Friction stir consolidation of aluminium chips: A new approach to overcome the inhomogeneous properties of the consolidated billet

Riccardo Puleo[1,a*], Giuseppe Ingarao[1,b], and Livan Fratini[1,c]
[1]Department of Engineering, University of Palermo, Viale delle Scienze, Palermo, 90128, Italy
[a]riccardo.puleo01@unipa.it, [b]giuseppe.ingarao@unipa.it, [c]livan.fratini@unipa.it
web page: https://www.unipa.it/

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Abstract. The need to improve the recycling process of metals to achieve sustainability goals is reflected in the growing interest in solid-state recycling approaches. One of these is the Friction Stir Consolidation (FSC), able to directly transform chips into consolidated billets. The main features of this process are the pressure and the rotational speed of the tool which compresses and heats up the chips collected inside a designed die. During the consolidation process, the friction between the tool and chips surfaces plays an important role because it is the main source of heat, therefore the heat transfer starts near the tool to the bottom of the billet resulting in an inhomogeneous material property. This aspect leads to both inhomogeneous microstructure and hardness characterization of the consolidated billet. To improve the effectiveness of the friction stir consolidation recycling process, this study focused on a numerical approach by proposing a new setup in which the structure where the die and the chips are placed on, namely backing plate, was heated up aiming to activate a heat flow also from the bottom.

Introduction

Nowadays lots of circular economy strategies have been proposed, however recycling is still the most common recycling method. This process is commonly used for recycling metals, and it is mainly based on the remelting of metal scraps. Despite this strategy helps to recycle metal scrap, it brings within an important drawback mainly related to permanent losses occurring during the melting phase, caused by the oxidation. The metal particles floating on the melting bath react with the oxygen causing the oxidation of the surface, such oxidation leads to permanent material losses.

In order to overcome these issues, the researchers shifted their focus on the Solid-State Recycling (SSR) methods where the scraps are directly turned into semi-finished products, skipping the melting phase and reducing all the oxidation-related issues. In the SSR processes, the main factors of influence are time, temperature, and pressure. Within the SSR category, the most common recycling processes are the Equal Channel Angular Pressing (ECAP) [1], [2], Spark Plasma Sintering (SPS) [3], [4], and the friction stir based processes such as Friction Stir Extrusion (FSE) [5], [6], and Friction Stir Consolidation (FSC) [7].

For most of these solid-state recycling processes, the bonding phenomenon between metal chips was investigated, and two models were developed: energy barrier theory and film theory. The first model is based on the assumption that the bonding between metal surfaces occurs when a certain energy level is reached [8], [9]. On the other hand, the film theory assumes that the bonding between metal surfaces occurs when the oxide layer between them is broken, so the metal is able to flow through and bond with other metal layers [10], [11].

In this paper the FSC process was investigated, and a new strategy was proposed as a solution to solve the friction stir consolidation's main issues: inhomogeneous heat transfer and strain distribution [12], [13]. For this reason, the authors proposed a new FSC setup where the backing plate component is heated up to 300 °C during the process, to provide a second heat transfer direction. The approach used in this paper is based on numerical simulations and solid bonding analysis; the data obtained from this new setup were compared to the ones obtained in the previous research.

Methodology

In this work the heated backing plate configuration was investigated by means of a numerical approach. The data used for the bonding evaluation between the new configuration here proposed and the previous one, were based on previous research [7], [14]. Specifically, in previous work a friction stir welding dedicated machine (ESAB LEGIO) was used for applying the FSC process to three different chips aluminium alloys: AA2024, AA6082 and AA7075. During the experimental campaign, a 25 mm diameter H-13 steel tool was used for processing 15g of recycling chips into a 25 mm inner diameter H-13 cylinder die (Fig. 1a). Before being processed, the chips were cleaned in acetone for 30 minutes and then dried. The experimental test was divided into three steps: the compacting phase performed at 5 kN, a transition phase where the tool has a rotational speed of 1500 RPM, and an initial vertical load equal to 5 kN which was constantly increased to 20 kN (0.5 kN/s) in the first 30, and a steady state phase where the vertical load was kept at 20 kN for other 10,20 and 30s. The result of this campaign was multiple consolidated billets characterized by a total process time of 30, 40, 50 and 60 seconds (Table 1). Moreover, this campaign resulted in an experimental bonding criterion developed to give a quantitative evaluation of the bonding occurrence, in terms of grain size and hardness value.

