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Process mechanics in continuous friction stir extrusion process of aluminum alloy

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Abstract. Friction Stir Extrusion (FSE) is an innovative direct-recycling technology developed for metal machining chips. A rotating die is plunged into a cylindrical chamber containing the material to be recycled during the procedure. The die's stirring action causes strong bonding, enabling for the back extrusion of a full dense rod. One of the technology's major flaws is the process' discontinuity, which limits the volume of extrudes to the chamber's capacity. Based on the previous experience of some of the authors have designed a machine tool for continuous solid-state recycling of metal chips with the aims to overcome the limitations of the discontinuous process which makes it potentially appealing to industry. In this work, Friction Stir Extrusion process is defined, the set-up machines tool is presented, and the experimental findings of case studies are shown and analyzed. Finally, with the goal the mechanics of the FSE continuous process, a numerical model was created starting from the experimental results obtained by discontinuous process.

Introduction

One of the main issues facing the current era is the development of environmentally sustainable industrial techniques. Numerous international agreements, including the Kyoto Protocol, oblige signatory nations to gradually cut their emissions of greenhouse gases over the following few years. It's interesting to note that the production of raw materials contributes significantly to these annual worldwide emissions. According to a study by Worrell et al. [1], five materials in particular steel, cement, paper, aluminum alloys, and polyethylene plastics have the greatest energy impact. For instance, cement has a very cheap production cost, but because it is a material that is utilized extensively, its impact is far from insignificant. Thus according to research by Worrel et al., around 20% of the world's CO_2 emissions are released into the atmosphere during the manufacture of materials. It is predicted that demand for aluminum will expand exponentially and at a faster rate than that of the other materials indicated above, based on the trend in demand seen in previous years. It is vital to put procedures in place that will extend the material's usable life as much as feasible in order to reduce the subsequent rise in emissions caused by the rising demand for the material. Since it has several technological and environmental advantages over other methods, including as large energy savings compared to original production, recycling is currently the most popular method for dealing with metals. Recycling can result in primary energy savings of up to 90% for aluminum alloys, as well as for magnesium and titanium [2]. The savings for steel are a little less, at 69 percent. [3], the demand for aluminum is anticipated to increase by a factor of 2.6 to 3.5 between 2005 and 2050, while the demand for steel is anticipated to increase by a factor of 1.8 to 2.2. Due to the circular economy is become more popular [4] the most popular method for recycling metals now is conventional recycling, which has numerous advantages over alternative technologies in terms of both technology and the environment. Recycling is significantly more cost-effective from an energy consumption point of view when it comes to light alloys, where main energy savings of up to 90% can be made [5]. Furthermore, metal scrap frequently consists of sheets from finishing after forming procedures and chips from machining operations. The type of scrap is categorized as "process scrap" or "new scrap" [6] according to European standards and is made up of leftover materials from the entire production chain of the product, from its creation to its sale to the consumer. Because of its high surface area to volume ratio and the presence of oxides and/or other impurities on its surface, this form of scrap is among the most difficult to recycle. Due to this, material losses of up to 15-20% can be attained when recycling light alloys using annealed scrap metal [7]. Even "old scraps" from used products can be transformed into "process scraps" through the application of the proper cleaning, sorting, and cutting procedures reducing the melting energy cost. According to Samuel's study [8], one of the first initiatives using this type of processing led to the recycling of 96% of the processed scrap with very little loss. A revolutionary process called friction stir extrusion (FSE), which is based on the FSW technology, has been created. Its distinctive characteristic is that frictional heat is also provided to the extrusion process in addition to the softening of materials. The FSE process, which is widely used in the creation of high-quality wires or rods from metal powders, chips, or billet, has recently been presented as a direct conversion technique of recycling. The limited length of wire that may be produced in a single operation using the FSE technique is one of its key drawbacks. This problem can be attributed to both the inherent discontinuity of the operation and the design of the extrusion machine itself. Most of the equipment used by researchers is an adaptation of milling machines, much as it was during the early development of FSW. In this paper a process design approach was carried out through numerical analyses based on FEM models, aimed to define the conditions for a continuous extrusion process. In particular, after preliminary analyses carried out using a Von Mises plastic yield surface of the material, the Shyma-Oyane models was used, modelling the incoherent chips as a porous material, to follow the density evolution during the stage of the process and to get closer to the transient condition of the chips.

