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A numerical model for Wire integrity prediction in Friction Stir Extrusion of magnesium alloys

Dario Baffari, Gianluca Buffa*, Livan Fratini

Department of Industrial and Digital Innovation (DIID), University of Palermo, Viale delle Scienze, 90128 Palermo, Italy

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ABSTRACT

A numerical model for the prediction of the wire quality produced by the novel direct machining chip recycling technique known as Friction Stir Extrusion (FSE) is presented. Wire microstructure and wire integrity have been predicted by embedding in the code the equations enabling the calculation of the Zener-Hollomon parameter as well as the W parameter of the Pivnik-Plata solid bonding criterion. The proposed model, developed for the AZ31 magnesium alloy using the commercial simulation package DEFORM, is 3D Lagrangian, thermo-mechanically coupled with visco-plastic material behavior. The model was first validated against experimental temperature measurements and then used to predict the main field variables distributions with varying process parameters.

1. Introduction

The production cycle used for most mechanical components includes machining operations. This implies that a huge amount of metallic material is wasted as scrap during in traditional cutting processes (Jovane et al., 2008). 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 way 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 as environmental issues, i.e. 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.

Friction Stir Extrusion (FSE) is a solid-state recycling process in which the mechanical action of a rotating tool is used to promote the solid binding of the chips and generate a backward extrusion. The chips to be recycled are placed into an extrusion chamber and a dedicated tool, characterized by an inner extrusion channel, is inserted in the chamber while rotating. The friction forces produce an increase of temperature and strain in the material which is forced to flow through the channel while, due to the large deformation imposed, solid bonding occurs thus producing a sound extruded wire. Some of the authors of this paper have already carried out an experimental campaign on the FSE of AZ31 Mg alloy imposing the extrusion speed through the control of rotating tool vertical displacement (Buffa et al., 2015). In the same paper, a comprehensive literature analysis on alternative methods to recycle magnesium alloys and current state of the art of FSE is reported and will be omitted in this paper. The obtained results show that the process is feasible and mechanical efficiency of about 80%, i.e. the ratio between the UTS of the produced wire and the one of the parent 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. The combined effect a given set of the main technological process parameters, i.e. tool rotation and extrusion force/speed, results in a peculiar distribution of temperature and strain in the processed material. The combination of these two field variables determines the effectiveness of the process, as it will be better explained in the following of this paragraph.

Although it is in an early stage of development, FSE seems promising from the process efficiency point of view, even compared to other direct methods based processes, due to the fact that the whole process (material heating, compaction and extrusion) requires just one step. However, the real potential of the process still has not been exploited due to industrial issues, related to the application of the process in a competitive way, and scientific issues, related to the significant knowledge gap in literature, especially regarding FEM

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* Corresponding author.
E-mail address: gianluca.buffa@unipa.it (G. Buffa).

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simulation. Among the former, as most direct recycling techniques, high forces are required for proper binding to occur between the chips, the chips must be carefully selected based on the material and the process is discontinuous, resulting in long production times (Duflou et al., 2015; Haase et al., 2012). As the latter are considered, analyzing and isolating the effects of each of the different technological parameters on the mechanical properties of the produced rod can be quite difficult. This problem results to be much more relevant when the extrusion is carried out assigning the extrusion force instead of the extrusion rate: in a force-controlled FSE process the extrusion rate depends on the extrusion force and the material flow stress which is in turn influenced by temperature and flow stress varying with tool rotation. On the other hand, the temperature of the process is also dependent on the extrusion rate, vertical force and tool rotation. Hence, the problem of isolating a single parameter influence on the process results to be quite a complex task requiring large experimental campaign in order to select the best parameters for each material. To reduce the amount of the experiments a numerical model able to predict the main field variables as well as the extrudes quality can represent a useful design tool, usually applied in other Friction Stir process i.e. FSW. Due to the similarities of the process mechanics between FSW and FSE, part of the know how acquired during the last years in the simulation of FSW can be carried over to FSE. In particular, the material model should be temperature, strain and strain rate dependent. Temperature should range from room temperature to about the solidus temperature; strain and strain rate can reach very large values, as high as 40 and 200 1/s, respectively, as shown by different authors (Buffa et al., 2006b; Alfaro et al., 2008). As the modelling approach is concerned, several strategies have been followed in literature for FSW, i.e. Eulerian solid mechanics (Zhang and Zhang, 2014), Lagrangian solid mechanics (Buffa et al., 2006a), ALE (Assidi et al., 2010) and CFD (Colegrove and Shercliff, 2005). Each of them presents peculiar advantages and drawbacks which must be taken into account also for FSE. However, only a very limited number of papers can be found in literature based on numerical simulation on FSE. Ansari et al. (2015) optimized the process parameters of FSE applied to commercially pure magnesium using statistical tools while Behnagh et al. (2015) investigated the metallurgical transformation during FSE of pure magnesium through a thermo-mechanical 2D analysis. The ALE model was implemented in Abaqus and allows the prediction of Dynamic Recrystallization (DRX) during the extrusion, also providing evaluation of the microhardness profiles along the radius of the rods. Zhang et al. (2014) proposed a CFD numerical model able to provide insights on the material flow occurring in FSE of aluminum alloys. The 3D CFD model is able to predict the velocity field and it has been validated using experiments with marker particles. The same authors furthermore investigated FSE proposing a two-dimensional axial symmetric model (Zhang et al., 2015) based on ANSYS FLUENT aimed at modeling heat transfer during the process using as input the experimentally measured mechanical power.