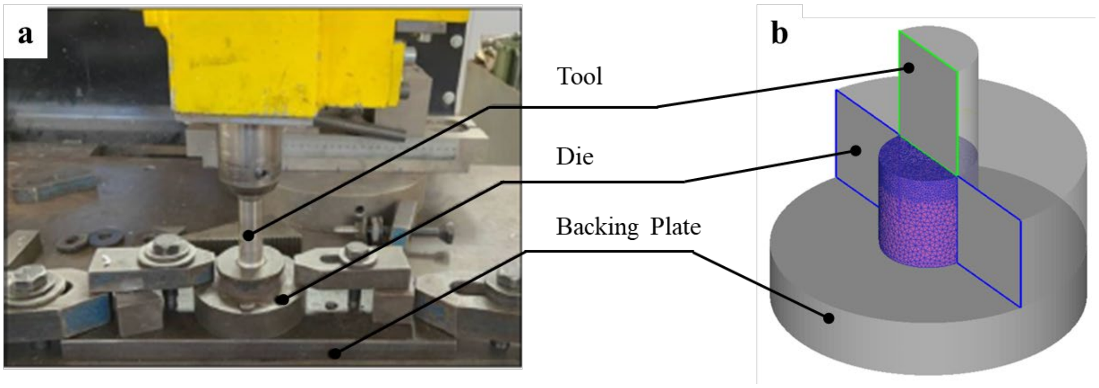


Figure 1 – a) Experimental [7] and b) numerical setup

Table 1 – Process parameters and time process of each FSC test [7]

Exp ID	Rotational speed [RPM]	Mass [g]	Transition period [s]	Consolidation time [s]
Exp 1	1500	15	30	0
Exp 2	1500	15	30	10
Exp 3	1500	15	30	20
Exp 4	1500	15	30	30

The numerical model has as base a previous campaign [15], developed using SFTC DEFORM 3D^{TM}. In this paper the numerical model involves a tool, a die, and a backing plate modelled as rigid bodies, whilst the chips were modelled as a compressible rigid - viscoplastic porous billet characterized by an initial relative density equal to 0.44. For the aluminium material characterization were used the material data already considered in the previous research [15]. The rigid bodies were defined by a mesh size of 30000 elements, H-13 material, a shear factor equal to 0.3, and a heat transfer coefficient equal to 11 W/mm^2/K. On the other hand, the porous billet was defined by a mesh size of 20000 elements, with a refining mesh window close to the tool-billet contact (Fig. 1b). To simulate the heating from the bottom, two different initial temperatures of the backing plate were selected: 300 °C and 400 °C. In Fig. 2 the effect of the different backing plate temperature is reported for the case study of AA7075. This figure proves that the configuration at 400 °C does not bring any appreciable improvement in terms of strain and density, compared to the configuration at 300 °C. For this reason, and for the sake of the reduction of energy consumption, the analysis was performed considering an initial temperature equal to 300 °C.

