

## Recycling magnesium alloy AZ31B chips via friction stir consolidation: A sustainable approach

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**Abstract.** The growing demand for lightweight alloys has resulted in significant environmental challenges due to the exponential growth of machining waste, such as magnesium alloy chips. Conventional recycling techniques for these chips are often associated with oxidation losses, energy inefficiencies, and elevated greenhouse gas (GHG) emissions. Friction Stir Consolidation (FSC) emerges as a sustainable and solid-state recycling technique that mitigates these drawbacks by consolidating magnesium alloy chips directly into solid billets. This study investigates the FSC process applied to AZ31B magnesium chips, focusing on the influence of processing time on the quality of the consolidated billets. An experimental campaign was conducted with four distinct consolidation times, evaluating the mechanical properties and energy consumption of the process. Additionally, numerical simulation was performed to analyze the process mechanics. The results revealed that FSC successfully produced consolidated billets, with the highest consolidation level achieved at a process time of 60 seconds. Hardness analysis revealed a decreasing trend from the top to the bottom of the billet, with maximum values below those of the base material.

### Introduction

The widespread use of products made of lightweight alloys has led to an exponential increase in material waste, such as chips generated during machining processes. The growing demand for engineering materials is expected to constitute the majority of greenhouse gas (GHG) emissions in the near future [1, 2]. The primary production processes for magnesium alloys can be categorized into two main types: electrolytic and thermal processes. Among these, the most widely adopted is the Pidgeon thermal process, which accounts for 91% of global magnesium production and it is predominantly utilized in China. For each kilogram of magnesium produced, 27 kg of CO<sub>2</sub>-equivalent emissions are generated, along with an energy consumption of 280 MJ five times the energy required for steel production [3].

The use of SF<sub>6</sub> as a cover gas in primary production poses a significant environmental challenge due to its global warming potential, which is 23,900 times higher than that of CO<sub>2</sub> [4].

The increasing primary production of these materials follows a linear economy model, which contrasts with the goals of reducing greenhouse gas emissions [5]. Policies promoting circular economy principles, including actions such as re-manufacturing, re-use, repair, and both open-loop and closed-loop recycling, are urgently needed [6].

Two main techniques for recycling process scrap can be considered: the “conventional” method and direct, solid state, recycling. It is worth noting that significant losses due to oxidation occur with conventional recycling techniques, attributed to the high surface-to-volume ratio of chips. These conventional methods include remelting, electrorefining, and vacuum distillation [7-9].

Direct recycling methods are attracting growing interest, as they bypass the liquid phase preventing oxidation-related losses.

However, proper cleaning of chips to remove residual lubricants from machining operations remains a critical step. These meltless processes can be further divided into two subcategories: Powder Metallurgy (PM)-based and deformation-based methods. For PM-based processes, Spark Plasma Sintering (SPS) energetically activates the material through the combined action of compression and pulsed electric energy, generating heat via the Joule effect [10].

Regarding deformation-based processes, Severe Plastic Deformation (SPD) techniques such as Equal Channel Angular Pressing (ECAP) [11], Cyclic Extrusion Compression (CEC) [12], Friction Stir Extrusion (FSE) [13, 14] and its continuous version (CFSE) [15], Friction Stir Consolidation (FSC) [16], and High-Pressure Torsion (HPT) [17] have been successfully employed in recycling aluminum and magnesium scraps. It is important to note that the high reactivity of magnesium alloys makes recycling processes involving elevated temperatures less advantageous. In this regard, deformation-based processes mitigate this drawback [18]. Although different techniques were applied to recycle magnesium chips, the FSC one was not widely investigated.

For this reason, this paper aims to enhance the capability of the FSC process to turn AZ31B magnesium chips into a consolidated billet. An experimental campaign was carried out with varying the total process time, and the electrical consumption was measured for each test.

A numerical approach was performed for a better understanding of the process mechanics. Finally, the electrical energy demand was experimentally quantified to provide insights concerning the energy efficiency of such an approach for understanding.

### Materials and Methods

A (30 x 80 mm) AZ31B bar, 76 HV of microhardness value, was used to obtain magnesium chips through a milling operation performed at 1250 rpm, feed rate of 28 mm/min and a cutting depth of 1 mm. The FSC process was performed by a dedicated machine ESAB Legio 3ST. The experimental setup consisted of a rotating tool, H-13 steel, 24.9 mm diameter (25 mm nominal diameter) coupled with the ESAB's head, a die, H-13 steel, 25 mm internal diameter placed on a backing plate also made of H-13 steel, fixed to the working table. 15 g of cleaned chips was processed for each test. A compacted phase of 5 kN vertical load was carried out after the filling phase. Fig. 1 shows a sketch of the process setup.

