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Design of continuous Friction Stir Extrusion machines for metal chip recycling: issues and difficulties

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Abstract

Friction Stir Extrusion is an innovative direct-recycling technology developed for metal machining chips. During the process, a rotating die is plunged into a cylindrical chamber containing the material to be recycled. The stirring action of the die prompts solid bonding phenomena allowing the back extrusion of a full dense rod. One of the main weakness of this technology is the discontinuity of the process itself that limits the extrudates volume to the capacity of the chamber. In order to overcome that limitation, a dedicated extrusion fixture has to be developed, keeping into account the concurrent needs of a continuous machine. The geometry of the die has to ensure proper pressure in the extrusion channel to prompt the extrusion while allowing the continuous loading of fresh charge. Furthermore, the chips entering the chamber have to find proper conditions for the solid bonding to happen. In this study, the design challenges of a continuous Friction Stir Extrusion machine are described and analyzed, giving an insight on the possible solutions using both experimental, numerical analysis, and keeping into account the sensor equipment necessary to monitor the process.

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Keywords: Continuous Friction Stir Extrusion; Chip recycling; Machine design

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1. Introduction

The production cycle used for most mechanical components includes machining operations. This implies that a significant amount of metallic material is wasted as scrap during the performance of traditional cutting processes [1].

The recovery of metal chips is an important challenge in order to obtain both environmental and economic advantages and researcher are always looking for innovative and efficient ways of recycling. Nevertheless, machining chip is one of the most difficult kinds of scrap to be recycled as it is characterized by elevated surface/volume ratio and it is usually oxidized and covered by different types of contaminants (i.e. lubricants used for the machining process). Due to these features, conventional melting recycling technologies may lead to different drawbacks and environmental issues, e.g. fumes and gas formation, energetic/economic issues, i.e. low efficiency in terms of obtained material and high energetic cost and technological issues, i.e. 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]. From these studies it arises that the recovery rate of the entire process usually hardly reaches 50%. Moreover, the whole process requires several intermediate operations: cleaning, dying, compacting, etc. as well as high energy usage, causing these conventional technologies to be inadequate for the modern industrial needs.

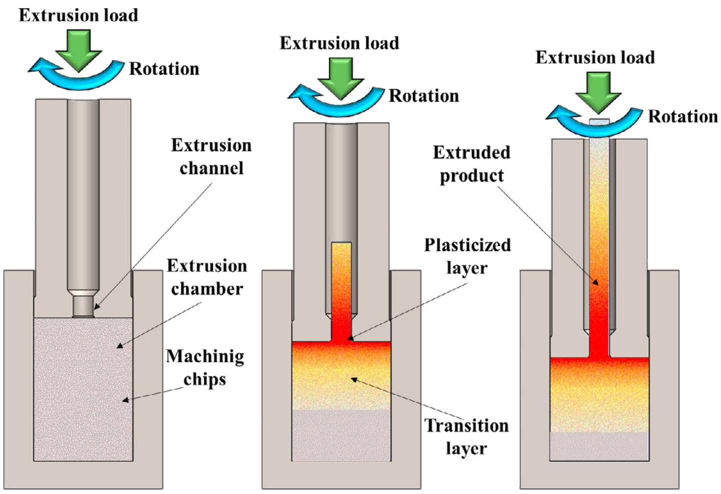

Fig. 1. Sketch of the Friction Stir Extrusion process.

In 1945, Stern proposed and patented hot extrusion as a way to recycle metal scrap without the melting of the material [4] and successively Sharma et al. obtained aluminum bars through hot extrusion of chips [5]. Gronostajski and Matuszak [6] first introduced in 1999 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. 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. [7]. Compared to the conventional method, the direct method allows significant savings in terms of material – up to 40% - energy – between 26% and 31% - and labor – between 16 and 61%. However, the irregular geometry of the chips requires a "chopping stage" to be undertaken in order to obtain proper compaction before the extrusion and, consequently, good quality recycled material. Tekkaya et al. [8] highlighted the importance of high pressure, temperature, and strain level inside the die for the recycling through hot extrusion of aluminum chips. Hu et al. [9] 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 obtained products presented very low porosity and elevated relative density. The effects of chips mean size and extrusion ratio on the microstructural, mechanical [10] and corrosion [11] properties have been also investigated. Overall, the final extruded product presents low porosity and high relative density, namely the ratio between the density of the extruded object and the density of parent material, equal to about 98%. Compared to the conventional method, the direct method allows significant savings in terms of material – up to 40% - energy – between 26% and 31% - and labor – between 16% to 61%. However, the shape and the dimension of the chip is a key factor for successful recycling. 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.