Experimental setups

Some of the authors of this research conducted FSE experimental campaigns on both aluminum alloys [9-10] and magnesium alloys, such as AZ31B, [11] to examine the effects of the key process parameter and create a specialized numerical model to study the mechanics of the process[12]. An ESAB LEGIO 3ST machine was used for the experiments. This machine was developed for FSW processes and allow to control the vertical force on the tool. This capability resulted to be particularly relevant since the extrusion force is one of the most important technological parameters to be controlled during FSE. The tools used for the experiments were a hollow chamber and a specifically designed rotary die mounted on the machine chuck. The extruded wire was housed inside the mandrel and successively extracted in between the extrusions. The die presented a conical shaped shoulder to guide the material flow toward the extrusion channel. The grasping of the die during the trials was a recurrent problem caused by the plasticized material flowing into the space between the die and the chamber itself, so the chamber was created as a detachable tool. This experimental setup enabled the production of sound wire using both magnesium and aluminum alloys. The following reference experiments were run with the fixture shown. As shown in Fig. 3, the Esab Legio 3ST machine could manufacture wires up to a maximum length of 70 mm (2 pieces), 40 mm (1 piece), and 30 mm (3 pieces). During a preliminary campaign that also enabled fine-tuning of the tool design with an emphasis on the extension in length of the extrusion channel, the process parameters for the extrusion (R = 900 rpm F = 22 kN) were chosen. Three times were given to each set of procedure parameters, and each time, samples were taken for further study.

Fig. 2 Extruded wire at 900 rpm and 22 kN with an extrusion ratio equal to 8

Numerical models

Such activity as mentioned was carried out through a numerical simulation-based study was carried out using the Deform software characterized by a lagrangian implicit solver able to carry out thermo-mechanical 3D analyses whose governing equation have been discussed in detail by Tekkaya [13]. The software was used with the aim to investigate the effects of the most relevant process parameters and to define an actual process window able to obtain sound continuous wires. In Fig. 3 sketches of some parts of the machine, designed through the numerical simulation are shown. The tools have been simulated as rigid parts by attributing as material AISI-H-13 present in the Deform library. While the chip, considered a coherent workpiece, was imported as a deformable element, attributing it as material AA2024 (20-550 °C). The geometry of the cochlea has also been optimized with the aid of simulation. To obtain the extrusion, two different mesh windows were created which allowed local refinement in critical points thus avoiding the need for recurrence to an excessive number of elements along the extrusion mouth and in the compacting area of the material. The single block cochlea, the container in which it rotates, with static walls of the extrusion chamber, and the rotating extrusion die were modelled as rigid bodies and meshed with 27778, 19915 and 14175, elements, respectively, to solve the thermal problem. The workpiece, representing the AA2024 aluminium alloy compacted chips, was modelled as a unique body and meshed with 40408 tetrahedral elements of variable size. It is assumed that the chips have already fulfilled the whole screw thread and the extrusion chamber. The cochlea rotated around its longitudinal axis and was considered fixed in its axial position; the extrusion chamber, together with the container, was fixed in space, while the extrusion die rotated around its longitudinal axis and was fixed in its axial position. No addition of chips was considered. An experimental campaign was carried out aimed at knowing the best process conditions. It was decided to perform a velocity control on the auger and matrix, thus reducing the computational difficulties that would have arisen in the case of a force control. A speed of 1600 rpm was set for the axial rotation of the die, and a rotational speed of 100 rpm for the screw; with all elements fixed in space. Having defined the movements of the various elements, the contacts between them were generated by establishing the friction conditions. A friction coefficient of $\mu = 0.7$ was imposed in the contact elements between chip and die.

Results

Several problems were encountered: the breakage of the plastic material during the process due to the shear action of the cochlea, that, as the rotation speed increased, determined the fact that the shear strength limit of the material was locally reached, the contacts between the tool and the material that can be estimated from the load trend (peaks on the load). The loss of contacts led to a reduction in temperature as well as pressure. To obtain an effective simulation a strong increase of the number of elements here and there in the mesh was necessary: in this way in the critical points two mesh windows (as shown in Fig. 4c) were used. Furthermore, a frequent remeshing was adopted due to the strong strain level and distortion of the elements. Once the model was set up, a proper calibration was needed: the latter was carried out through an inverse approach starting from experimental evidence using temperature history data derived from the discontinuous FSE process, where a proper thermocouple was placed in the scrap metal chamber. For the tuning phase of the simulation, therefore, an analysis was made using the temperature acquired in the scrap metal chamber. To proceed with the actual tuning referred to the new fixture, 4 temperatures loci were tacked on the basis of the positions of the four thermocouples placed in the actual machine. In the Fig. 9 show the comparison between the numerically calculated temperatures in positions 1 and 2.