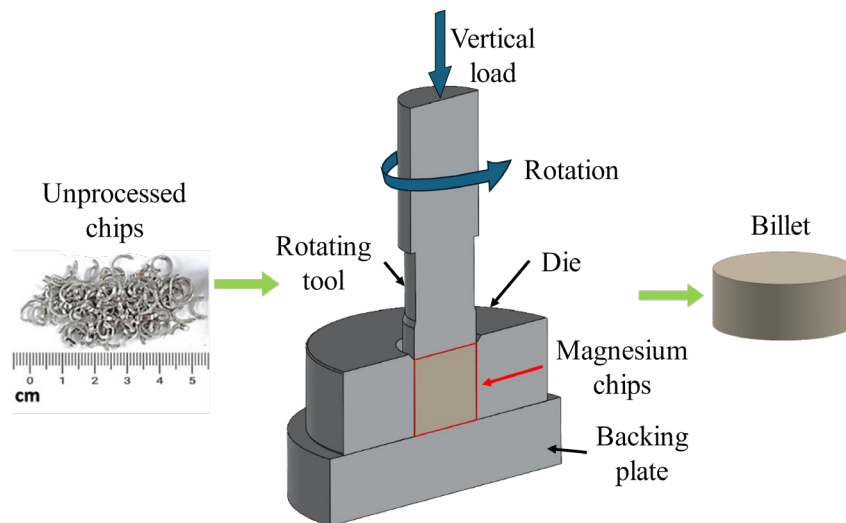


Figure 1 – Chips, experimental setup and consolidated billet, for the FSC process

Once the pre-compaction was completed, a rotational speed and a vertical load were applied to the tool; the starting load was 5 kN, and a constant increment of 0.5 kN/s was used to bring the vertical load from 5 kN to 20 kN. This strategy was adopted to overcome the inability of the

machine to change immediately the vertical load with the workload. This first step was considered as transitory phase of 30s. After this step, three more tests were performed keeping the force at 20 kN for a consolidation time of 10, 20 and 30 seconds, resulting in 3 more processing times, namely 40, 50 and 60 seconds. The process parameters and the process times are listed in Table 1. Overall, four tests were carried out to investigate the AZ31B magnesium alloy consolidation during the FSC process.

After producing the samples, in order to prepare the specimens for hardness measurement, were cut in two halves and the cross-sections were mechanically grinded using abrasive papers of different grit sizes and polished with a diamond suspension. Details about harness measurements are provided in the discussion of the results section.

Table 1 – Process parameters and time, for the FSC of AZ31B magnesium alloy

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

For each test, the power-time data was collected by connecting the power meter CHAUVIN ARNOUX C.A 8331 to the input electrical connection of the ESAB machine. The recording started at the first compaction, until the end of the process.