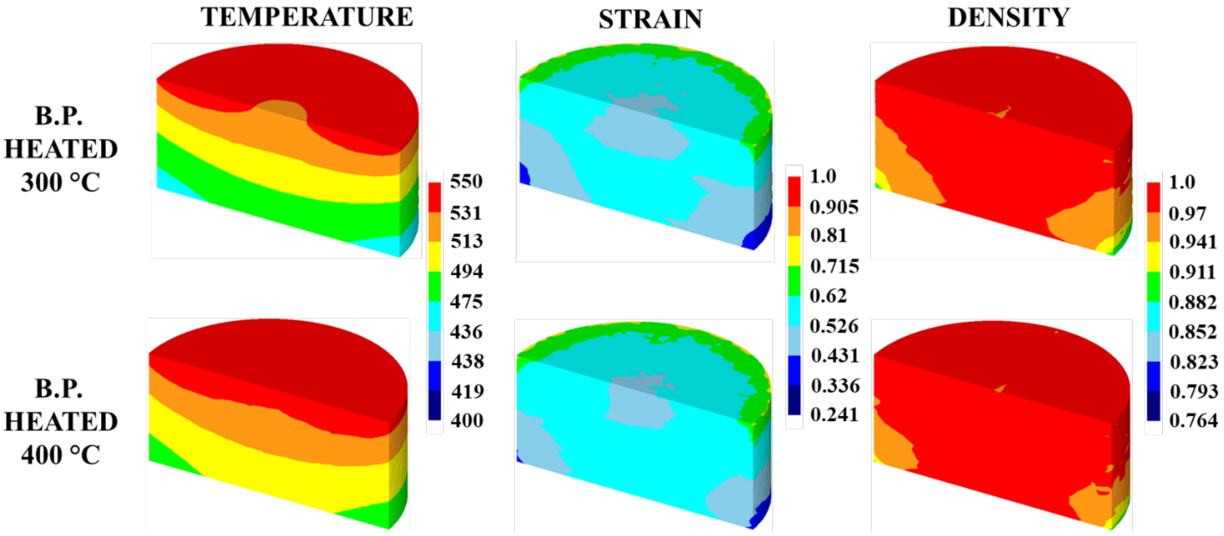


Figure 2 – Temperature, strain and density comparison for the case of backing plate heated at 300 and 400 °C, at 30 seconds process time

For both the campaigns, the middle cross section of the consolidated billet was analyzed using a matrix of 17x7 loci. In these 119 loci the bonding occurrence was evaluated by two different methods: from the numerical side, the temperature and stress values were acquired, and the solid bonding value (W) was calculated (Eq. 1) as well as the solid bonding limit value for the three material AA2024 (Eq. 2), AA6082 (Eq. 3) and AA7075 (Eq. 4) [15]. In the experimental campaign, from the same matrix of points, the hardness and the grain size were obtained in order to identify the consolidation occurrence according to the following experimental criterion [7]. This resulted into a theoretical approach which only considers as consolidated the zone characterized by a specific hardness and grain size limit values:

"The bonding occurs when grain size and hardness value exceed simultaneously the threshold of 2 μm and 60% of base material hardness, respectively. This means that when the grain size and hardness value of an observed locus are greater than 2 μm and 60% of base material hardness respectively, it can be considered as consolidated".

For each point of the 119 matrix the W^{Lim} value was compared to the W value, when the bonding value calculated using the Eq. 1 was higher than the W^{Lim} calculated using the Eq. 3-5, the point was considered consolidated. This approach was used to define a bonding map of the cross section of the billet divided in two zones namely "consolidated zone" and "not consolidated zone".

$$W = w_t \cdot w_s \cdot \int \frac{|\sigma_{mean}|}{\sigma_f} dt \tag{1}$$

where w_T and w_s are two "weights" related to the temperature and strain. These weights have the effect of reducing the count of the integer on time where the temperature and strain impact is lower [15], and they are calculated considering the i-th time step and the i-1 th time step; the equations of w_T and w_s are shown in Eq. 2.

$$w_T = \frac{T_i - T_{i-1}}{T_i} = \frac{\Delta T}{T_i} \qquad w_S = \frac{\varepsilon_i - \varepsilon_{i-1}}{\varepsilon_i} = \frac{\Delta \varepsilon}{\varepsilon_i}, \tag{2}$$

$$W^{Lim} = -7.35 \cdot 10^{-6}\, T + 0.0042, \tag{3}$$

$$W^{Lim} = -1.62 \cdot 10^{-6}\, T + 0.0015, \tag{4}$$

$$W^{Lim} = -1.3 \cdot 10^{-6}\, T + 0.0013, \tag{5}$$

Discussion of the results

For each material a numerical simulation was performed, and the cross section was studied. It can be assumed that the bonding quality is related to the oxide breakage during the consolidation process, and the main factors which help this phenomenon are the temperature and strain condition [16]. To clearly show the effect of the heated backing plate the data related to 60 seconds of FSC process, for both heated and cold baking plate, have been plotted in Fig.s 3-5. The comparison between the cold backing plate and the new strategy of the heated backing plate shows that the temperature has obviously increased, slightly affecting the strain for the cases AA7075 and AA6082. On the other hand, AA2024 showed the biggest strain improvement, as well as for the temperature and density; this could be related to the higher ductility of this aluminium alloy. This combined effect led to a better consolidation (in terms of material density) along the cross section. The bottom edge of the billet is still the coldest point of the material since this zone has the highest thermal exchange surface with the rigid bodies.

