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Technical Paper

Process mechanics in Friction Stir Extrusion of magnesium alloys chips through experiments and numerical simulation

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ABSTRACT

Friction Stir Extrusion (FSE) is a novel process designed to directly recycle machining chips. An experimental campaign was carried out on AZ31 milling chips using variations in extrusion ratio, force and tool rotation rate. The process mechanics were studied and correlated to the material flow, which was elucidated through use of a copper marker. A 3D, Lagrangian, thermo-mechanically coupled dedicated numerical model was set up and validated through temperature measurements. The combination of experimental and numerical results permitted to reconstruct the complex 3D material flow induced by tool rotation and plunge into the extrusion billet chamber.

1. Introduction

Machining operations are commonly used to produce many mechanical components. This implies that a huge amount of material is wasted as scraps during many of the manufacturing cycles [1]. The metal chips produced by machining processes are characterised by irregular geometry with high surface/volume ratio, low density, presence of contaminants (i.e. lubricant fluids and oxide layers) and non-uniform composition. These peculiar characteristics cause the chips to be one of the most difficult metal scraps to be recycled. The use of "conventional" methods, which implies melting and re-casting of the metal to be recycled, leads to environmental issues (e.g. gas emission during the process), economic issues, e.g. energy cost, low efficiency of the recycling in terms of obtained material, and technological issues, e.g. defects in the final product such as porosities and inclusions or low mechanical resistance. In the past, the recycling by melting of aluminium and magnesium alloys has been deeply investigated both considering "traditional" techniques [2,3] and innovative melting technology [4,5], but the recovery rate of the entire process usually hardly reaches 60%. Moreover, the whole process requires several intermediate operations (cleaning, drying, compacting, etc.) and high-energy usage, causing these conventional technologies to be inadequate for the modern industrial needs. Gronostajski and Matsuszak [6] introduced in 1999 the so-called "direct conversion method": the metal scraps were separated according to their compositions, cleaned, chopped, compacted and hot extruded between 500 °C and 550 °C. This technology enables the chips to be relatively quickly and easily recycled with low environmental impact and high recycling rate, especially if compared to melting process. Since the introduction of the "direct method", several researchers have investigated this technology. Duflou et al. [7] discussed the environmental assessment of solid state recycling focusing on the reduced material loss in comparison with traditional melting technology. Tokarski [8] investigated the effect of 4xxx chip size on the mechanical properties and anisotropy of hot extruded billet. Chiba et al. [9] showed how aluminium machining chips can be consolidated and hot extruded into c-channels while Shamsudin et al. [10] investigated the influence of temperature on extrudates quality during solid state recycling of AA6061 milling chips.

The use of magnesium alloys has great potential in terms of reduction of component weight with consequent fuel consumption and environmental impact reduction [11]. However, most magnesium is currently produced through extraction process (Pidgeon or electrolytic), characterised by intense energy consumption and concomitant emission of Greenhouse Gas (GHG) that may offset the above-cited advantages linked to the usage of magnesium alloys [12], leading the researcher to investigate innovative recycling technologies. Gesing et al. [13] investigated the extraction of Mg through electrorefining from secondary Al alloy scrap being recy-

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cled by melting, showing the technical feasibility of this technology that is effectively applicable in to the existing aluminium recycling facilities. Hu et al. [14] demonstrated the feasibility of the direct method for the recycling of magnesium alloys and highlighted the influence of different chip geometries on product quality. The effect of chips mean size and extrusion ratio on the porosity [15], microstructural, mechanical [16,17] and corrosion [18] properties have been investigated. According to many researchers, the most influential parameters to be optimised in order to enhance the product quality were matrix temperature and extrusion ratio. Anilchandra et al. [19] extruded cold compacted chips at different temperatures in order to compare damping properties and dynamic modulus of the recycled material with commercially pure cast magnesium extruded under analogous conditions, while Paraskevas et al. [20] achieved through spark plasma sintering fast and full consolidation of Mg alloy chips into bulk material characterised by finer microstructure and improved mechanical properties with respect to the parent material. Haiping et al. [21] applied the Hydriding-Dehydriding to AZ40 scarp to be recycled through compaction and extrusion, obtaining high resistant bars characterised by ultrafine grain microstructure. The direct method allows relevant savings in terms of material (up to 40%) and energy (up to 31%) [2], but these promising results are affected by the high influence of the scrap geometry on the quality of the extruded parts. The irregular geometry of the chips requires a "chopping stage" to be undertaken in order to obtain regular chip geometry leading to proper compaction before the extrusion and, consequently, good quality recycled material.