Nevertheless, none of these models is able to predict the extruded product integrity via a unique 3D FEM simulation. In order to pursue this goal, the presented model capable to calculate the Zener-Hollomon (Z) parameter, to gather quantitative information on the final microstructure of the extruded wire, and to calculate the Piwnik and Plata solid bonding parameter to assess the occurrence of proper solid bonding. The Z parameter has been successfully used to correlate the distribution of temperature and strain rate to the final microstructure of light alloy components manufactured in hot conditions. Chang et al. (2004) were among the firsts to highlight the relationship between grain size and Zener-Hollomon parameter in FSW, tube extrusion and profile extrusion of AZ31 magnesium alloy. Xu et al. (2009) studied the dynamic recrystallization during hot compression of AZ91 magnesium alloy, finding that the influence of precipitates must be also taken in to account in order to successfully utilized the Z parameter for high Al content magnesium alloys. Finally, Fatemi-Varzaneh et al. (2007) found a strong correlation between the amount of recrystallized volume fraction, grain size and Z, with the first two increasing for decreasing Z. As the Piwnik and Plata criterion is regarded (Plata and Piwnik, 2000), the integral in time of the ratio between the contact pressure and the flow stress of the material is calculated to determine a threshold value representing the limit condition between ineffective and effective solid bonding. In the past years, the Piwnik and Plata criterion has been successfully applied to identify a threshold value for the onset of effective solid bonding in porthole die extrusion, thus allowing the prediction of the presence of flow defects, as shown in the research work of Donati et al. (2007) and Ceretti et al. (2009) for the Porthole Die Extrusion (PDE) process, and Buffa et al. (2014b) for FSW.

In this paper, the development of a “single block” 3D FEM model for FSE, based on a Lagrangian implicit solver is presented. The numerical model is thermo-mechanically coupled, with rigid-viscoplastic material behavior. The numerical model was calibrated and validated using temperature data measured during a dedicated experimental campaign.

2. Process modeling and experiments

2.1. Model setup

The numerical model was implemented on the commercial FEM software “SFTC DEFORM”, characterized by a lagrangian implicit solver whose governing equation can be found in the book by Tekkaya (2000). Three different objects were modeled (Fig. 1): the extrusion chamber and the rotating punch were modeled as rigid bodies and meshed with 6000 elements each in order to solve the thermal problem considering heat transfer. The workpiece, representing the AZ31 magnesium alloy compacted chips, was modeled as a unique cylinder. The extrusion chamber was fixed in space, while the punch rotated around its longitudinal axe and was plunged into the extrusion chamber. The vertical speed of the punch was assigned as a time-dependent law obtained from experimental measurements during force controlled trials. It is worth noticing that this expedient was needed to simulate force-controlled extrusion in order to save CPU time, which can be significantly higher when force controlled boundary conditions are assigned. Fig. 1a shows a sketch of the process while Fig. 1b shows the “single-block” workpiece, characterized by a mesh of 80,000 tetrahedral elements of variable size. The area of the workpiece close to the contact interface with the rotating tool was meshed with elements 10 times smaller than the largest one, i.e. about 1 mm in edge.

One of the main issues to deal with during the development of this model was the definition of the material model. The model should take into account the discrete nature of metals chips, considering that it would be extremely time consuming to correctly model them in their real form. Firstly, the Shima-Oyane formulation for porous material was tested (Shima and Oyane, 1976). Metal chips are usually compacted into the extrusion chamber before the beginning of the extrusion process due to the action of the tool. This billet of compacted metal scraps can be considered a single porous object, allowing the identification of defects and voids in the extruded wires through the analysis of the relative density variation, namely the ratio between the compacted billet density and base material density. The yield surface implemented by this model is based on a modified von Mises criterion that takes into account the presence of micro voids in the material matrix. According to this model, starting from an initial relative density, material densification may occur as a compressive stress state is generated during the process. In this way, it is possible to model the presence of voids in the material pushed in the extrusion channel by the tool action.

The Shima-Oyane yield surface is presented in Eq. (1), where R_0 is the initial relative density of the porous material (namely of the billet of compacted chips), R is the actual (instantaneous) relative density and $\Delta\varepsilon v$ is the deformation due to volume variation of microvoids (whose number does not change according to the base hypothesis of this formulation).