

A Simulative Method for Studying the Bonding Condition of Friction Stir Extrusion

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Abstract. In the manufacturing industry, the problem related to the management of metal waste is of considerable importance, since it is produced in large quantities during mechanical processing.

However, its recovery is not always a simple task, especially with regard to the metal cutting processes. In fact, due to the presence of surface oxide and contaminating oily residues, the recovery process of these components is often very expensive and polluting. This problem can be solved with the FSE process, patented in 1993 by The Welding Institute. The FSE can be counted among the main innovative processing techniques developed in Industry 4.0, as it involves only metal scraps coming from the machining processes as starting material, without providing for their preliminary re-melting in a billet form, and it uses only the heat generated by the friction between the tool and the metal. Since FSE is a quite recent process, the development of simulative models is useful for understanding its basic mechanisms. The objective of this research is to analyze if and how the bonding phenomena occur considering both the thermal and the stress conditions involved and generated by the process parameters.

As a result, FEM analysis proved to be a valid tool to correctly forecast if bonding phenomena really take place and how process parameters affect the bonding quality. Moreover, it was possible to confirm that the Piwnik and Plata bonding model is a good criterion for predicting the effects of this technology.

Introduction

Since 2010, the European Commission has tried to develop a plan for sustainable growth, promoting competitive energy resources considering both the environmental impact and the economic point of view. In addition, the focus was mainly on the efficiency of resources and their use, in order to address environmental problems and make Europe competitive with the rest of the world. From then to today, the main objectives are the reduction of the exploitation of coal, better resource efficiency, greater investments in the green sector and technological development that aims at the recycling of resources [1].

In fact, mechanical processes, such as milling and turning, generate a large amount of metal waste which must be remelted to create a new raw starting products (e.g. ingots or billets), but these reworks involve additional energy consumption.

However, the recovery of the metal scraps through traditional techniques is not always simple due to their high surface/volume ratio, the covering oxide layers (as far the aluminum, the Al₂O₃ oxide film) and the contaminating oil residues [2,3]. All impurities must be eliminated before reworking; but in general, it is difficult to completely eliminate these substances: the result is a different composition of the alloy from the starting one. Consequently, aluminum waste has a lower quality and a difficult-to control composition.

Furthermore, from the energy point of view, conventional recycling technologies lead to several problems [2]. In fact, to recover a material, it must be brought to high temperatures and this takes place often through a combustion process.

To date, therefore, conventional technologies are proved to be inadequate for the needs of modern industry. For this reason, in 1993 the Welding Institute devised a new metal scraps recycling process, called Friction Stir Extrusion (FSE). In this process, a rotating tool compresses the chips and, deforming them plastically, extrudes them through a hole: what is obtained is a cylindrical bar, which dimensions depend on the diameter of the hole and the quantity of chips used. A roto-translatory movement must be imparted to the tool: the rotation generates heat; the translation is directed vertically downwards to exert pressure on the material.

FSE is a solid state recycling material technology with a very high energy efficiency [4]: the novelty consists in the exploiting of the heat generated only through the friction between the metallic scraps and the tool [5]. Thus, it leads to an unnecessary external heat source, resulting in significant energy savings, as less of 15% of the energy of a conventional aluminum alloy melting process is needed [6]. The reached temperatures, around 400 °C, generate a high plastic deformation that allows to bind the scraps and obtain extruded products with good mechanical properties, without the need of further processing [5].

In addition to aluminum, this technology is easily adapted to the processing of magnesium of its various alloys, of Mg-RE alloys [7] and biodegradable magnesium alloys [8]. Furthermore, the FSE has also been applied in the joining of dissimilar materials [9].

The characteristics of the products obtained through Friction Stir Extrusion are strongly influenced by the parameters used, in particular, the rotational speed of the tool and the descent speed of the crossbar. For example, a high descent speed could cause the formation of cavities in the products, while a low tool rotational speed could cause cold cracks on the surface of the friction stir extruded pieces, due to an insufficient quantity of heat generated by friction [10].

Since the Friction Stir Extrusion is a quite recent technology, in order to forecast the relation between the process parameters and the physics of the process, the development of simulative models is very useful. For this reason, especially in the last years, some FEA models were implemented for the simulation of the FSE process.

Zhang et al. developed a 2D and axisymmetric heat exchange model for predicting the temperature trend during the process, considering only a linear distribution of the heat flux in radial direction [11].

