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Numerical Analysis of Process Parameters and Tool Geometry in Friction Stir Back Extrusion of Pure Aluminum

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Abstract

Friction Stir Back Extrusion (FSBE) is an innovative process that offers efficient aluminum waste recycling and wire production. This process boasts economic and environmental advantages, as it requires minimal energy compared to traditional recycling casting methods. The objective of this study is to analyze the impact of process parameters using a Finite Element Method (FEM) model based on thermo-mechanical 3D Lagrangian. The study focuses on an AA1080 aluminum alloy and employs different geometric tools, including hole extrusion diameters of 4 mm and 8 mm, as well as a shoulder with two distinct angles of 10° and 15°. Furthermore, variations in several process parameters, such as a constant axial feed rate of 0.5 and 1 mm/min and a constant rotational speed of the die set at 100, 300, and 500 rpm, are considered. The simulation plan encompasses a total of 24 combinations of these parameters to identify the optimal conditions for chips extrusion. Subsequently, the obtained results were analyzed using Design of Experiments (DoE) analysis to assess the influence of each parameter on peak force, torque, and temperature during the process.

Keywords: Friction Stir Extrusion; Numerical simulation; Aluminum recycling; Aluminum chips.

1. Introduction

Aluminum machining processes, such as milling and turning, generate a significant amount of metal chips as waste [1]. To create new materials like ingots or billets, these chips typically need to undergo remelting. However, this additional remelting step results in higher energy consumption. The recovery of metal scraps using conventional techniques can be challenging due to factors such as their high surface-to-volume ratio, the presence of oxide layers, and the potential contamination from oil residues [2]. Furthermore, it is crucial to ensure the elimination of all impurities prior to the remelting process. However, achieving complete removal of impurities can be challenging, leading to potential variations in the chemical composition of the resulting alloy compared to the original starting material. [3]. Conventional recovery techniques in metal recycling pose several environmental concerns, including gas emissions during the process. Additionally, they are associated with economic challenges such as high energy costs. Moreover, these techniques often suffer from low efficiency in the recycling process, resulting in inadequate quality of the recycled materials [4]. Moreover, there can be occurrences of porosity, inclusions, or inadequate mechanical resistance, which adversely affect the quality of the final product. Friction Stir Extrusion (FSE), introduced and patented by the Welding Institute in 1993, is an innovative recycling process that utilizes the mechanical action of a rotating tool to achieve the bonding of metal chips through

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backward extrusion. In this process, metal chips are loaded into an extrusion chamber, and a specialized rotating tool with an inner extrusion channel is inserted. The frictional force generates heat within the material flow as it passes through the channel. Through significant deformation, the material consolidates, resulting in the formation of a wire upon extrusion. Despite its potential, the FSE process is still in its early stages of development, hindered by limited literature and challenges in industrial competitiveness. Currently, only a handful of publications are available on the FSE process for aluminum and its alloys, leaving the technique's full potential largely untapped. Tang et al. [5] used FSE to create wires of aluminum AA2050 and AA2195 using machining chips. They varied the tool rotation rate while maintaining a constant extrusion force and discovered that the wires exhibited a desirable combination of microhardness and bend ductility. El Mehtedi et al. [6,7] investigated the possibility of using the FSE method to manufacture defect-free wires of pure AA1090 and AA1099 aluminum chips. Additional studies examined the FSE technique using pure magnesium and AZ31 chips [8–12]. As mentioned earlier, friction stir extrusion (FSE) is a relatively new technology, and the use of simulations is highly advantageous in establishing correlations between process parameters and the underlying physics. In recent years, FEA (Finite Element Analysis) and CFD (Computational Fluid Dynamics) models have increasingly been employed to simulate the FSE process. Zhang et al. [13] developed a 2D and axisymmetric thermal exchange model based on ANSYS FLUENT to predict temperature variations during the FSE process. Their model incorporated a simplified linear heat flux distribution in the radial direction, with measured power serving as input. The same authors also proposed a 3D CFD model, validated through experiments with marker particles, to predict the velocity field [14]. Baffari et al. [4] focused on magnesium scraps and utilized the DEFORM software to design a model for predicting product quality and validating temperature distribution in the extrusion chamber. They discovered that the rotational speed of the tool had a positive effect on the process parameters. Behnagh et al. [12] employed the ABAQUS software to develop a model investigating the thermal, mechanical, and microstructural behavior of magnesium products during the FSE process. Through tests conducted at different tool rotational speeds, they concluded that this parameter had a significant impact on heat exchange, surpassing the influence of the descent speed. Bocchi et al. [3] introduced a FEM analysis to explore the occurrence of the bonding phenomenon and how process parameters influenced bonding quality. These studies exemplify the utilization of FEA and CFD models to gain insights into the FSE process, enabling the prediction of temperature trends, assessment of product quality, and examination of the effects of various process parameters.

