An insight into friction stir consolidation process mechanics through advanced numerical model development

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Abstract. Friction stir consolidation (FSC) is a solid-state process adopted to recycle machining scraps with aim to reduce the adverse impact of obtaining metals from their primary source. FSC was also applied to offer plausible new routes for alloying and upcycling from powder and scrap metal and thus drew the attention of many researchers. During FSC process, a rotating tool with a certain force is applied to a given chips batch enclosed in a die chamber turning it into a consolidated billet. It is assumed that favorable process conditions for chips bonding are acquired by the combined effect of friction, stirring action, and pressure of the tool. However, the real process is quite complex, and it can be understood only by developing proper solid bonding criteria through numerical modeling that can forecast the consolidation process. Therefore, in this research, an attempt was made to implement different existing bonding criteria. Some of these were good enough to predict favorable conditions for sound bonding of particular case studies, however a uniform criteria with a single threshold value that is applicable to all case studies could not be achieved. Therefore, this study suggests for a new approach to accurately predict the bonding integrity of the FSC process.

Introduction

Aluminum consumption is rapidly increasing due to its growing demand for lightweight applications particularly in the transport, packaging, construction, and electronic industries. The accelerating demand is putting immense pressure on industries to increase the production rate [1]. Roughly 100 million metric tons of aluminum are currently produced per year. But for each 1 ton of aluminum production from the primary source, 12-16 tons of greenhouse gas (GHG) are produced and thus obtaining aluminum from its primary source is also one of the greatest causes of greenhouse gas (GHG) emission. Further, aluminum production is an energy-intensive process causing 13 Exajoules of energy consumption that accounts for almost 1% of total global energy consumption [2].

Interestingly, aluminum is an infinitely recyclable material [3]. Almost 35 % of the aluminum demand is met by recycling aluminum scraps [4]. Recycling is a highly energy efficient process, and it requires 5% of the energy compared to obtaining aluminum from bauxite ore (primary source) [1]. Nevertheless, the conventional recycling method has significant limitations, especially during recycling aluminum machining chips. Due to their high surface-to-volume ratio, these machining chips are prone to oxidation, causing permanent material loss during the melting process. They cause adverse environmental impact, high cost, and significant permanent material loss. Therefore, the researchers turned to Solid-State Recycling (SSR) techniques. During SSR methods, metal scraps transform into finished or semi-finished billet through mechanical means such as high pressure, friction, rotational speed, and force [5]. Recently, SSR processes have been analyzed as a potential alternative for recycling machining scraps.

The complex interactions between the process parameters make the SSR process difficult to be designed and controlled. Accurate predictions rely on the formulation of comprehensive weld models or criteria taking into account all physical aspects. Güley et al. [6] reported that the main challenges to predict the chips welding are connected to the complex stress states, and random position and orientation of contacting surfaces.

Akeret et .al [7] proposed a maximum pressure criterion where the contact pressure between the surfaces to be bonded is greater than the flow stress of the material at that point, however the model did not provide information effect of process parameters on weld quality. This aspect was studied by Plata and Piwnik [8], that compared the deformation energy as the sum of energies in the shear and compressive directions with the threshold value of the adhesion energy at the given point. The authors assumed that the energy in shear is much smaller compared with that in compressive strain. It was proved that Plata-Piwnik approach overestimated the weld quality at dead zone of extrusion process [9]. In this respect, Donati and Tomesani [9] introduced the flow speed as an additional correction factor to the Plata and Piwnik criterion. Then several numerical models were proposed for solid state process.