Baffari et al. focused on magnesium scraps, implementing a model in the DEFORM software to predict the quality of the products obtained by FSE. As regards the effect of the process parameters, it was noticed that a positive influence was determined by the tool rotational speed: with 500 rpm a temperature of about 250 °C is reached, while with 900 rpm it reaches almost 500 °C [12].

Behnagh et al., using the ABAQUS software, implemented a model for studying the thermal, mechanical and microstructural behavior of magnesium products during the FSE process. By carrying out the tests at different rotational tool speed, it was observed by the authors that this parameter greatly influences the heat exchange, much more than the descent speed [13].

In the present paper, a simulative model was developed in order to understand how the process parameters, namely the tool rotational speed and the descent speed, influence the process conditions, i.e. the reached temperatures and the final volume of the workpiece.

Moreover, the stress conditions resulting from the simulations were used to study if and how the bonding phenomenon occurred. For this purpose, the Piwnik and Plata criterion was chosen [14].

The final aim of this research was to analyze the bonding conditions considering both the thermal and the stress conditions generated by the process parameters.

Procedure

A 3D FEM Lagrangian model was set up using the commercial software DEFORM™. The tool and the container were modelled as rigid objects using AISI-1043 steel as reference material. The metal scraps to be extruded, placed inside the container, were considered as a single porous workpiece of Aluminum-6061. During the simulation, the initial compacting phase of the chips was eliminated to reduce the time required for the computation and the initial density for the simulation was set equal to 78% of the base aluminum. This value derives from experimental chip pre-compaction tests executed by the authors, where a maximum density of 2.11 g/cm³ was obtained.

Both aluminum and steel material flow stress data were chosen among the DEFORM library database.

In conclusion, the porous workpiece was meshed using 50000 tetrahedral elements, as shown in Figure 1.

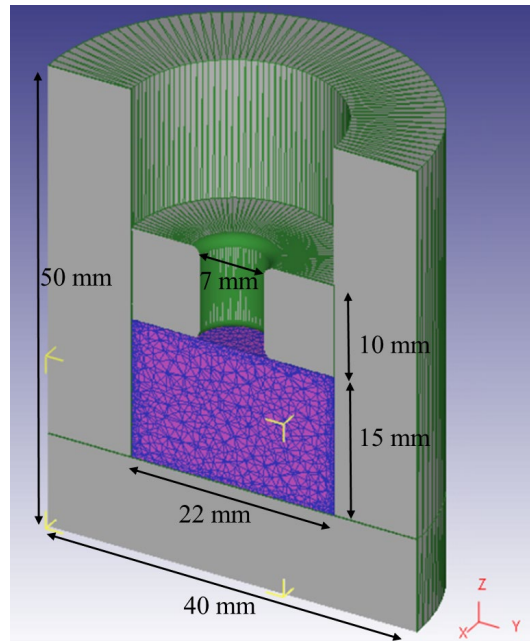


Figure 1: Mesh of the workpiece and geometry of the all simulated structure.

The thermal parameters were kept constant and the values reported in Table 1 were used.

Table 1: Thermal parameters used in the simulations.

Parameters	Value
Friction coefficient aluminum-tool	0.60
Thermal conductivity [N/(s·°C)]	450.00
Aluminum emissivity	0.25
Heat transfer coefficient aluminum-tool [N/s/mm/°C]	11.00
Heat exchange with the environment [N/s/mm/°C]	0.02
Mechanical conversion to heat	0.80

The simulations were conducted varying the main process parameters, i.e. the tool rotational speed and the descent speed. The combinations between the rotational speed (S) and the descent speed (F) taken into account are reported in Table 2.

Table 2: Combinations between the S and F considered for the simulations.

Combination	S [rpm]	F [mm/s]	Combination	S [rpm]	F [mm/s]
#1	400	0.1	#7	800	0.1
#2	400	0.5	#8	800	0.5
#3	400	1	#9	800	1
#4	600	0.1	#10	1200	0.1
#5	600	0.5	#11	1200	0.5
#6	600	1	#12	1200	1

The stop criterion was chosen to be the tool (primary die) displacement equal to 3 mm in $-Z$ direction.

At the end of the simulations, the maximum reached temperature, the final workpiece volume and the stress conditions of the workpiece were extracted from the FEM model.

Therefore, ANOVA technique was applied in order to define which parameters influence the temperatures and the volume. For this purpose, two factors were considered: the rotational speed, defined on four levels, and the descent speed, varying on three levels.