The aim of this study is to evaluate the influence of both geometric and process parameters on the extrusion process of AA1080 aluminum chips. Various parameters have been examined, while others have been kept constant, and their impact on the required force, torque, and temperature achieved during the process has been analyzed. It is worth mentioning that the simulations were carried out using velocity control rather than load control. Peak force and peak torque were identified as the key parameters with cost implications for the process machine. Minimizing these parameters could help prevent the need for over-dimensioning, making the process more cost-effective.

2. Numerical simulation

A 3D Lagrangian incremental thermo-mechanical FEM model was developed using DeformTM to analyze Friction Stir Back Extrusion. In the model, the die and extrusion chamber were represented as rigid elements, while the billet was simulated using AA1080 aluminum alloy as cast material, utilizing the available material data in the program. To optimize simulation efficiency while maintaining accurate results, a simplification was implemented for the billet. It was assumed that the extrusion of chips occurs after the porosity material density reaches approximately 100% of the cast material, as supported by previous studies [4,10]. Figure 1 illustrates the setup for the simulations, showcasing the main geometry parameters. In Figure 1a, the essential geometric parameters are depicted. Additionally, Figure 1b presents the mesh of the billet, which includes two windows that effectively increase the number of elements within the mesh. The billet mesh exhibits distinct layering, with the central area having the highest density since it corresponds to the region where the extruded filament is expected to form. The remaining surfaces exhibit a different texture, with the lower area being of the "coarse" type. This distinction arises from the fact that the process is halted before complete billet extrusion, rendering further calculations irrelevant for the specific objectives of the study.

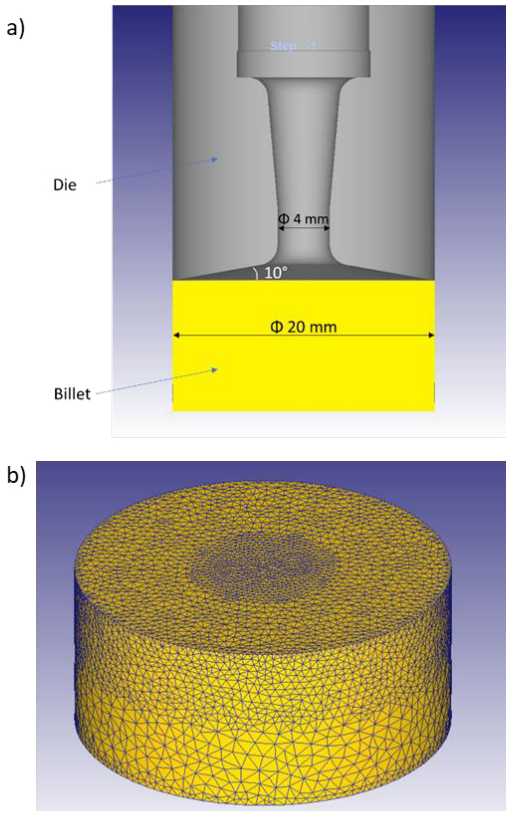

Figure 1 – (a) Simulation Setup, illustrating the main geometry parameters; (b) Billet Mesh showing two windows enlarging the mesh element count.

In Table 1, significant parameters utilized in the simulations are presented, which were set as constant to simplify handling. The simulations incorporated various geometry tools, including hole extrusion diameters of 4 mm and 8 mm, and a shoulder characterized by two different angles: 10° and 15°. Additionally, several variations in process parameters were examined, such as a constant axial feed rate of 0.5 and 1 mm/min, and a constant rotational speed of the die set at 100, 300, and 500 rpm. This resulted in a total of 24 parameter combinations that were simulated to investigate their impact on extrusion force, torque, and temperature. The outcomes of the simulations were subjected to analysis using Minitab software, with ANOVA analysis applied to evaluate the effect of each parameter. The Full Factorial Design Summary Table can be found in Table 2.

Table 1 – an overview of the parameters utilized in the simulations.

Parameters	Value
Friction coefficient Al-Die	0.4
Internal friction	0.01
Heat transfer coefficient Al-Al	11 N/s/mm/°C
Heat transfer coefficient Al-die	5 N/s/mm/°C

Table 2 – Full factorial Design summary table.

Factor Name	Units	Symbols	1	2	3
Rotational speed	[rpm]	n	100	300	500
Descent Feed	[mm/min]	Vf	0.5	1.0	-
Angle	[°]	α	10	15	-
Diameter	[mm]	d	4	8	-

3. Results and discussion

Table 3 presents the results obtained from the simulations, including the peak force, peak torque, and maximum temperature for each condition.