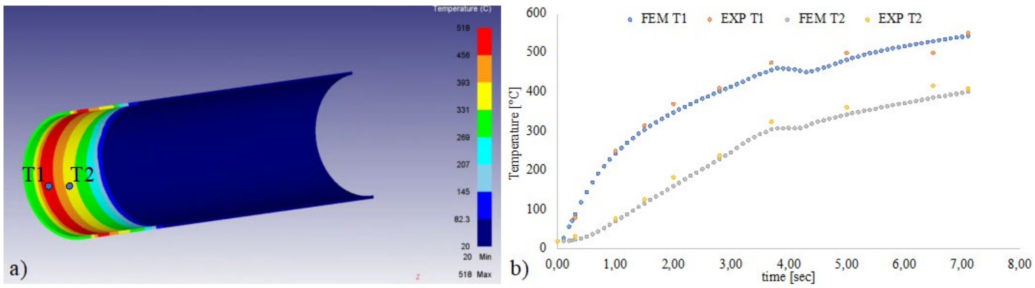

Fig. 9 (a) Position of the thermocouples in the scrap metal chamber and (b) comparison between temperature acquired by thermocouples T1 and T2 and numerical prediction - R=900 rpm, F=22 kN

Using the point tracking was possible to perform a study on the flow of the material generated during the process. Fig. 10 show the positioning of these points.

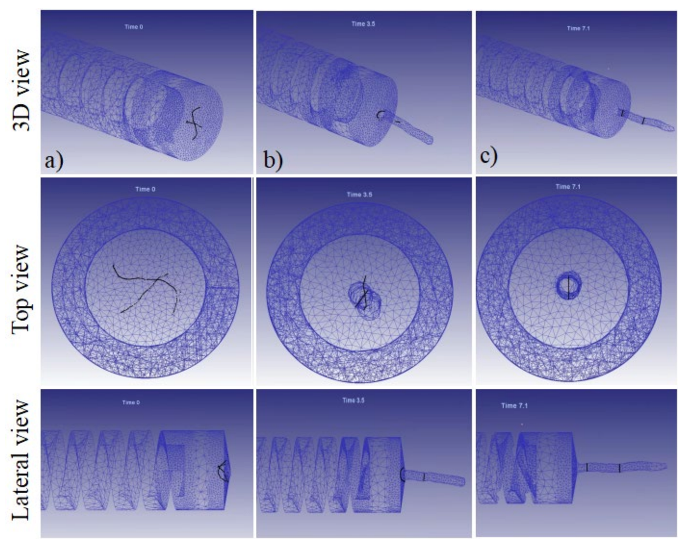

Fig. 10 Point tracking positions in three different steps: (a) initial, b)-c) out of the extrusion channel at different time – R = 900 rpm, F = 22 kN

Once the simulation of the process was established, the material modeled by Shyma-Oyane yield surface was used, with an initial density of 0.8. The process therefore remains the same with the only new filed variable being the porosity of the material. It has been observed that the extrusion mechanics is activated only after reaching the full density (1) of the material (Fig. 11)

Numerical instabilities were observed due to the quite low value of the material density with some sudden variations of temperature due to local losses of contact. In Fig. 11 (a and b) are shown difference noted in the achievement of the unitary value of the density, compared to what happens in the traditional process [14]. In such continuous process an intermediate compacted layer of the material is obtained depending on the actual distance between the cochlea and the scrap metal chamber during the process. This observation led to the conclusion that the process must consist of the following three distinct phases:

I. Pre-compacting by cochlea with zero tool rotation: in such stage just the axial motion of the cochlea is acted determining a sort of upsetting process mechanics and the consequent compacting of the chips.
II. Under a constant load by the cochlea, the tool starts rotating with established rotational speed: the axial force by the cochlea increases step by step until reaching the imposed value (process parameter); (at this stage, the process becomes a load controlled one).
III. Locking the advancement of the cochlea and starting the rotation of the cochlea to intake new scrap metal maintaining thus a constant pressure in the chamber.

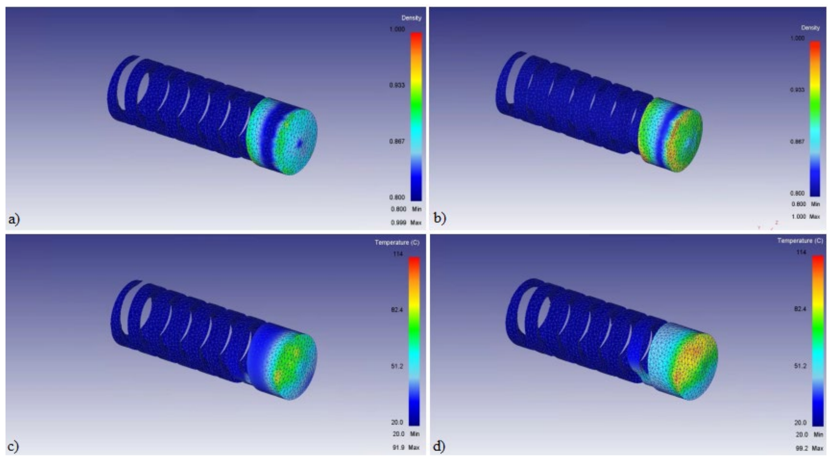

Fig. 11 Relative density and temperature at a)-c) 1.5 sec and b)-d) 2.5 sec

The contact between the chip and the tool is also linked to the inclination of the thread, therefore there is a point of maximum pressure and a minimum point, a hypothesis in the verification phase provides for a linear displacement of the auger, by means of application of a force towards the tool, in order to self-regulate the pressure in the chamber avoiding lack of pressure phenomena which contribute to the interruption of the material plastic flow directed towards the tool and then the interruption of the consolidated material extrusion. Once the obtained numerical data will be verified with the experimental ones, it will then be possible to proceed with the full process engineering.