The last step of this analysis involved the implementation of the Piwnik and Plata criterion. This criterion states that the material bonding occurs when the parameter w , defined as the ratio integrated along the time between the pressure and the effective stress acting on the material, reaches a limit value, called w_{lim} , identified as a function of the temperature.

In particular, w is defined as:

$$w = \int_0^t \frac{p}{\sigma_{eff}} \cdot dt \quad (1)$$

where: p is the local contact pressure, σ_{eff} is the local effective stress of the material and t is the time for which the contact takes place.

In this paper, the integral expression reported in the Equation (1) was transformed in a sum extended to the number of simulation steps:

$$w_{i,n} = \sum_{j=1}^n \left(\frac{p}{\sigma_{eff}} \right)_{i,j} \cdot \Delta t_j \quad (2)$$

where:

n is the total number of steps until the stop criterion is reached,

j is the generic j -th simulation step,

i is the generic i -th profile node,

Δt_j is the time per step of the j -th simulation step (until the stop criterion was reached).

The analysis was focused on a grid of 9x5 nodes, located in the area supposed to be the most affected by the FSE effects (Figure 2).

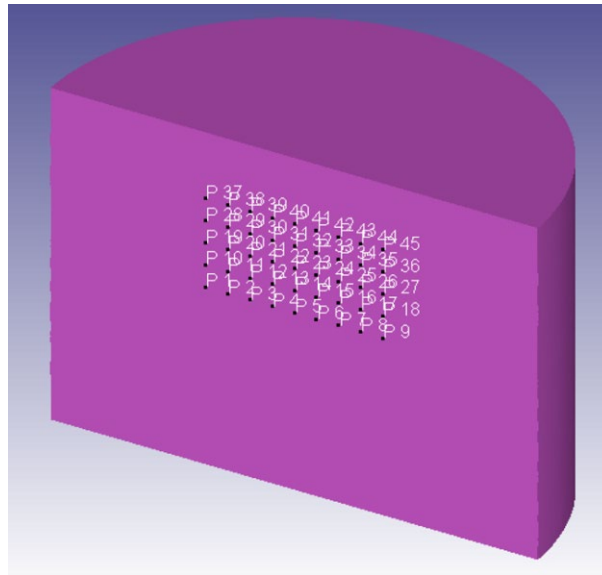


Figure 2: Grid of 9x5 considered nodes lying on the Z-Y plane of the workpiece.

In literature, a procedure for the w_{lim} identification as a function of the temperature, based on a coupled experimental-simulative strategy, was already proposed in [15,16].

In this case, w_{lim} is identified as a function of the steady-state temperature (T). E. Ceretti et al. proposed an experimentally found interpolation curve to define the limit parameter w_{lim} [15]. In particular, they defined w_{lim} as:

$$w_{lim} = 4.9063e^{-0.0017T} \quad (3)$$

This equation was verified by E. Ceretti et al. only for $T > 320^\circ\text{C}$, but this totally agree with the entire temperature window of a typical FSE process, which takes place at about 400°C .

Results and Discussion

The maximum temperature and the volumes achieved by workpieces were taken into account as a function of the ratio S/F (Table 3). Indeed, it is well known that within the family of Friction Stir Processing, where the FSE process stands, a good indication about the amount of the heat generated during the processing is given by the ratio between the rotational speed of the tool and its advancing feed (in this case called descent speed).