Figure 2 displays two examples depicting the torque and force required to be applied to the die throughout the process (Vf = 1 mm/min, d = 4 mm, α = 15°, varying n). A consistent pattern was observed across all analyzed conditions. The torque initially increases until it reaches a peak value, followed by a slight decrease. Similarly, the force exerted experiences a rise until it reaches a maximum, after which it remains relatively stable with minor oscillations. The peak values for both torque and force are observed when the displacement reaches approximately 1 mm, which corresponds to the initiation of filament extrusion.

Figure 3 illustrates a temperature color plot obtained from a simulation with α = 10°, Vf = 0.5 mm/min, and varying diameters of 4 mm and 8 mm, along with different rotational speeds: n = 100, 300 and 500 rpm. The plot clearly indicates that the temperature rises as the rotational speed increases. These findings align with similar results reported by other researchers [3].

Table 3 – Results of the simulations.

n [rpm]	Vf [mm/min]	α [°]	d [mm]	Peak force [N]	Peak Torque [Nm]	Max Temp. [°C]
100	0.5	10	4	164499	56038	83
100	0.5	10	8	105470	53938	86
100	0.5	15	4	157576	58072	82
100	0.5	15	8	99923	55408	87
100	1	10	4	173208	56627	84
100	1	10	8	102575	55256	85
100	1	15	4	167085	58939	81
100	1	15	8	98885	56620	85
300	0.5	10	4	138888	51968	164
300	0.5	10	8	88031	48925	174
300	0.5	15	4	140273	54520	161
300	0.5	15	8	87556	50170	177
300	1	10	4	157417	53968	143
300	1	10	8	96497	50393	168
300	1	15	4	151444	56094	137
300	1	15	8	92515	52612	170
500	0.5	10	4	122421	48413	220
500	0.5	10	8	74997	43727	228
500	0.5	15	4	121490	49676	217
500	0.5	15	8	71695	44809	231
500	1	10	4	141823	51836	197
500	1	10	8	84859	47492	222
500	1	15	4	133418	52689	192
500	1	15	8	79823	48422	225

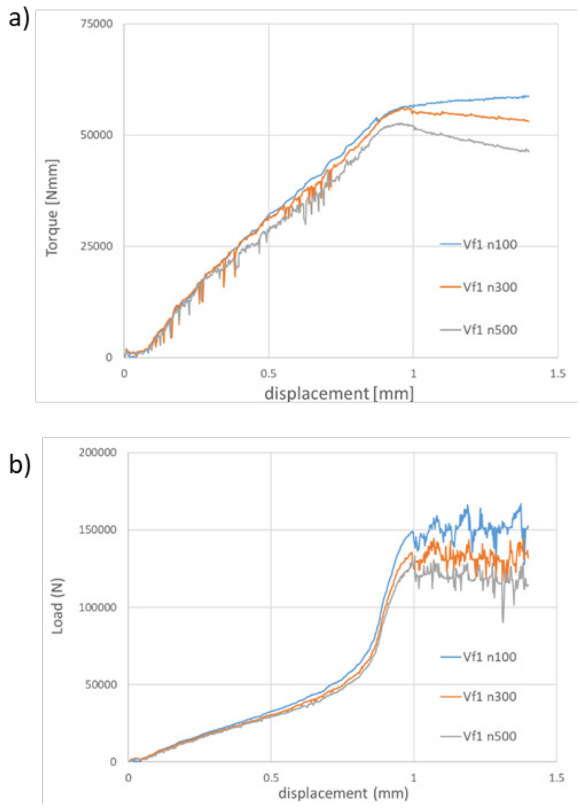

Figure 2 – (a) Torque vs displacement of the die; (b) Load vs displacement of the die.

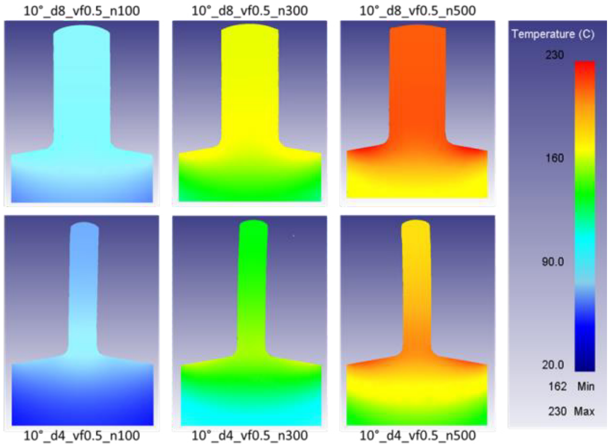

Figure 3 – It depicts the temperature trend observed in the simulation with α = 10°, Vf = 0.5 mm/min, considering different diameters of 4 mm and 8 mm, as well as varying rotational speeds: n = 100, 300 and 500 rpm.