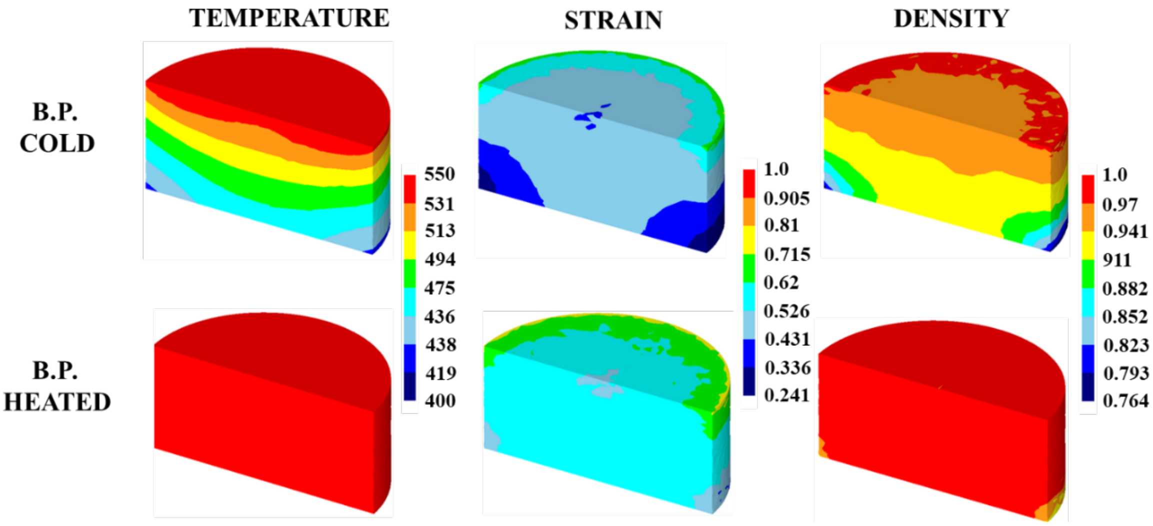


Figure 3 – AA2024 numerical results at 60s time process

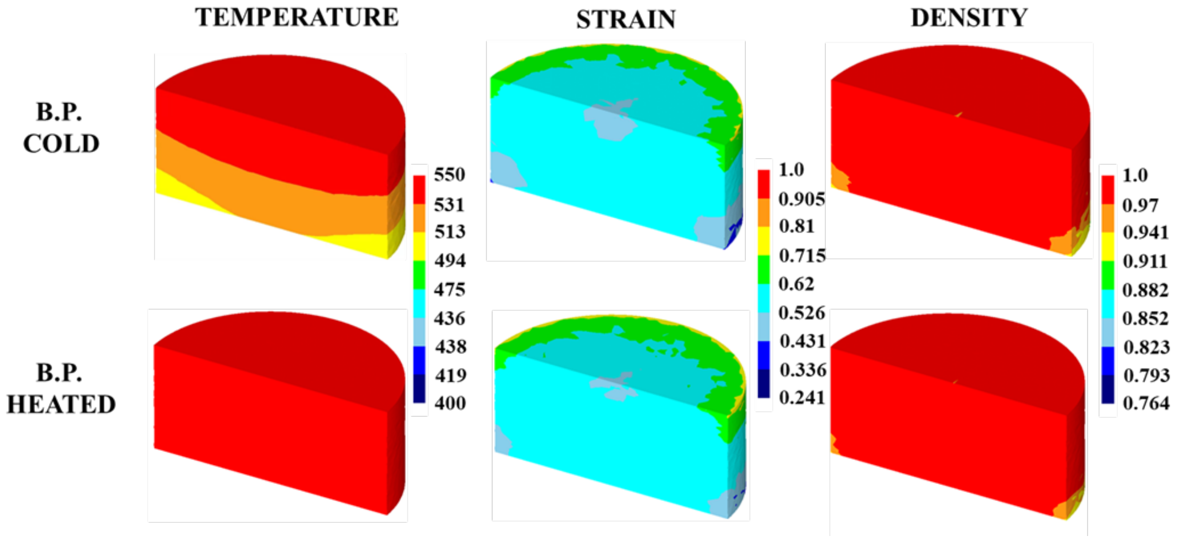