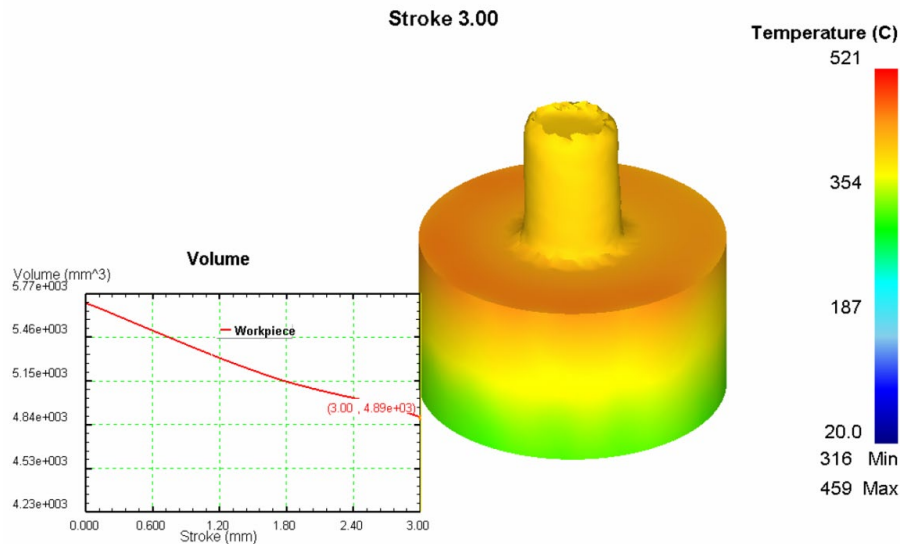


Figure 3: Graphical results of a FEM model simulation ($S=1200$ rpm and $F=1$ mm/s, $S/F=1200$): Temperature and Volume.

Table 3: Data recorded from the FEM simulations.

S	F	S/F	Stroke 3 mm	
			T max [°C]	Final Volume [mm ³]
400	0.1	4000	480	4986
400	0.5	800	395	4816
400	1	400	394	4743
600	0.1	6000	604	4681
600	0.5	1200	407	4881
600	1	600	402	4801
800	0.1	8000	638	4671
800	0.5	1600	422	4862
800	1	800	411	4850
1200	0.1	12000	650	4672
1200	0.5	2400	576	4860
1200	1	1200	459	4895

In order to define which parameters mostly influence the process, the ANOVA technique was applied.

Table 4 reports the P-values about the effects of rotational speed (S) and descent speed (F) on the maximum temperature reached during the process and on the final volume of the initially porous workpieces.

Since the cut-off limit was set equal to 0.05, a factor was considered to have a relevant influence if its P-value is lower than this value. For this reason, in Table 4, a clear dependence of the temperature from both the rotational and descent speeds can be observed, whilst the final volume of the workpiece is not directly correlated to a change in either of the two considered factors.

Figure 4 shows the main effects plot for the maximum reached temperature: the relation between the factors and the response is clearly expressed from the graphic point of view.

Table 4: ANOVA Results.

Factor Information			
Factor	Type	Levels	Values
S	Fixed	4	400; 600; 800; 1200
F	Fixed	3	0,1; 0,5; 1,0

Response	Factor	P-Value
Temperature	S	0.049
	F	0.003
Final Volume	S	0.917
	F	0.489

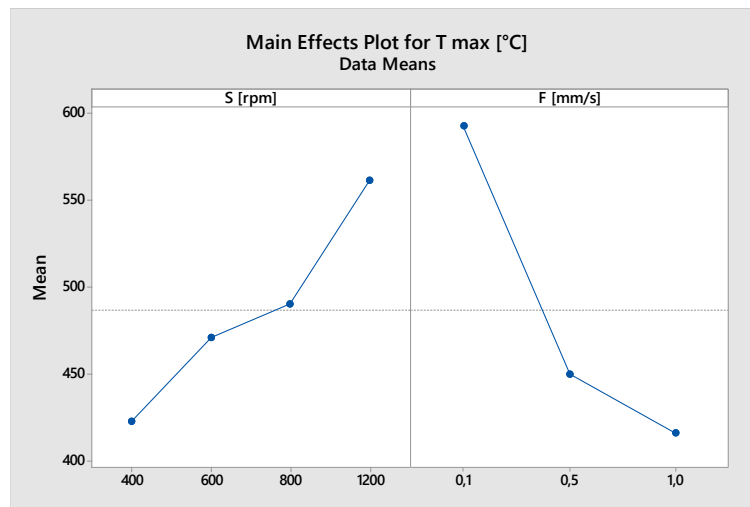


Figure 4: Main effects plot for T_{max} .

The relationships between the combination of parameters (declared in Table 2) and the maximum reached temperatures during the Friction Stir Extrusion process are reported in Figure 5.