In 1993 TWI patented a new recycling process to be applied to metal chips, named Friction Stir Extrusion (FSE). This technique belongs to the family of Friction Stir Processing (FSP) technologies, developed following the invention of "Friction Stir Welding" (FSW). The FSE process uses the heat and the plastic deformation generated by the friction between a rotating tool and the chips to be recycled (contained into a hollow cylindrical chamber into which the tool is plunged) to compact, stir and extrude the chips. The conversion of scrap into extrudate using a unique process allows significant cost, energy and labour reduction with respect to both conventional and direct recycling techniques. The process is currently in its early development stage and only few papers can be found in literature about its application on aluminium alloys and fewer on magnesium alloys. Tang and Reynolds [22] produced solid wires from AA2050 and AA2195 chips with varying tool rotation rate maintaining a fixed extrusion force. Narvan et al. [23] used the shear compaction process (conceptually similar to FSE) to produce bulk magnesium and SiC nanocomposite from machining chips. The analysis of the obtained rods showed the formation of an equiaxed, fine-grained microstructure resulting in good mechanical properties including microhardness and bend ductility. Ansari et al. [24] optimised the process parameters of FSE applied to commercially pure magnesium using statistical tools while Behnagh et al. [25] investigated the metallurgical transformation during FSE of pure magnesium through a thermo-mechanical 2D analysis. The effect of the oxide layer covering the metal scrap on product mechanical properties has not yet been investigated. Some of the authors of this paper have already carried out a preliminary experimental campaign on the FSE of AZ31 Mg alloy varying the extrusion speed through the control of rotating tool vertical displacement [26]. Direct wire manufacturing from magnesium alloy scrap can be very relevant in the optic of both base material production for Wire Arc Additive Manufacturing (WAAM) [27] and of process scalability that would allow recycling in form of concrete metal billets. Although FSE can be considered competitive even with respect to the direct method, as near-zero emissions of carbon dioxide (other than those associated with the power generation needed to perform the operation) and no emissions of metal oxide particulates are produced, the real potential of the process has not been demonstrated due to the significant knowledge gap in the literature especially regarding material flow analysis and defect prediction via complete 3D FEM simulation. This lack of a comprehensive know-how has also inhibited further researches on process scalability. Zhang et al. [28] recently proposed a CFD numerical model able to provide initial insights on the material flow occurring in FSE of AA6061 aluminium alloys while Behnagh et al. [25] investigated metallurgical transformation during FSE of commercially pure magnesium using a thermo-mechanical 2D analysis.

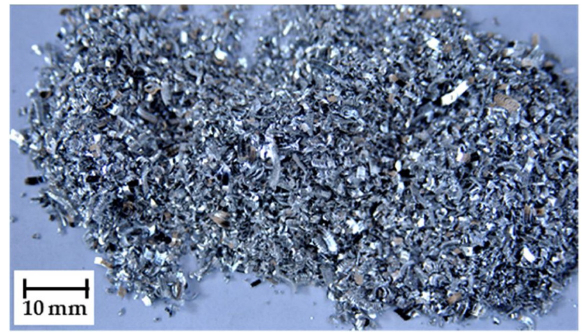

Fig. 1. Magnesium chips used during experiments.

In this paper, an experimental campaign has been carried out on AZ31B magnesium alloy in order to investigate material flow during the extrusion process. Constant extrusion force was considered during each test causing 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. Magnesium chips were Friction Stir Extruded with varying tool rotation, extrusion ratio, and extrusion force. A copper marker was embedded in the chips to visualise the material flow occurring during the extrusion process. A previously validated [29] "single block", 3D numerical model, capable of simulating the FSE process and enabling the prediction of microstructure, temperature, strain, and strain rate distribution was used to elucidate the occurring material flow.

2. Materials and methods

AZ31 magnesium metal plates were milled without lubricants in order to obtain clean and regular chips (Fig. 1). The base material is characterised by Ultimate Tensile Strength (UTS) equal to 220 MPa. The obtained chips had average dimensions of 5 mm in length, 2 mm in width, and 0.2 mm in thickness.

Three different rotating tools were manufactured with varying diameter of the extrusion channel, d, (5 mm, 7 mm and 9 mm) and constant extrusion channel height h and die diameter D of 14 mm and 25 mm respectively. Hence, three different extrusion ratios (i.e. the ratio between initial cross-sectional area and the cross-sectional area of the final extrudate) equal to 25, 12.8 and 7.7 respectively, were obtained. A Friction Stir Welding machine ESAB LEGIO FSW 3ST was used for the experimental campaign and three different extrusion forces (14 kN, 18 kN and 22 kN) and tool rotation rates (500 rpm, 700 rpm and 900 rpm) were investigated. In this way, 27 different process conditions were tested. Each test was repeated three times. Extrusion rate was monitored during the tests and temperature in the matrix was acquired through a K-type thermocouple. The material flow was highlighted by embedding a copper wire, 0.7 mm in diameter, in the chip billet in a diametric position as shown in Fig. 2. In particular, the marker was put on top of a billet of previously compacted chips and a fixed amount of additional material was compacted over it.