Ceretti et .al [10] presented a new approach in determining the critical value of the bonding criterion for flat rolling. They reported that solid bonding was dependent not only on the interface pressure, but also on the temperature at which the contact takes place. Schulze et al. [11] developed a numerical model to predict individual chips welding during hot extrusion. They found that local chips weld quality depended on the die type and hot extrusion parameters for different profile geometries. However, in Friction Stir Consolidation (FSC) process a rotating tool is applied to a desired chips mass enclosed inside a die chamber. The chips welding is due to the combined effect of pressure, force, friction and other factors characterizing the process mechanics [12]. Baffari et al. [13] developed a preliminary numerical model for bonding integrity of FSC process based on temperature and density. Although researchers have attempted numerical modeling of solid-state processing [11-13], proper bonding criteria are still under investigation to accurately predict the chips welding during FSC process. The current study proceeds with a detailed experimental campaign and numerical simulation for FSC process. To understand the bonding integrity, four different numerical criteria: Plata-Piwnik, Donati-Tomesani, Akeret and Plata-Piwnik-Zener were implemented. These criteria are widely used to quantify the bonding quality during solid-state processing. The goal was to develop a more accurate bonding criterion that can forecast the quality of FSCed recycled billet at given process conditions. Implementing such criterion as a quality indicator might be one of the key interests that can pave the path of FSC applicability at the industrial scale.

Materials and Methods

Aluminum alloy AA7075 was considered in the current study due to its popularity in aerospace manufacturing industries, where 90% of the input material turns into machining chips and is available as pre-consumer scraps [14]. Further, AA7075 is the hardest among wrought aluminum alloys with relatively low ductility. Therefore, analyzing the quality of AA7075 recycled billet can provide a broad understanding to forecast the quality of relatively soft and ductile alloys. In the ongoing investigation, the as-received material had an average Vickers hardness value of HV 150. As-received material was a 3 mm thick rolled sheet of AA7075-T6 that was turned into chips by milling operations. The chips were cleaned by submerging them in acetone for 30 minutes. First, 15 g chips were loaded in a cylindrical die with a nominal diameter of 25.4 mm and then compacted at 5 kN force by an H13 steel cylindrical tool with a 25 mm diameter. The die and pressing tool system were integrated with ESAB-LEGIO (Fig. 1a and Fig. 1b), a dedicated friction stir welding machine. Finally, a consolidated billet was manufactured after applying the tool at 20 kN with a tool rotational speed of 1500 rpm. It is important to note that due to machine limitation, it was not possible to instantly increase load from 5 kN compaction force to 20 kN consolidation force, but rather it was gradually increased with a step increment of 0.5 kN/s. Upon reaching the desired load, finally, the whole charge was consolidated at 20 kN constant force for the processing time of

40 and 60 seconds. In short, the whole process was completed in two steps: the transition phase, and the consolidation phase. Two billets were manufactured at processing time 40 and 60 seconds. The process parameters were selected based on the previous studies [15].

Measured outputs

The billet was sectioned, mounted, and polished with a series of abrasive papers assisted by distilled water and alumina. The hardness and microstructure were analyzed throughout the section at 119 points equally spaced at a distance of 1.5 mm, as shown in Fig. 1d. The hardness was measured through the Vickers hardness test by applying a load of 49 N (5 kg) for 15 seconds. Keller's reagent was used to reveal the microstructure.

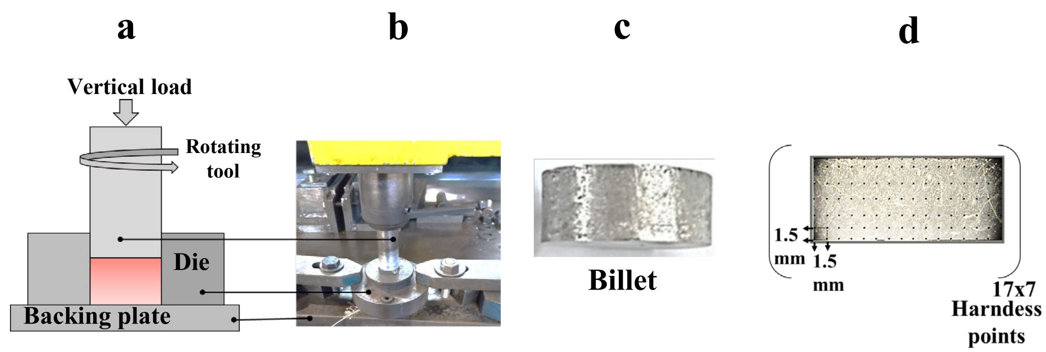

Fig.1: (a) Schematic diagram, (b) Friction stir consolidation (c) billet and (d) Analyzed loci on billet section.

