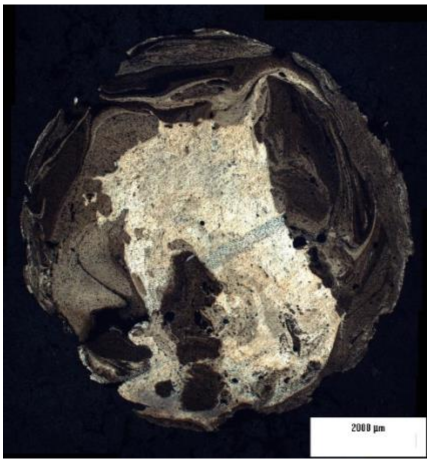

Fig. 8: metallography of the transversal section of the wire.

The metallography of Fig. 7 and Fig. 8 shows mainly the total lack of a homogeneous and uniform structure for the extruded product.

In fact, a set of undefined microstructures was obtained from the tests, with the presence of grains of varying sizes, and above all with defects sometimes not classifiable, accentuated by the presence of real holes (visible with the naked eye on the surface and therefore perfectly framed by optical microscopy). All this is obviously linked to the lack of compaction of the plastic material during extrusion, caused by many factors already analyzed, such as the centrifugal effect due to the high rotation speeds and the not perfect adaptation of the head channels to the processing conditions. However, it is possible to identify the flow of the material quite easily, leaving an indelible trace in its movement from the outside towards the inside of the tablet, conditioned by the rotation of the head on the upper surface.

Moreover, it is possible to observe in Fig.10, a substantial difference in the morphology of the material remained "trapped" inside the residual tablet between the center and the sides; in the center, as also confirmed by the metallography, the aluminum chips were completely bonded with a very fine microstructure. Whereas, the chips boundary is still visible in the stirred zone far from the center extrusion hole (Fig.10d).

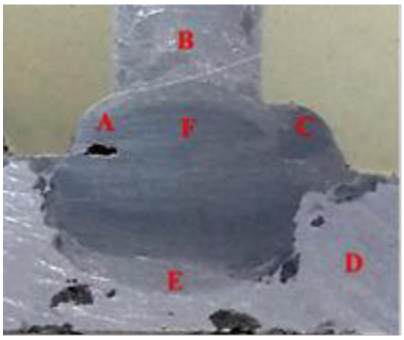

Fig. 9: Section of the residual tablet.

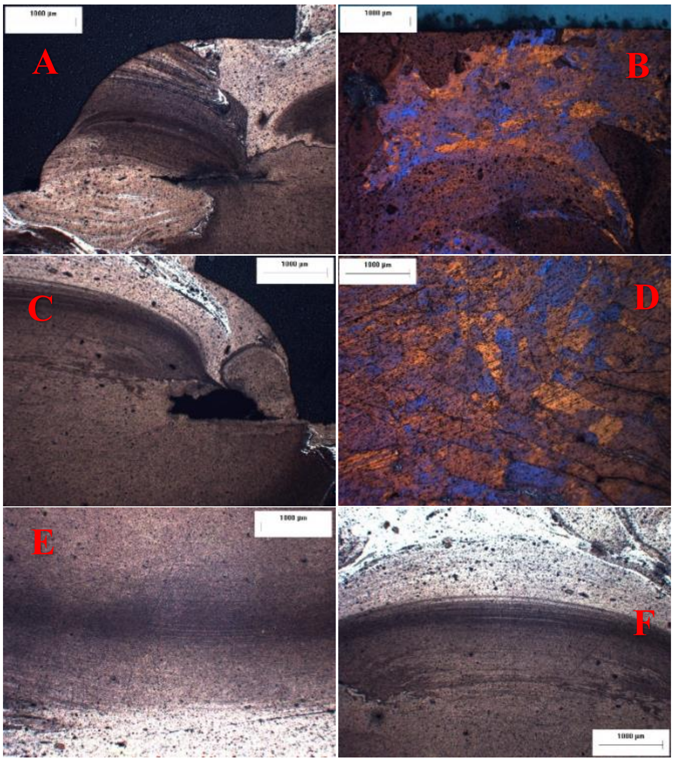

Fig. 10: metallography of the section of the residual tablet.

