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## Al-SiC Metal Matrix Composite production through Friction Stir Extrusion of aluminum chips

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### Abstract

The production of most mechanical component requires machining operation, thus usually implying the cut material to be wasted as scrap. Traditional recycling techniques are not able to efficiently recycle metal chips because of some critical aspects that characterize such kind of scraps (shape, oxide layers, contaminating residues, etc). Friction Stir Extrusion is an innovative solid state direct-recycling technique for metal machining chips. During the process, a rotating tool is plunged into a hollows matrix to compact, stir and finally, back extrudes the chips to be recycled in a full dense rod. This process results to be particularly relevant since no preliminary treatment of the scrap is required. Experimental campaigns have been carried out in order to investigate the effects on process mechanics of the introduction of silicon carbide micro powders.

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**Keywords:** Friction Stir Extrusion; Recycle; Chips; Metal Matrix Composites; Silicon Carbide.

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### 1. Introduction

The production of most mechanical component requires machining operation, thus usually implying the cut material to be wasted as scrap during in traditional cutting processes [1]. The recovery of these materials results to be nowadays a crucial challenge in order to obtain both environmental and economic advantages thus leading many researchers and

industries to look for innovative and effective recycling technologies. Unfortunately, machining chip is one of the most difficult kinds of scrap to be processed because of some critical characteristics as elevated surface/volume ratio, the presence of oxide layers and different types of contaminants residues i.e. lubricants used during the cutting process. The conventional melting recycling technologies may be applied with many different drawbacks in terms environmental issues (fumes and gas formation), energetic/economic issues, (low efficiency in terms of obtained material and high energetic cost) and technological issues (defectiveness in the final product). In the last years, the recycling by melting of aluminum and magnesium alloys has been deeply investigated by many researchers [2, 3] showing that usually the overall recovery rate hardly reaches 50%. All the above-cited issues these conventional technologies to be generally inadequate for the modern industrial needs.

Gronostajski and Matuszak [4] first introduced in 1999 the direct conversion method. The metal scraps were separated according to the composition, cleaned, chopped and finally compacted and hot extruded between 500°C and 550°C. The direct chip recycling is a relatively simple technology, providing high recovery efficiency and characterized by lower environmental impact compared to the conventional methods, as showed by Duflou et al. [5].

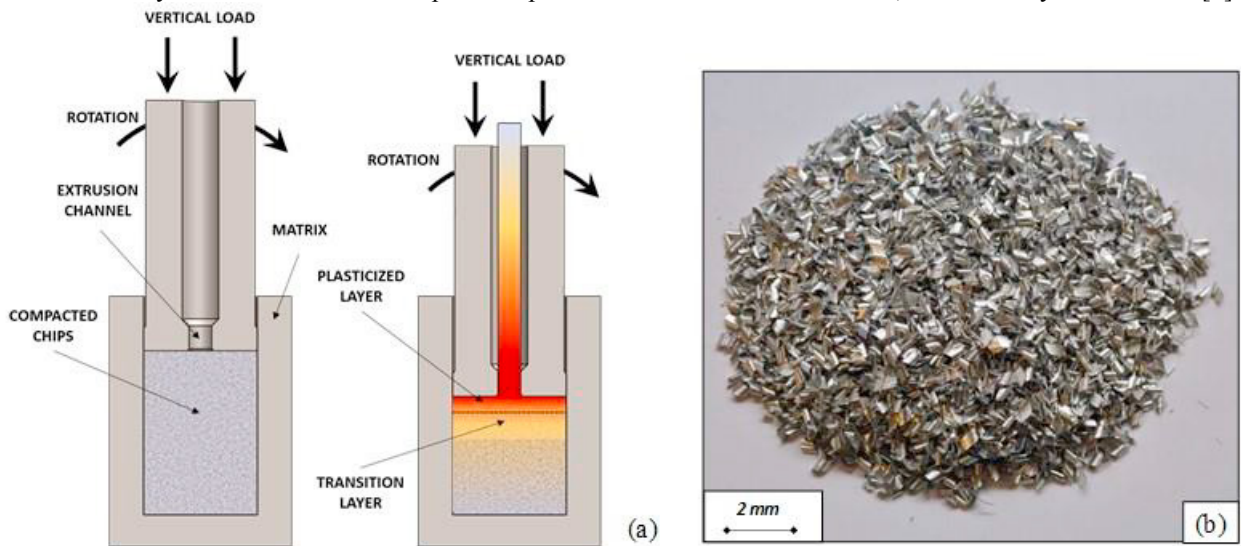


Fig. 1. (a) Sketch of the Friction Stir Extrusion process and (b) AA2024 metal chips used during the experimental campaign

In 1993 TWI patented a new recycling process to be applied to metal chips, named Friction Stir Extrusion (FSE). This technique belongs to the Friction Stir Processing (FSP) technologies, developed following up the “Friction Stir Welding” (FSW). 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 conventional method and direct method. For this reason, the FSE technique appears very attractive to industry for the recycling of machining chips. Fig. 1a 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.