In 1975 Andrew and Gilpin [12] developed the first friction based forging process that lead to the development of the Friction Stir Extrusion process that was patented by The Welding Institute of Cambridge in 1991. A rotating tool (Fig. 1) is used to produce heat and plastic deformation through friction between the tool itself and the chips to be recycled (into a hollow cylindrical chamber) by compacting, stirring and extruding the material. In this way the recycling process takes place in a single operation, resulting in significant cost, energy, and labor saving with respect to both the conventional method and the direct method. This technology lay dormant for more than a decade before investigation began again after the TWI patent expiration due to failure to pay maintenance fee in 2002. FSE is currently being adopted for producing high quality wires and rods from direct recycling of metal scrap or primary manufacturing from metal powders. Tang and Reynolds [13] 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.

One of the main limitations of the FSE process is the limited length of wire that is possible to produce in a single operation. This issue is imputable both to the intrinsic discontinuity of the process and the structure of the machines used to carry out the extrusion. As happened during the early development of FSW, most of the machines use by researcher are adapted milling machines. In this paper the main design challenges of a dedicated FSE machine are described and analyzed, giving an insight on the possible solutions using both experimental and numerical analysis.

2. Case studies

Some of the authors of this paper carried out FSE experimental campaigns on both magnesium, i.e. AZ31B [14] and aluminum [15, 16] alloys, investigating the influence of the main process parameter and developing a dedicated numerical model [17] to analyze the process mechanics. The experiments were carried out on an ESAB LEGIO 3ST machine (see Fig. 2(a)). 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 parameter to be controlled during FSE. The tools used for the experiments were a hollow chamber (Fig. 2(b)) 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 in order to guide the material flow toward the extrusion channel.

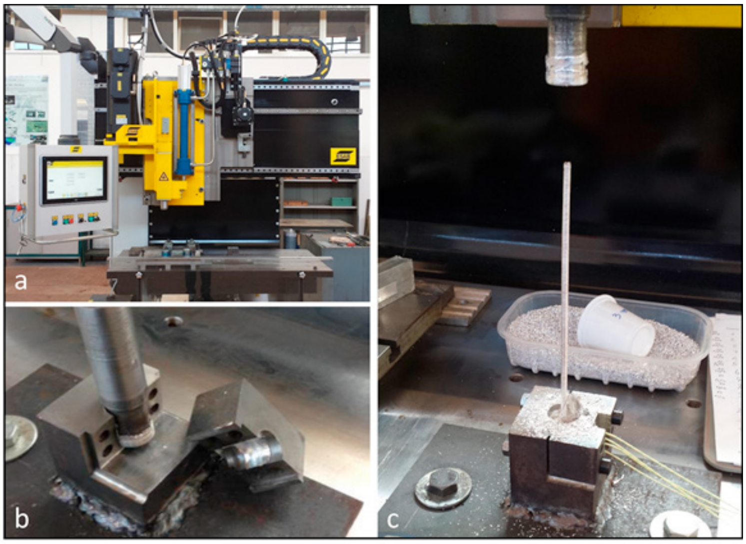

Fig. 2. Experimental set-up on FSW machine.

The chamber was designed as a dismountable tool since one of the recurring issues during the experiments was the gripping of the die because of the plasticized material flowing into the clearance between die and chamber themselves. This experimental set-up allowed to produce sound wire from both aluminum and magnesium alloys (Fig. 2(c)). Most of the obtained wire (Fig. 3) showed a fine equiaxial microstructure and good mechanical resistance, comparable to the parent material. However only the case studies characterized by the higher extrusion ratio were defect free.