Analysis of solid-state welding of the chips

The numerical model was implemented using the commercial FEA software SFTC DEFORM. The chips were modeled as a single block porous material part, using a Shime-Oyane model [16], with a relative density of 0.44 and a mesh of 60000 elements. Particular attention was paid to the tool-material contact zone using a mesh refinement. The relative density was found experimentally through a known volume of compacted chips at 5 kN and the volume of the consolidated billet at 20 kN force. The other three objects: the tool, die, and backing plate, were modeled as a rigid body with 15000 mesh elements (Fig. 2a). The simulation was a force-based numerical model in which the input was the force registered during the experimental process. The numerical model was validated through vertical tool velocity-time and stroke-time data that were obtained experimentally from the machine database, as shown in Fig. 2b.

To understand the bonding integrity, four different solid bonding criteria: Akeret [7], Plata-Piwnik [8], Donati-Tomesani [9], and Plata-Piwnik-Zener, were implemented. These criteria are widely used to quantify the quality of bonding during solid-state processing. For example, Plata-Piwnik uses a threshold value (W_{lim}) that indicates the ratio between the normal pressure (p) and the actual material effective stress (σ_{eff}) with the time integral. The Plata-Piwnik criterion is reported below in Eq. (1); once the ratio reaches this threshold value, then the solid bonding is assumed to be occurred.

$$W = \int \frac{p}{\sigma_{eff}} dt \geq W_{lim}. \quad (1)$$

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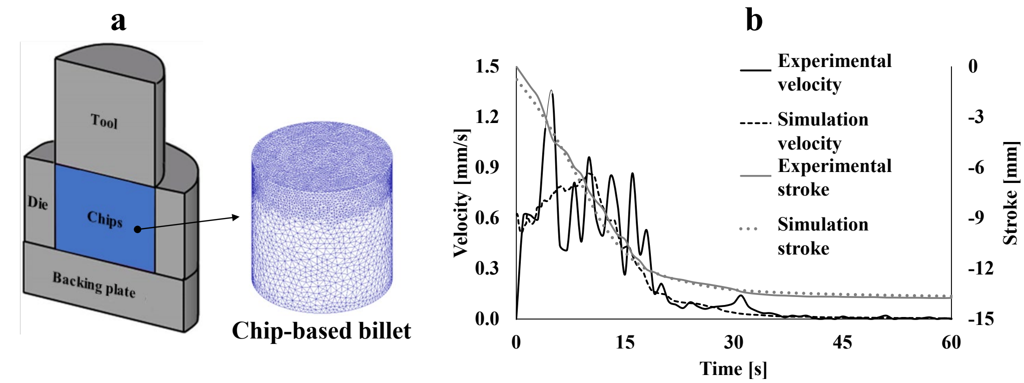

Fig. 2: (a) Numerical model for FSC, and (b) Tool experimental and simulated velocity-time and stroke-time graphs for model validation.

Results and Discussion

The numerical model was developed from two different data sets that were obtained through experimental measurements and numerical simulation for billets of processing time 40s and 60s. The experimental data collected were Vickers hardness values and grain size measured at 119 observation loci across the section, as shown in Fig 3 and Fig. 4. In order to interpolate the experimental values for hardness and grain size for the whole section, heatmap MATLAB in-built function was used. The hardness values were ranging 80-140 HV, while the grain's size was around 1.5-7 µm. The top zone of the billet was characterized by a high hardness value around HV 140 with a bigger grain size of 5-7µm compared to the bottom portion, which had a hardness value and grain size below HV 80 and 2 µm, respectively. It is assumed that the top portion of the billet is subject to high strain, strain rate, pressure, and temperature compared to the bottom portion. Furthermore, increasing processing time led to expanding the consolidated zone, and therefore, higher hardness and grain size can be noticed in the consolidated area of the 60s billet, compared to the section of the 40s billet.