After the TWI patent expiration, due to failure to pay maintenance fee in 2002, only very few papers have been published on the process. In particular, Tang and Reynolds [6] produced AA2050 and AA2195 wires from chips using fixed extrusion force and varying tool rotation. The microstructure of the extruded wires is characterized by small equiaxial grains resulting in good mechanical properties of the wires in terms of microhardness and bend ductility. Some of the authors of this paper have already carried out an experimental campaign on the FSE of AZ31 Mg alloy

imposing both extrusion speed [7] and force [8] through the control of rotating tool vertical movement. The obtained results show that the process is feasible and mechanical resistance above 90% of the base material can be reached. Tool rotation is key process parameter for the effectiveness of the process. With low rotation values, corresponding to low heat input, no extrusion is obtained. On the contrary, the combination of large rotation values and high strain can result in swirl defects compromising the specimen mechanical properties. A complex 3D helical material flow is generated by the tool action, and distinct areas are observed in the cross section of the extruded parts, with heavily stretched grain in the periphery and recrystallized grain in the center. Although FSE can be considered extremely competitive even compared to the direct method, the real potential of the process has not been still highlighted due to the significant knowledge gap in literature. Analyzing and isolating the effects of each of the different technological parameters on the mechanical properties of the produced rod can be quite difficult. To reduce the amount of the experiments a numerical model able to predict the main fields variable as well as the extrudates quality can represent a useful design tool, usually applied in other Friction Stir process i.e. FSW [9]. Some of the authors of this paper have developed a “single-block” 3D FEM model [8] to simulate most relevant field variables, material flow and embedding a bonding parameter capable of predicting defectiveness. In the last decades, many researchers have investigated the possibility to produce metal matrix composites recurring to innovative technologies, such as friction stir-based technologies. Dolatkhan et al. [10] investigated the effect of process parameter on the fabrication of AA5052/SiC Metal Matrix Composite (MMC) through Friction Stir Processing, while the same technology was applied to AA2024/SiC [11] and Al/Graphene [12]. No paper is known to the authors on the capability of FSE of directly fabricating MMC.

In this paper, the results of an experimental campaign on FSE of AA2024 aluminum alloy chips, aimed at the production of MMC within the recycling process by adding SiC powder to the chips, are presented. Different values of the percentage of the SiC powder with respect to the chips to be recycled have been studied. Numerical simulation was used to highlight the material flow during the process and identify the process mechanics leading to the formation of big SiC agglomerates in case of high initial percentage.

### Nomenclature

|   |   |
|---|---|
| R | rotational speed of the tool in RPM                         |
| F | extrusion force in kN                                       |
| p | volumetric percentage of reinforce added to the metal chips |

## 2. Material and methods

The experimental campaign described in this study was carried out using AA2024 chips, aluminum alloys used in most industrial fields, whose mechanical and chemical properties are shown in Table 1. The base material was received as sheet metal and was milled without using any lubricant obtaining uniform and clean chips with an average dimension of 5 mm length, 2 mm width and 0.2 mm thickness (see Figure 1b). A micro powder of Silicon Carbide with 2µm average size was chosen as reinforce and mixed to metal chips prior to the loading into the matrix in order to obtain proper dispersion of the powder itself.