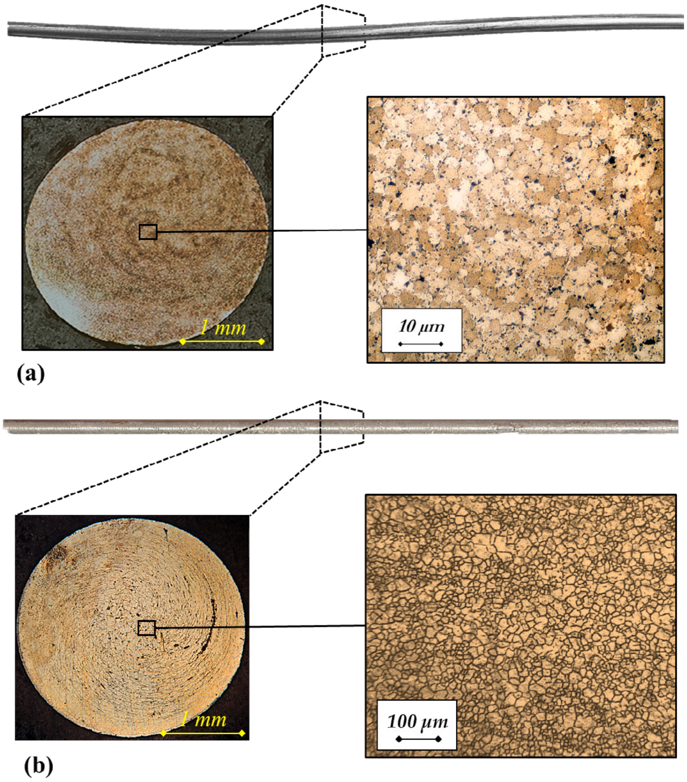

Fig. 3. Cross section and microstructure for (a) AA2024, 18 kN, 700 rpm and (b) AZ31B, 14 kN, 700 rpm case studies.

The main drawback of this solution is the limited amount of material that is possible to process because of the volume of the chamber. In particular, the chamber height is limited both by the maximum vertical stroke of the used FSW machine and the length of the die. In fact, using an excessively long die may lead to vibration due to the high compression load acting on it. Moreover, the increase of the die diameter would cause the torque and the vertical force required to carry out the process to overcome the machine limits. On the other hand, larger die would also allow to obtain bigger wire diameter maintaining the optimal extrusion ratio.

3. Machine design

To overcome the above-described issues, a new dedicated machine for FSE has to be developed. The structure of this machine was designed thanks to the expertise acquired during the previous experimental campaign. In particular, in order to maximize the frame stiffness, 4 columns design with horizontal axes was chosen (Fig. 4). The machine is composed by a ram controlled by four hydraulic actuators that moves against a backing basement housing the chips feeding system (Fig. 5). This system was developed in order to make the extrusion process continuous; it is composed by a specifically designed cochlea driven by the feeding motor. The feeding system is analogous to a conventional screw extruder used for both plastics and metals [18]. The implementation of this system together with the rotary extrusion die allows not to use any external heat source to achieve proper material softening.

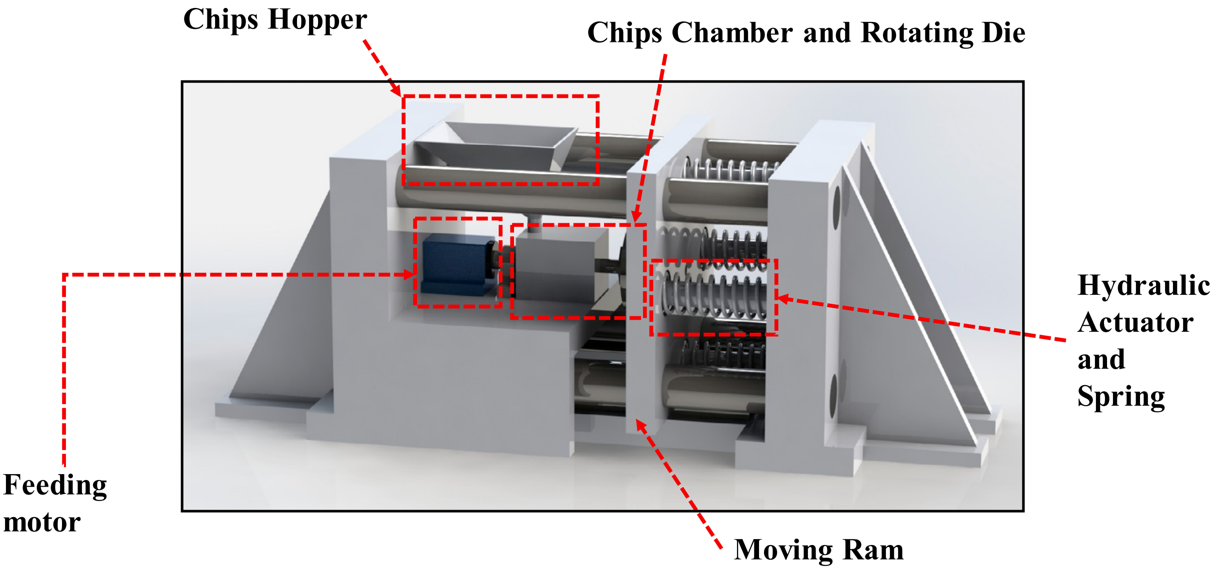

Fig. 4. CAD of proposed machine.