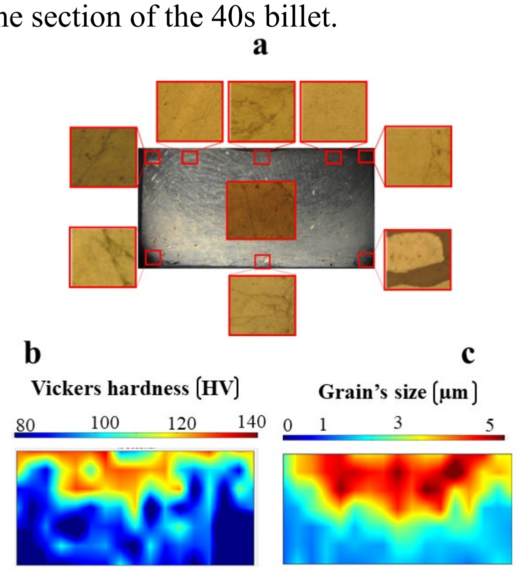

Fig. 3: FSC billet 40 seconds sample (a) microstructure (b) hardness (c) grain's size distribution.

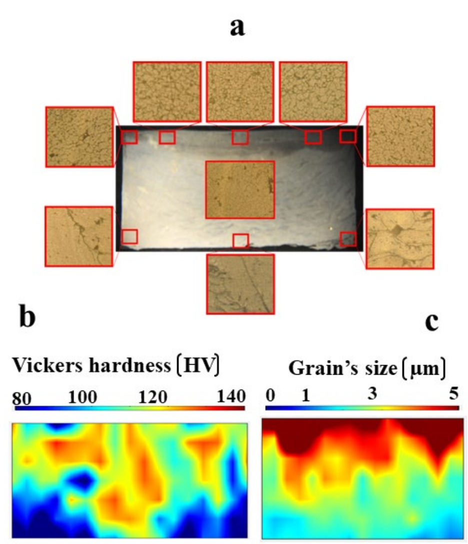

Fig. 4: FSC billet 60 seconds sample (a) microstructure (b) hardness (c) grain size distribution.

Based on hardness value and grain size, an experimental criterion was designed by setting a specific threshold value that indicated the fully consolidated zone. This study considers both hardness and grain size values for setting up the experimental criterion. After detailed analysis, the threshold for full consolidation was set to a minimum HV 90 for hardness and 2 µm for grain size. Regions of FSCed billet characterized by values exceeding these threshold values represent a fully consolidated zone; if either of these values was satisfied, that means partial consolidation occurred; if neither of these two values was satisfied no consolidation occurred at all. For numerical solid bonding criteria: Plata-Piwnik, Donati-Tomesani, Akeret, and Plata-Piwnik-Zener were implemented. The input data such as temperature, stress, strain, strain rate, pressure, etc. were obtained from numerical simulation. For a given criterion, the threshold was identified for both of the analyzed processing times (40s, 60s), this threshold will be referred to as local thresholds and all these numerical criteria were plotted using the local threshold as the upper bound of the scale. All the numerical criteria were plotted using an image comparison procedure by using MATLAB. The bonding map area was compared with the experimental criteria map. The local threshold of bonding criteria was varied until similarity between numerical bonding criteria and experimental bonding one reached the best value. For the sake of simplicity, the similar index was defined only for the consolidated zones. The schematic of the implemented procedure is presented in Fig. 5.