Conclusion

The study conducted demonstrates that Friction Stir Extrusion technology operated continuously represents a state-of-the-art solution for the primary recycling of light alloys, such as aluminum.
The continuous process represents a very viable alternative to more classical material remelting methods and an excellent alternative to the Solid-State Recycling landscape. The numerical analyses carried out show how the proposed FEM model fully represents the reality of the process, being able to provide that information which is not directly measurable by the experimental test.
It has been shown how the model is able to help the experimental campaign by providing useful data such as: output parameters for the achievement of the solid bonding phenomenon such as, the temperature distribution, the strain rate trend and thus the material flow; but also input parameters necessary for the proper operation of the process such as the force trend required for the extrusion and the rotation speeds of the moving elements. The solution, identified in the continuous extrusion process, allows recycling to be carried out directly "on site". An additional advantage of the application of continuous FSE is that it overcomes the geometric limitations associated with its "single block" version. Finally, it is noted that the developed FEM model is a first attempt model,

which has shown encouraging and plausible results, but to become an industrial design tool it will have to be calibrated appropriately. A study should, in the future, be carried out as parameters such as friction, conductivity coefficients and mesh sensitivity.

References

[1] Gutowski, T. G., Sahni, S., Allwood, J. M., Ashby, M. F., & Worrell, E. (2013). The energy required to produce materials: Constraints on energy-intensity improvements, parameters of demand. https://doi.org/10.1098/rsta.2012.0003

[2] Ingarao, G. (2017). Manufacturing strategies for efficiency in energy and resources use: The role of metal shaping processes. Journal of Cleaner Production, 142, 2872–2886. https://doi.org/10.1016/j.jclepro.2016.10.182

[3] European Aluminum Association, 2013. Environmental Profile Report for the European Aluminium Industry.

[4] The energy required to produce materials: Constraints on energy-intensity improvements, parameters of demand. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 371(1986).

[5] Vargel, C., 2004. Corrosion of Aluminium. Elsevier. https://doi.org/10.1016/B978-008044495-6/50012-4

[6] Simon, L., Moraes, C. A. M., Modolo, R. C. E., Vargas, M., Calheiro, D., & Brehm, F. A. (2017). Recycling of contaminated metallic chip based on eco-efficiency and eco-effectiveness approaches. Journal of Cleaner Production, 153, 417–424. https://doi.org/10.1016/j.jclepro.2016.11.058

[7] Grayson J., 2017. Reducing Melt Loss and Dross Generation.

[8] Baffari D, Buffa G, Campanella D, Fratini L, Micari F. 2014. Friction based Solid State Welding Techniques for Transportation Industry Applications. https://doi.org/10.1016/j.procir.2014.06.125

[9] D. Baffari, A.P. Reynolds, X. Li, L. Fratini, Influence of processing parameters and initial temper on friction stir extrusion of 2050 aluminum alloy, Journal of Manufacturing Processes, 28 (2017) 319–325. https://doi.org/10.1016/j.jmapro.2017.06.013

[10] D. Baffari, G. Buffa, D. Campanella, L. Fratini, Al-SiC metal matrix composite production through friction stir extrusion of aluminum chips, Procedia Engineering, 207 (2017) 419–424. https://doi.org/10.1016/j.proeng.2017.10.798

[11] D. Baffari, G. Buffa, D. Campanella, L. Fratini, A.P. Reynolds, Process mechanics in friction stir extrusion of magnesium alloys chips through experiments and numerical simulation, Journal of Manufacturing Processes, 29 (2017) 41–49. https://doi.org/10.1016/j.jmapro.2017.07.010

[12] D. Baffari, G. Buffa, L. Fratini, A numerical model for wire integrity prediction in friction stir extrusion of magnesium alloys, Journal of Materials Processing Technology, 247 (2017) 1–10. https://doi.org/10.1016/j.jmatprotec.2017.04.007

[13] Tekkaya AE. Simulation of Metal Forming Processes 2000:251–302. https://doi.org/10.1007/978-3-662-04013-3_7

[14] Baffari Dario; Buffa Gianluca; Fratini Livan (2017). A numerical model for Wire integrity prediction in Friction Stir Extrusion of magnesium alloys. Journal of Materials Processing Technology, 247, 1. https://doi.org/10.1016/j.jmatprotec.2017.04.007