Metal chips are directed by a hopper toward the screw that pushes them inside the chamber against the rotary die. The die is mounted on a mandrel driven by a dedicated motor on the moving ram. The ram slides on the four main columns and on two complementary gibs in order to increase the overall stiffness.

One of the main challenges undergone during the design of the machine was the cochlea geometry. In fact, this component of the feeding system has to ensure that new material is driven into the extrusion chamber while the process take place in order to maintain the extrusion pressure. Numerical simulations were carried out with varying cochlea geometry in order to minimize thread deflection during the process. Moreover, the steam geometry designed in order to guarantee and even stress distribution in the whole tool.

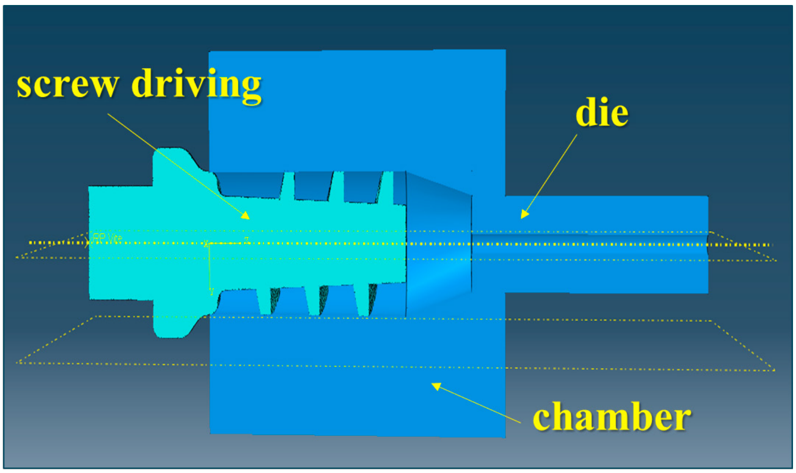

Fig. 5. Chip feeding system.

In Fig. 6, Von Mises stress for two different geometry are presented, showing how the optimized design (Fig. 6(b)) effectively reduces stress concentrations. The shoulder introduced in the optimized design (Fig. 6(b)) allow both to effectively reduce stress concentration and to close the chamber to ease chip loading. Moreover, the conical shape of the screw increases the axial material flow and allows to reduce the threads height in the area of the tool subjected to the higher stresses.

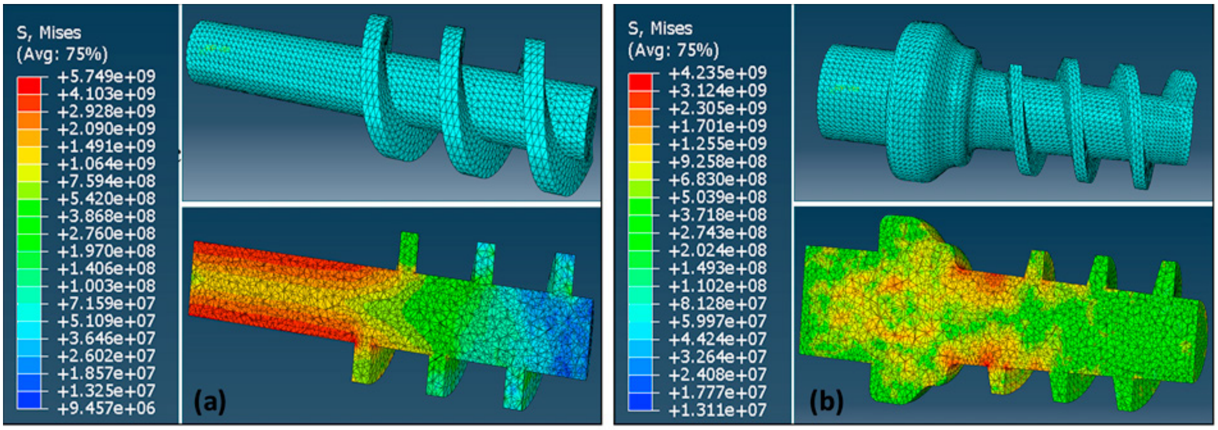

Fig. 6. Von Mises stress distributions under 50 kN, 450 Nm for initial (a) and optimized (b) design.