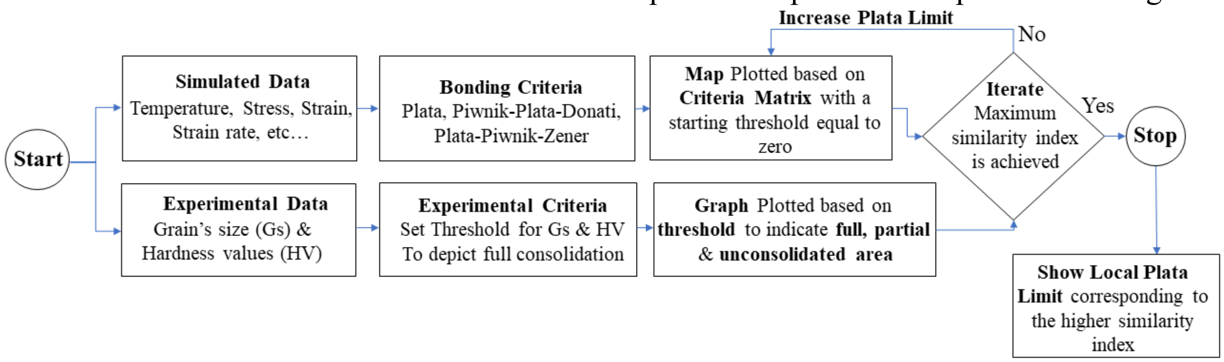

Fig. 5: Flow diagram for developing numerical model and their comparison with experimental criteria to forecast bonding integrity.

The comparison of experimental criteria and four different bonding criteria are presented in Fig. 6. The consolidated zone of the experimental criteria was considered as a reference, and all four numerical criteria were compared. No bonding criteria were found to accurately predict the experimental bonding occurrence. Although, Plata-Piwnik-Zener criterion seems to provide a better prediction of the shape of the bonding area, actually the best performance is provided by the Donati and Tomesani one as reported in Table 1. All the obtained results are summarized in Fig. 6 and Table 1. It is important to note that the error and the local limit value for each numerical bonding criteria are different and were found to be dependent on the processing time of the two analyzed billets. Further, the change in processing time also led to a variation in the local bonding limit.

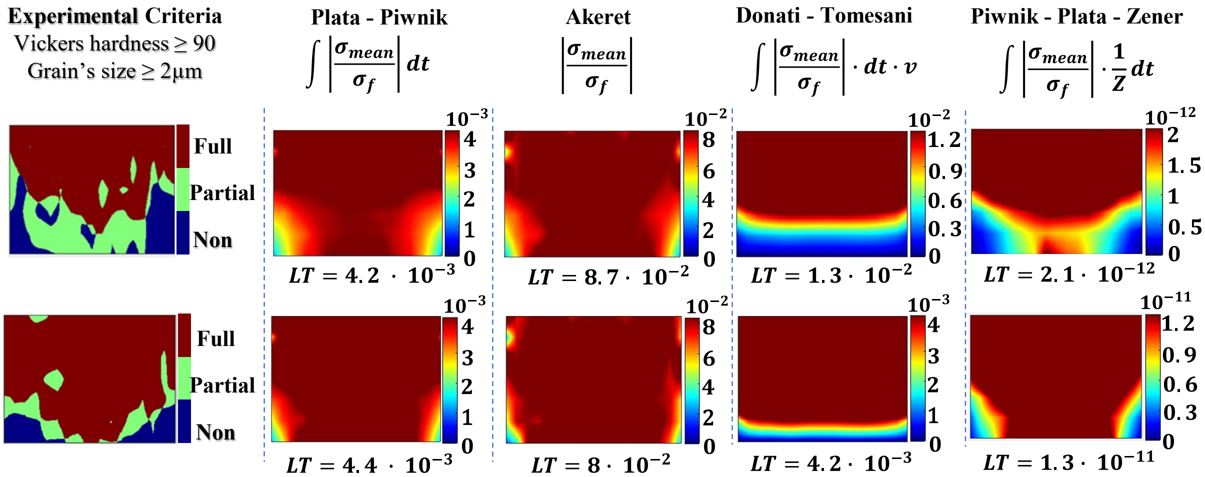

Fig. 6: Comparison of numerical local thresholds (LT) bonding value map with experimental criteria map for 40s and 60s.

Table 1. Comparison of bonding criteria in terms of numerical local thresholds (LT) and similarity index.