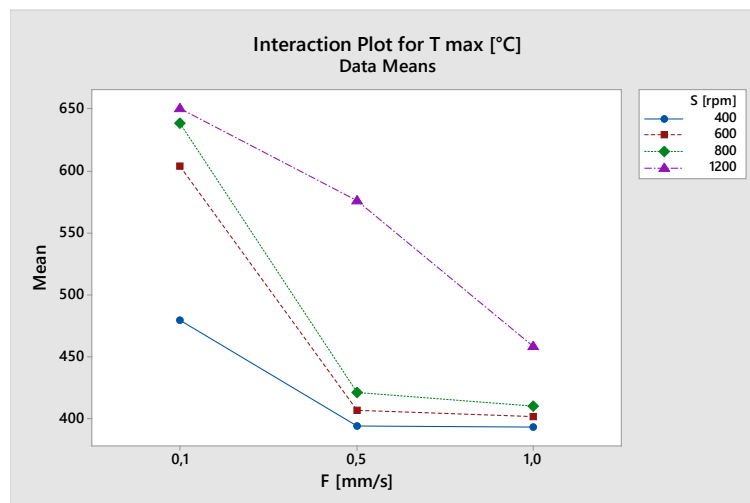


Figure 5: Interaction plot for T_{max} as a function of the rotational and descent speeds.

Once the relationship between temperatures and process parameters was demonstrated, the regression line of the studied conditions was built starting from the peak temperatures reported in Table 3 (Figure 6).

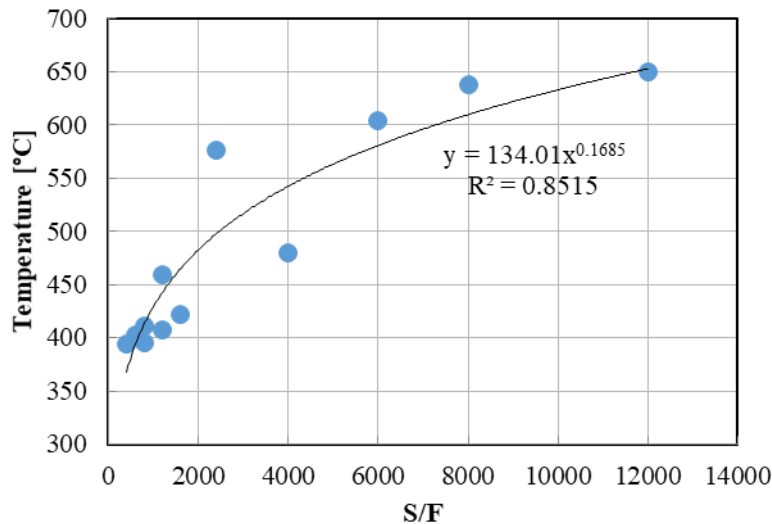


Figure 6: Exponential regression line.

The regression line well approximate the actual trend of the measured temperatures (R^2 equal to 0.8515).

This regression line also allows to correlate three different parameters with each other: temperature, tool rotational speed and crosshead descent speed. In this way, knowing that the bonding starting temperature is about 400 °C, it is possible to identify the optimal S/F ratio and from here, for example, once the rotation speed has been set, it is possible to obtain the speed of descent optimized in order to guarantee the required temperature.

As regards the Piwnik and Plata criterion, the w_{lim} was calculated considering the Equation (3), where the parameter T was assumed as the average value reached by the 45 nodes at their steady state condition (Figure 7).

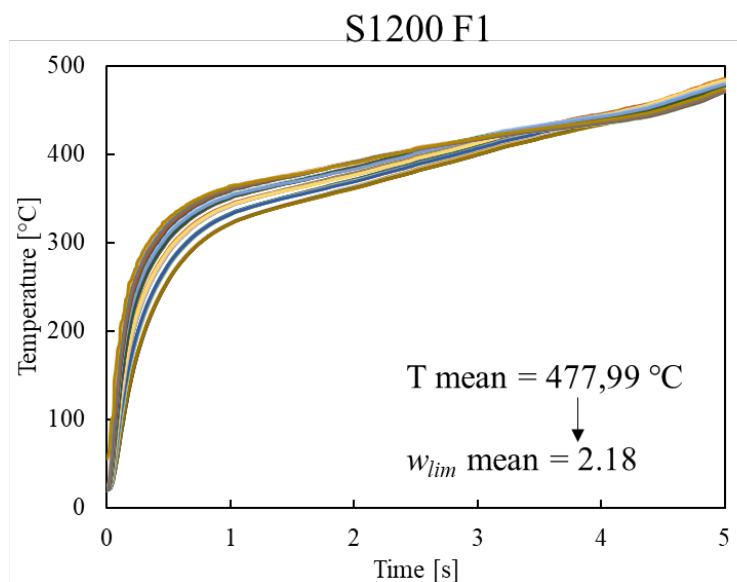


Figure 7: Temperature trends and w_{lim} calculation for the combination: $S=1200$ rpm, $F=1$ mm/s, $S/F=1200$.