Table 1. Chemical composition and mechanical properties of AA2024

| <i>YS</i> [MPa]                   |           |           | <i>UTS</i> [MPa] |           |           | <i>HV</i> |           |
|-----------------------------------|-----------|-----------|------------------|-----------|-----------|-----------|-----------|
| 110                               |           |           | 186              |           |           | 95        |           |
| <i>Chemical composition</i> % w/w |           |           |                  |           |           |           |           |
| <i>Fe</i>                         | <i>Si</i> | <i>Cu</i> | <i>Mn</i>        | <i>Mg</i> | <i>Zn</i> | <i>Ti</i> | <i>Cr</i> |
| 0.5                               | 0.5       | 3.8-4.9   | 0.3-0.9          | 1.2-1.8   | 0.25      | 0.15      | 0.1       |

A dedicated tooling set was manufactured out of AISI H13 steel quenched at 1020°C (52 HRC), composed by a matrix and rotating tool characterized by a 3 mm extrusion channel with an external diameter equal to 12 mm. The shoulder was characterized by a 10° conical surface in order to extend the contact surface with the chips and convey the plasticized material toward the extrusion channel. The experiments were carried out on a dedicated FSW machine ESAB LEGIO, with varying the percentage of powder added to the initial load (0.5%, 0.75%, 1%, 3%, 5% and 15%). The process parameters for the extrusion ( $R=700$  rpm  $F=22$  kN) were selected during a preliminary campaign that also allowed to fine-tune the tool design with particular focus on the extension in length of the extrusion channel. Each combination of process parameter was processed three times and specimens for subsequent analysis were cut from each obtained specimen. Most relevant process variable (i.e. torque and extrusion rate) were monitored during the extrusion. A previously developed numerical model [8] was modified to use the AA2024 material model. This FEM model is based on the commercial FEA software DEFORM-3D, Lagrangian implicit code specifically designed for metal forming process simulations. Some of the authors of this paper dealt with the detailed development of this model in a dedicated paper [8].

### 3. Results

The specimens obtained with the different values of  $p$  were presented in Figure 2. It can be observed that the external surfaces of the extrudates characterized by elevate percentage of reinforce present deep cracks due to both the increased heat flux caused by the enhanced friction (SiC powders are known to be highly abrasive) and the ineffective dispersion of reinforce itself.



Fig. 2. (a) Extruded wire with varying the added volumetric percentage of SiC powder and (b) detail of the cracks for the  $p=15\%$  case study

The chosen process parameters were first been tested on chips without any added reinforce, to verify the effectiveness of the parameters themselves, allowing to produce a defectiveness reference sample. The whole cross section of this sample (Figure 3a) is characterized by fine equiaxial grains (Figure 3b) produced by dynamic recrystallization typically happening during Friction Stir processes.

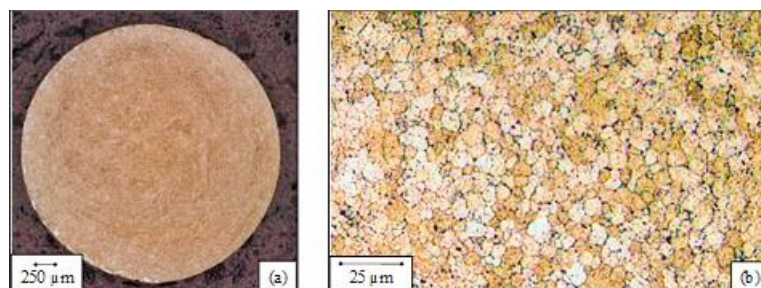


Fig. 3. (a) Cross-section and (b) micrograph of the  $p=0\%$  case study



When a proper amount of reinforce is introduced into the plastic flow occurring during the extrusion, the carbide particles are dispersed between the grain boundaries (Figure 4b), the grain size slightly increase due to grain growth prompted by the higher thermal input while the microhardness sensibly increase far above the sheet base material state (Fig 4c). Increasing  $p$ , the carbide powder starts conglomerating themselves forming incoherent groups on grain boundaries that can become real defect (Figure 4d-g) causing the formation of cracks immediately after extrusion, as already observed by preliminary observation of the specimens external surface. In the case studies characterized by  $p > 1\%$ , microhardness profiles result to be particularly discontinuous due to the presence of the reinforce conglomerate. It is worth noticing that the shape of this defective areas result to be caused by the helical flow inside the extrusion chamber predicted by the numerical model and visualized using the point taking option (Figure 5). The reinforce appears to gather itself in the boundaries of the metal flows uprising the extrusion channel, preventing an effective bonding between them