Figure 4 – AA6082 numerical results at 60s time process

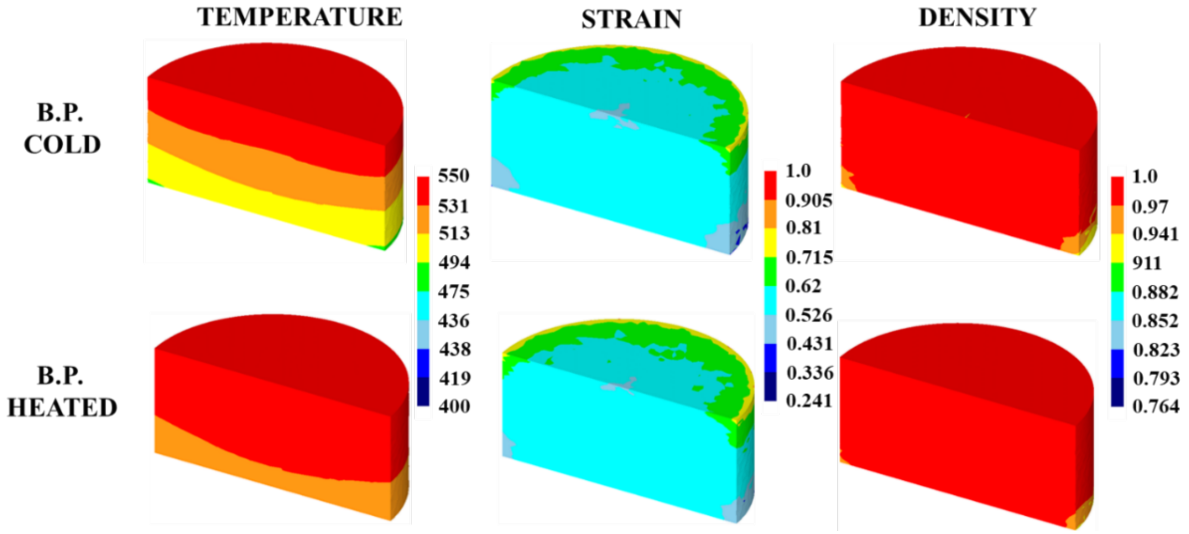
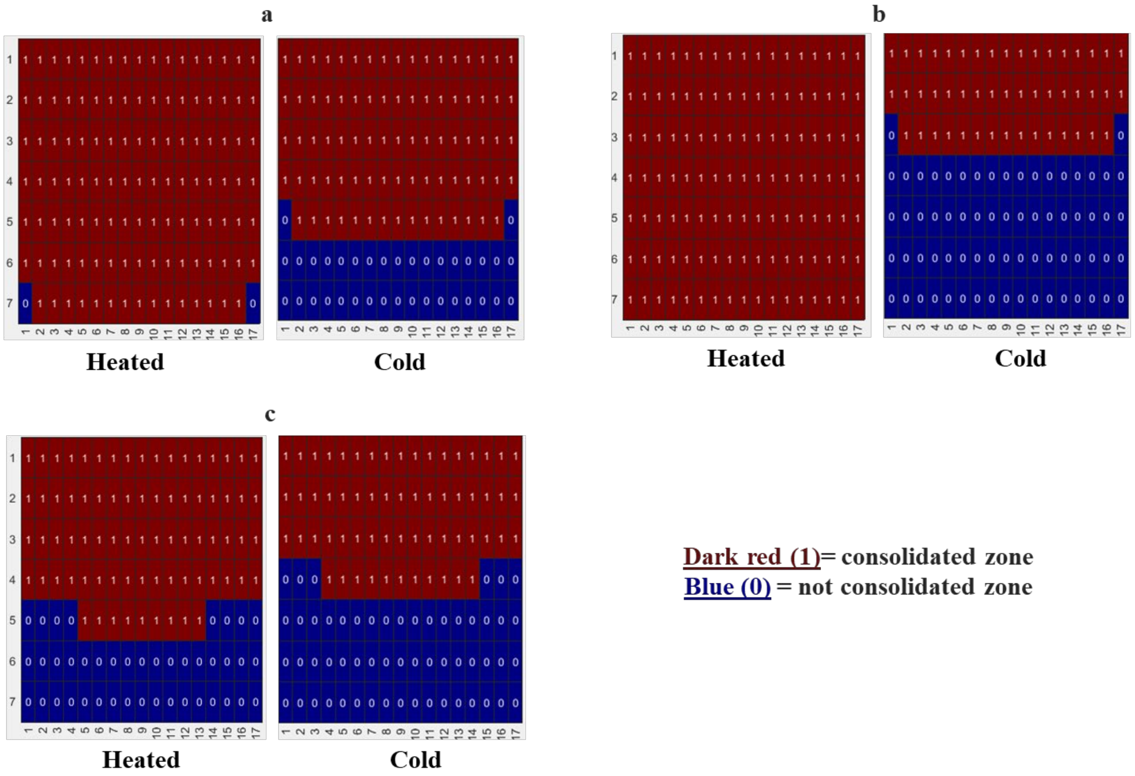