Table 4 displays the p-values obtained from the ANOVA test. With a significance level set at 0.05, the results indicate that each factor exerts a statistically significant influence on the process. Combinations of factors are not included in the table to streamline the analysis. The main effect plot for each studied response is presented in Figure 4.

Table 4 – P-values for each factor.

	P-values		
Factors	Peak force	Peak torque	Max temperature
n	0,000	0,001	0,000
Vf	0,001	0,004	0,000
α	0,007	0,006	0,028
d	0,000	0,001	0,000

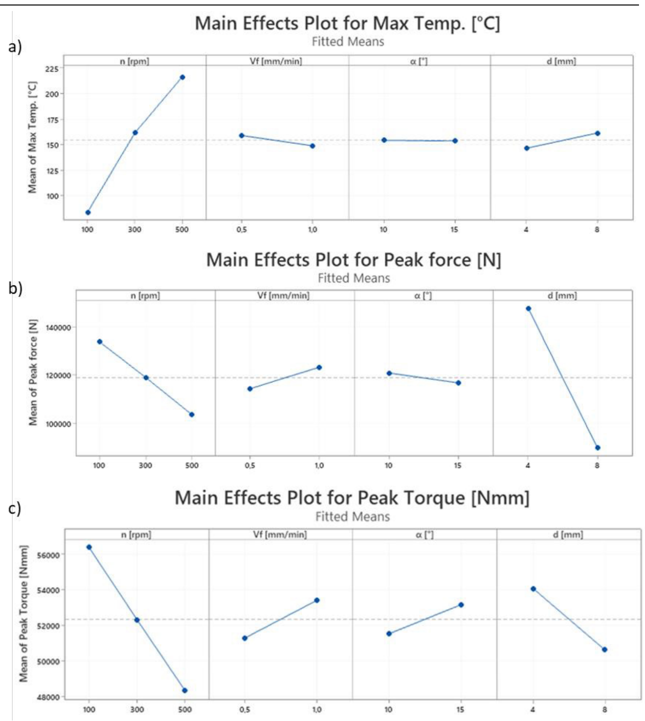

Figure 4 -Main effect plot for (a) maximum temperature, (b) peak force, and (c) peak torque.

The main effect plot offers valuable insights into the influence of each parameter on the selected response. In Figure 4a, the factorial plots for temperature are presented, revealing that an increase in rotational speed and diameter leads to higher temperatures in the extruded material. Conversely, a slight decrease in temperature is observed with increasing Vf (axial feed rate) and angle (α). This behavior is similar to the one found by other authors [3].

Figure 4b illustrates that an increase in rotational speed leads to a decrease in the force required for extrusion. This can be attributed to the reduced material strength at higher temperatures. Additionally, the peak force increases with Vf (axial feed rate) but decreases with an increase in angle and diameter. This promotes material flow during the extrusion process. Moving on to Figure 4c, the factorial plots for peak torque exhibit a similar behavior to that of peak force. As the rotational speed increases, the torque required for extrusion decreases due to the softening of the material at higher temperatures. The peak torque increases with an increase in axial feed rate (Vf) and the angle of the shoulder but decreases with a larger extrusion diameter.

4. Conclusions

Friction Stir Back Extrusion (FSBE) is a process that reverses the extrusion method capable to recycle aluminum chips and is employed to obtain various products such as wires and tubes. To simulate this process, DEFORM™ was utilized, allowing for the manipulation of both geometrical parameters (invitation angle, extrusion diameter) and process parameters (punch rotational speed and feed rate). A total of 24 trials were conducted as part of a campaign aimed at identifying the optimal combination of process and geometric parameters necessary to produce 4 mm and 8 mm wire samples through the extrusion of aluminum chips.

The reduction of peak force and torque has the potential to yield cost-effectiveness by preventing machine over-dimensioning. The FE analysis reveals that to achieve a decrease in peak force and torque, a higher rotational speed and a lower descent speed should be employed. This, however, results in an increase in the process temperature, potentially facilitating the bonding between the chips and ensuring the integrity of the wires. Conversely, higher extrusion diameters can reduce peak force and torque, but there is a risk that the increased extrusion hole may not induce sufficient strain and temperature to effectively bond the chips, leading to the formation of voids and non-consolidated wires.

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1.5, "Creation and strengthening of Ecosystems of innovation" and construction of "Territorial R&D Leaders".

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