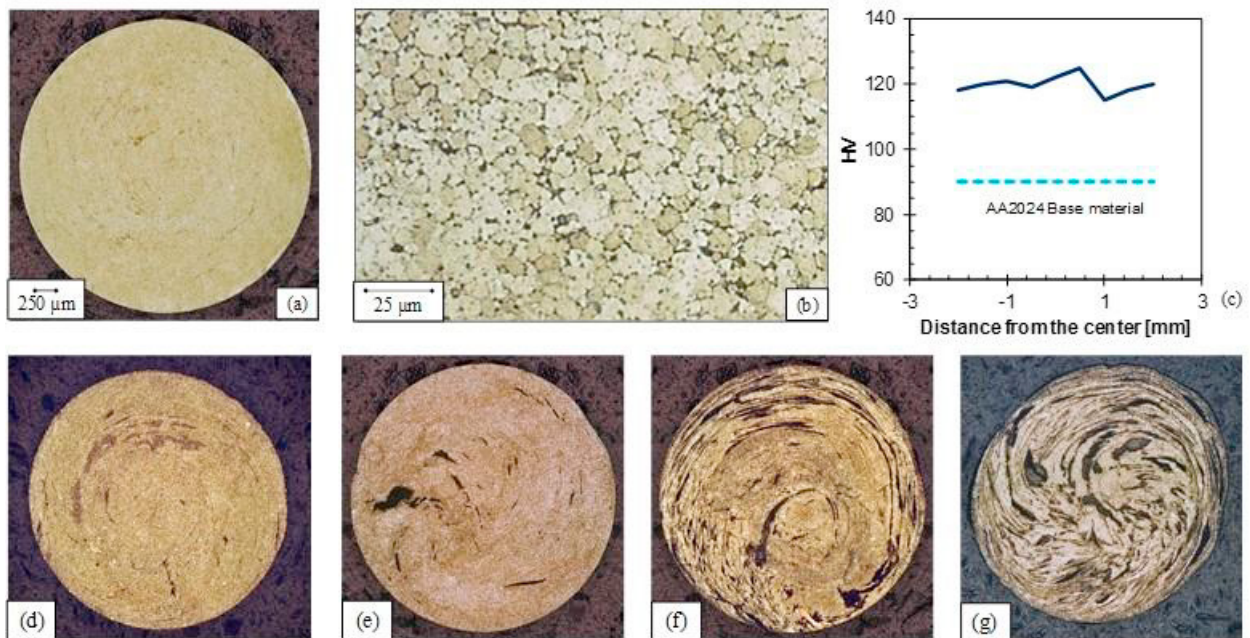


Fig. 4. (a) Cross section, (b) micrograph and (c) microhardness profile of the  $p=0.5\%$  case study, cross section of the (d)  $p=1\%$ , (e)  $p=3\%$ , (f)  $p=5\%$ , (g)  $p=15\%$  case studies

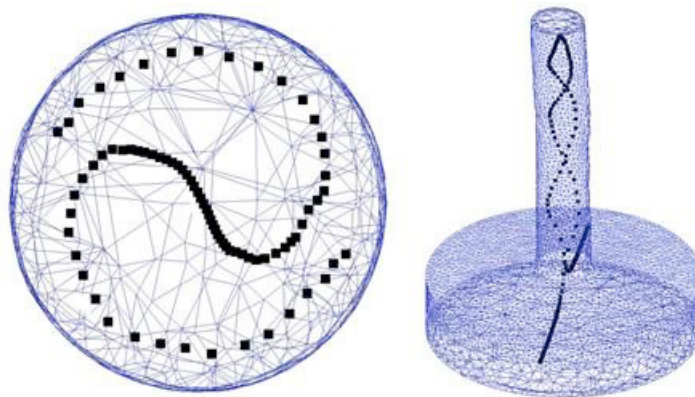


Fig. 5. Numerical simulation of material flow during the extrusion

#### 4. Conclusions

Based on the obtained result, the following main conclusions can be drawn:

- ✓ Solid state recycling through Friction Stir Extrusion is feasible on aluminum alloy AA2024 chips and enables the production of defect free extrudes;
- ✓ The introduction of SiC powders allows the production of MMC using FSE process;
- ✓ Excessive amount of reinforce ( $p > 1\%$ ) causes the formation of big inter-granular conglomerate that affects deeply extrudes quality, causing crack opening and non-uniform mechanical properties;
- ✓ A helical material flow was found through numerical simulation reflecting the spiral shape of the conglomerates of specimens' cross sections.

Future developments include the quantitative study of the combined effects of the main process variables, i.e. tool rotation, tool force and extrusion ratio on extrudes quality and mechanical resistance. The influence of reinforce grain size and chemical composition have to be taken into account. Finally, temperature measurements should be carried out in order to evaluate the influence of reinforce powder on heat production through friction during the process.

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