Figure 5 – AA7075 numerical results at 60s time process

Concerning the solid bonding phenomenon, it is worth mentioning that the bonding was also investigated using the criterion developed by authors as it was clearly demonstrated that this criterion has the best prediction performances, specifically for the FSC process, compared to the already existing in literature. The study of the solid bonding is shown in Fig.s 6a, 6b, and 6c, and was performed for the case 30 seconds, to guarantee a better visualization of the difference in terms of consolidation. In these images the previous predicted bonding maps and the new ones were compared. As is possible to notice, for all the materials investigated the effect of the new setup is reflected in a larger consolidated area. This difference is more visible looking at case AA6082 (Fig. 6b) than the other case study, because the bonding condition of all loci for this material were close to the consolidation threshold value [15]. Therefore, a slight increase in temperature resulted in bonding values over the limit. The results in Fig. 8 were summarized in Table 2.



Dark red (1)= consolidated zone
Blue (0) = not consolidated zone

Figure 6 – Bonding occurrence maps of the 30s cross section of the billet. Cold-Heated comparison for a) AA2024, b) AAA6082 and c) AA7075

Table 2 – Comparison of the consolidated number of loci for the three materials, at 30 seconds time process.

	N° CONSOLIDATED LOCI		**PERCENTAGE OF CONSOLIDATED LOCI**	
	Heated	*Cold*	*Heated*	*Cold*
AA2024	117	83	98%	70%
AA6082	119	49	100%	41%
AA7075	77	62	65%	52%

Conclusion

A numerical approach for improving the friction stir consolidation process was performed by means of backing plate heating. Three materials were tested, and the following conclusions were drawn:

- The heated backing plate has increased the average temperature of the porous billet during the process, although strain has been slightly increased
- The combined effect of the new level of temperature and strain has increased the relative density of the porous billet in the first 30 seconds
- The W^{Lim} curve prediction previously developed by the authors is consistent and allowed to evaluate the bonding occurrence with the new setup here proposed
- Looking at the prediction of the bonding occurrence, the heated backing plate is a solution for increasing the consolidated zone/surface, especially for the AA6082

As future work, an experimental campaign to validate this numerical approach will be conducted. Moreover, an energy consumption analysis must be performed aiming to ensure that the heating of the backing plate does not represent a loss in terms of sustainability.

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