Bonding criteria	LT (40 s)	% Similarity index (40 s)	LT (60 s)	% Similarity index (60 s)
Plata-Piwnik	0.0042	58	0.0044	39
Akeret	0.087	64	0.08	40
Donati-Tomesani	0.013	80	0.0042	87
Plata-Piwnik-Zener	2.1E-12	84	1.3E-11	84

Due to the variations of the local bonding criteria limit with processing time, an average value of a criterion was utilized to analyze the effect of a unique value on estimating the bonding quality. The Plata-Piwnik-Zener was used for this purpose and the obtained maps are reported in Fig. 7, with details mentioned in Table 2. The results show that the average Plata-Piwnik-Zener threshold cannot satisfactorily predict the bonding quality compared to the maps of experimental criteria (Fig. 7a and b). Either underestimation or overestimation are clearly visible for the consolidated zone of the 40s and 60s (Fig. 7c and Fig. 7d), respectively. Then setting a limit suitable to 60s on a given local Plata-Piwnik-Zener provided underestimated consolidated zone for 40s (Fig. 7e). On the other hand, setting a local bonding limit favorable to 40s overestimated consolidated zone for 60s (Fig. 7f). These results reveal that no single unique threshold was achieved that can properly represent the consolidated zone for both case studies. Such kind of misleading results occurred for all the criteria analyzed in the present paper.

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Table 2. Details of thresholds value for Plata-Piwnik-Zener.

Bonding criteria	LT (40 s)	LT (60 s)	Average LT
Plata-Piwnik- Zener	2.1E-12	1.3E-11	7.5E-12

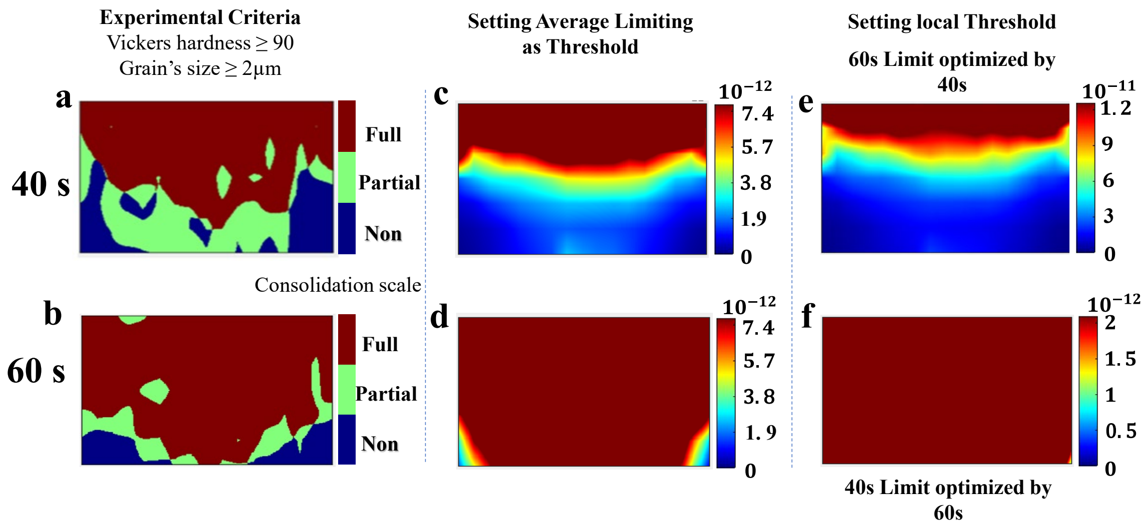

Fig. 7: Estimation of Plata-Piwnik-Zener maps based on different single average and local thresholds values.

Conclusions

In this paper a numerical-experimental procedure was proposed to set-up solid bonding criteria in Friction Stir Consolidation processes. The adopted procedure was implemented on different bonding criteria and the results were compared one another. The selected criteria can qualitatively predict the consolidation trends of the FSC processes; despite that some research is still needed to obtain a robust and reliable criterion for predicting the consolidation level of FSC samples; the following conclusions can be drawn.

1. No single bonding threshold value exists that can be applied to predict the bonding integrity for FSC billet.
2. The bonding thresholds were dependent on processing time, and therefore each case study has its own local threshold value.
3. If a single bonding threshold value e.g., average limiting value, was applied for all case studies, then it could not lead to satisfactory results, either causing underestimating or overestimating consolidated zones.

The peculiarity of FSC process demands the development of comprehensive bonding criteria that can predict the quality of chips bonding during the FSC process. New variables and methodologies should be considered in the analyses in order to find the correct metric that actually affect the chips bonding in FSC processes.

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