The designed direct chip recycling device will be then developed with the following innovative features:

- ✓ Proper range of process parameters determined in an automatic manner by monitoring in-process the key parameters: rotation, torque, displacement, force, extrusion, temperature & extrusion rate
- ✓ Modular tooling system for automatically changing the geometry of the die and of the friction surface according the thermo-mechanical properties of the material used.
- ✓ In-process cooling system for the extruded wire for enhancing its microstructure
- ✓ Dedicated feeding system for making the direct recycling process continuous, in such a way that the extruded wire will be automatically recirculated and re-added to the part being manufactured.

4. Conclusions

In the paper, the main issues to be addressed in order to allow the full exploitation of the Friction Stir Extrusion potential are presented and discussed. In particular, although it was assessed that full density and high mechanical properties products can be obtained from machined scraps of different light alloys, it arises that a major limitation is given by the discontinuous nature of the process. In this way, a new machine, characterized by a specifically designed cochlea and feeding system, was designed and presented with the aim to make the process continuous. The authors believe that the use of such machine can boost the wide spread of the process in different industry fields. Adding the process to complex production lines in which the recycled scrap is used as filler wire for additive manufacturing process, can lead to obtain a 100% material use within the same production plant.

References

[1] F. Jovane, H. Yoshikawa, L. Alting, C.R. Boër, E. Westkamper, D. Williams, M. Tseng, G. Seliger, A.M. Paci, The incoming global technological and industrial revolution towards competitive sustainable manufacturing, CIRP Annals - Manufacturing Technology, 57 (2008) 641–659.

[2] T.G. Gutowski, J.M. Allwood, C. Herrmann, S. Sahni, A global assessment of manufacturing: economic development, energy use, carbon emissions, and the potential for energy efficiency and materials recycling, Annual Review of Environment and Resources, 38 (2013) 81–106.

[3] G. Hanko, H. Antrekowitsch, P. Ebner, Recycling automotive magnesium scrap, JOM, 54 (2002) 51–54.

[4] M. Stern, Method for treating aluminum or aluminum alloy scrap, (1945). https://www.google.com/patents/US2391752

[5] C.S. Sharma, T. Nakagawa, Recent development in the recycling of machining swarfs by sintering and powder forging, Manufacturing Technology, Gen Assem CIRP, 26 (1977) 121–125.

[6] J. Gronostajski, A. Matuszak, The recycling of metals by plastic deformation: an example of recycling of aluminium and its alloys chips, Journal of Materials Processing Technology, 92–93 (1999) 35–41.
[7] J.R. Duflou, A.E. Tekkaya, M. Haase, T. Welo, K. Vanmeensel, K. Kellens, W. Dewulf, D. Paraskevas, Environmental assessment of solid state recycling routes for aluminium alloys: Can solid state processes significantly reduce the environmental impact of aluminium recycling?, CIRP Annals - Manufacturing Technology, 64 (2015) 37–40.
[8] A.E. Tekkaya, M. Schikorra, D. Becker, D. Biermann, N. Hammer, K. Pantke, Hot profile extrusion of AA-6060 aluminum chips, Journal of Materials Processing Technology, 209 (2009) 3343–3350.
[9] M. Hu, Z. Ji, X. Chen, Z. Zhang, Effect of chip size on mechanical property and microstructure of AZ91D magnesium alloy prepared by solid state recycling, Materials Characterization, 59 (2008) 385–389.
[10] S. Wu, Z. Ji, S. Rong, M. Hu, Microstructure and mechanical properties of AZ31B magnesium alloy prepared by solid-state recycling process from chips, Transactions of Nonferrous Metals Society of China, 20 (2010) 783–788.
[11] Y. Chino, K. Sassa, A. Kamiya, M. Mabuchi, Enhanced formability at elevated temperature of a cross-rolled magnesium alloy sheet, Materials Science and Engineering: A, 441 (2006) 349–356.
[12] D.R. Andrews, M.J. Gilpin, Friction forming - a preliminary study, Metall. Mater. Technol., 7 (1975) 355–358.
[13] W. Tang, A.P. Reynolds, Production of wire via friction extrusion of aluminum alloy machining chips, Journal of Materials Processing Technology, 210 (2010) 2231–2237.
[14] 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.
[15] 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.
[16] 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.
[17] 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.
[18] F. Widerøe, T. Welo, Using contrast material techniques to determine metal flow in screw extrusion of aluminium, Journal of Materials Processing Technology, 213 (2013) 1007–1018.