Conversely, the calculation of w involved in considering each node separately, as indicated in Equation (2).

The results obtained from the calculation of w of each considered node, once the steady state condition is reached, are reported in Figure 8. This figure shows the contourplot of the w values, as well as the final position of the nodes initially considered in Figure 2.

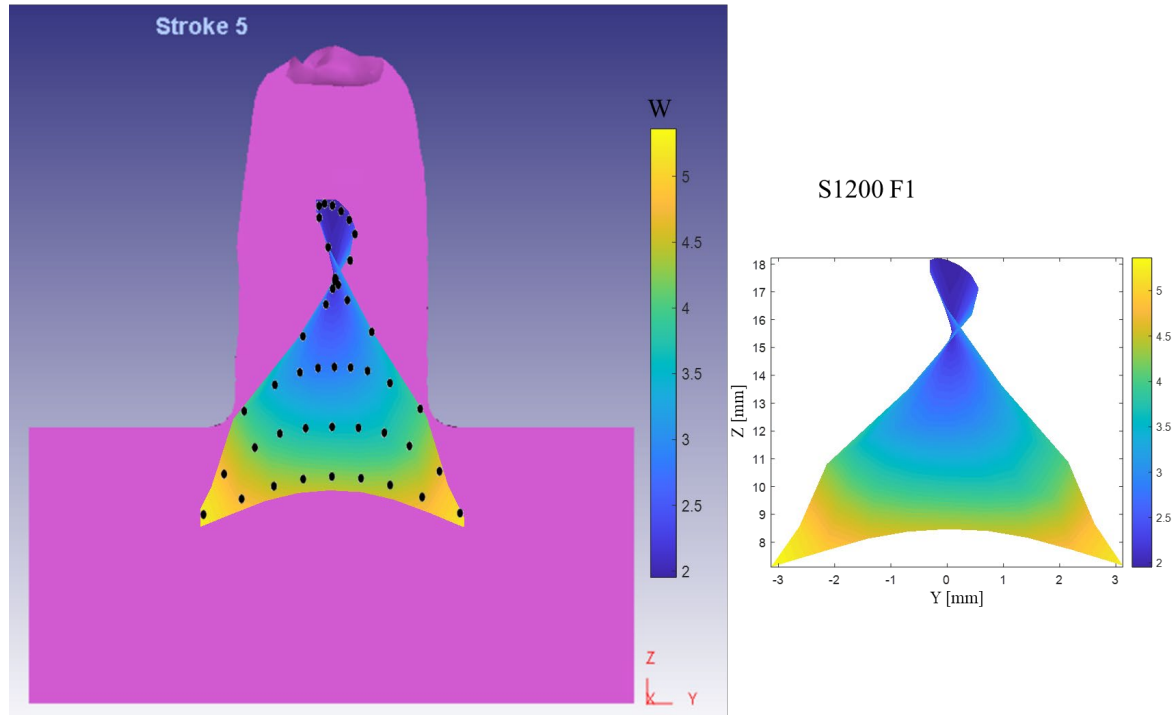


Figure 8: Contourplot of w values and final position of the 45 considered nodes (black points in the graph on the left).

From a comparison between the calculated values of w and w_{lim} , it is evident that in the area of variation of the section, i.e. at the interface between the tool and the chip still to be extruded, the stresses generated by the process are sufficient to ensure complete bonding of the material. In fact, the value of w is always greater than the value of w_{lim} , with the exception of the zone corresponding to $Z > 17$ mm.

Conclusions

The objective of this study was to predict the bonding conditions in Friction Stir Extrusion. For this purpose, a robust FEM model was developed considering the tool rotational and the descent speeds and the Piwnik and Plata bonding criterion was applied.

It was found that both the speed parameters strictly influence the temperature but they do not affect the final volume of the workpiece.

With the FEM data, a good regression function was found between the temperature and the process parameters, thus allowing the definition of the technological window for a reliable FSE process.

With the application of Piwnik and Plata criterion, the bonding conditions were deeperly analyzed as a function of the stress state, resulting in the workpiece at the steady-state condition.

In conclusion, in this paper it has been proved that:

- The Finite Element model set-up for the FSE process can provide a good prediction of the temperature distribution which the scraps are subjected to during the entire process.
- FEM analysis can be a valid tool to correctly forecast if the bonding phenomenon really takes place and how process parameters affect the bonding quality.
- Piwnik and Plata has proved to be a good criterion for this technology.

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