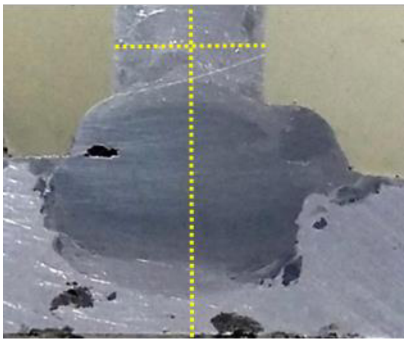

Fig. 11: acquisition lines for micro-hardness analysis.

To check the mechanical characteristics of the recycled material by FSE, micro-hardness tests were carried out on the same surface as in Fig. 9, along the lines shown in Fig. 11.

The data were acquired using a durometer with an acquisition criterion that foresees the distance between the successive points of 0.5 mm. In the Fig. 12 and Fig. 13 are shown the micro-hardness trends along the two analysed lines and the average values are 41.4 HV for the horizontal and 48 HV for the vertical.

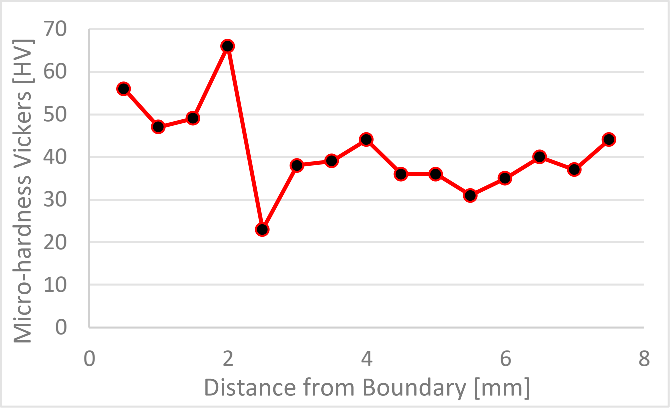

Fig. 12: micro-hardness Vickers for the horizontal line of the remaining tablet.

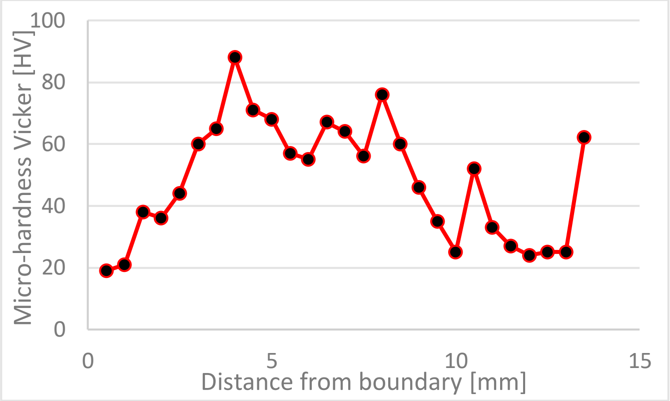

Fig. 13: micro-hardness Vickers for the vertical line of the remaining tablet.

4. Conclusion

In this work, the feasibility of solid-state recycling of pure aluminum AA1090 chips was investigated using the FSE process to produce defect-free wires. A finite element simulation was initially carried out in order to optimize both the design of the main and secondary components used in the tests, and the process parameters in terms of rotation speed and extrusion speed. The main results obtained can be summarized as follows:

I. Excluding the initial transient phase, the temperature greatly influences the extrusion load during the process; as the temperature increases, the machine load progressively decreases until a steady state value.

II. FSE process applied to recycle AA1099 chips allows to obtain wires manufactured with good surface quality, but with non-homogeneous microstructure and presence of small internal voids.

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