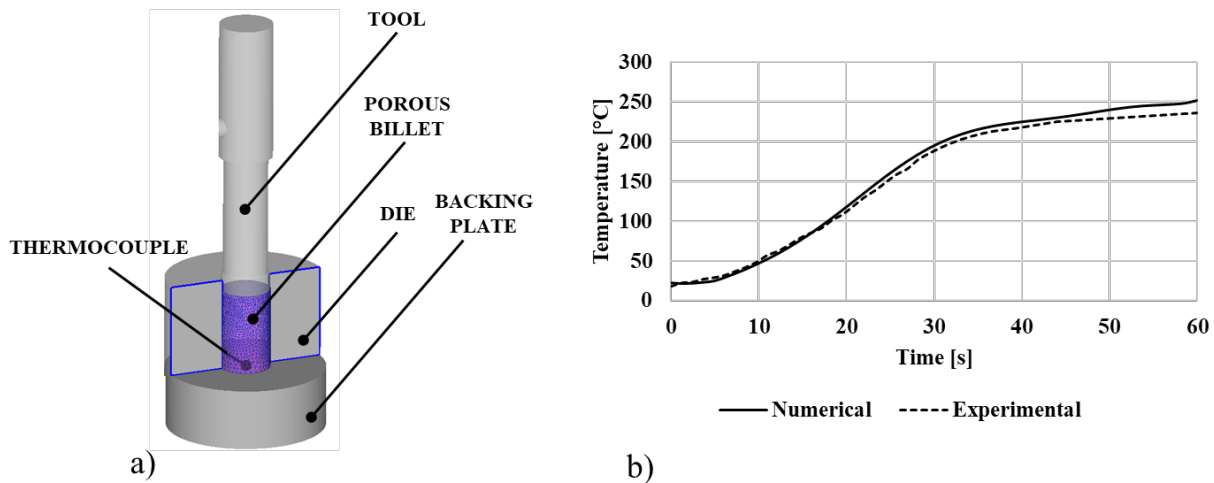


Figure 2 – a) FSC numerical setup and b) temperature tuning

The numerical simulation of the process was performed by using the commercial software SFTC DEFORM 3D™. As for the experimental campaign, this model involves four different parts: a die, a tool, a backing plate and chips (Fig. 2a). The first three parts were considered as H-13 steel rigid bodies with a mesh size of 30000 elements. On other hand, the chips were modelled as a porous-billet, characterized by a Shime-Oyane formulation [19] for porous material, initial relative density equal to 0.44, meshed by 20000 elements, with a refining mesh window located near the tool-billet contact. By a temperature tuning sing a K-thermocouple at the bottom center of the billet (Fig. 2b), the shear factor equal to 0.3, and the heat transfer coefficient equal to 11 W/mm<sup>2</sup>/K.

### Discussion of the results

The variation in consolidation time was performed to assess the effect of the parameters on the chips' consolidation. The experimental campaign resulted in four billets having different levels of consolidation. The samples were cut, mounted and the cross-section was analyzed. From the cross-section, it is clear to notice that the main issue of the FSC process, namely the low tier consolidation at the bottom, was still but, the portion of the billet that was not consolidated decreases with the increasing of the consolidation time (Fig. 3c).

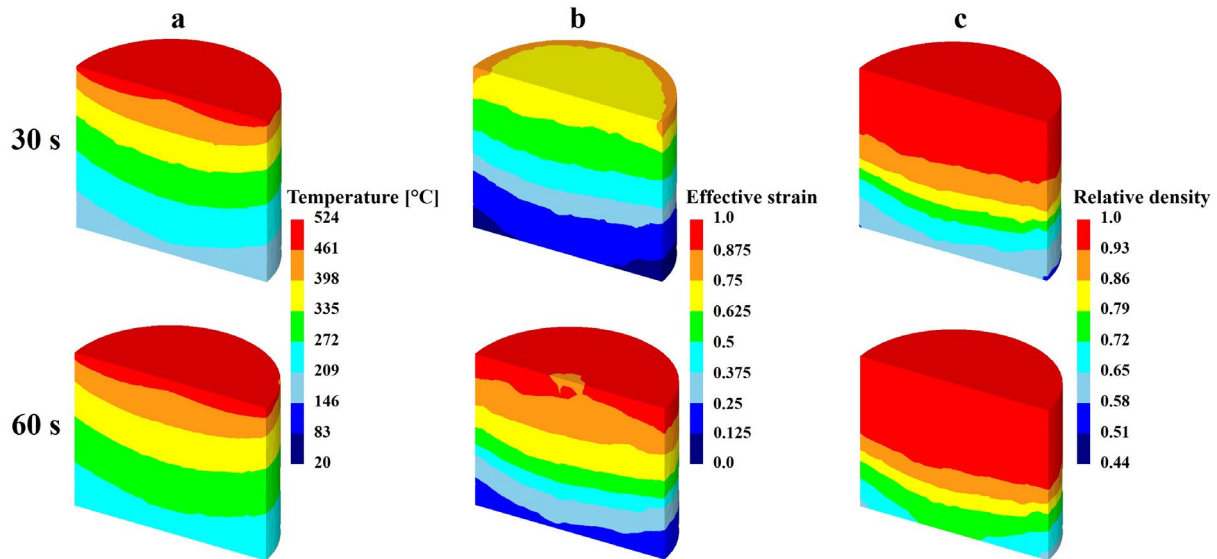


Figure 3 – Cross section of the billets at 30 and 60 seconds of consolidation time; a) temperature, b) strain and c) density plot

For verifying the chips consolidation, a hardness analysis was conducted. The evolution of the hardness values was evaluated by means of a vertical set of 15 points, starting from the top of the billet, tool action zone, to the bottom. Fig. 4 shows the HV measured in a cross-section along 3 vertical lines equally spaced with a horizontal pitch of 5 mm with respect to the center of the specimen (0, +5, +10 on x-axis) and with a vertical pitch of 1mm.

The study of the hardness for a FSCed billed was already performed by the authors for the aluminium chips consolidation [20, 21], and a decreasing trend was expected from the top to the bottom of the billet. This effect is mainly due to the inhomogeneity of heat transfer during the process and the localized stirring action of the tool; the heat generation belongs to the friction between tool and metal material, and for this reason it starts from the top of the billet. Consequently, the bottom corner of the billet is the part which has the biggest heat exchange, so it will be the least consolidated part (Fig. 3a). On other hand, the material is stirred mostly near the tool-material contact zone (Fig. 3b), therefore the tool is less affecting the oxide breakage at the bottom part of the billet, leading to a lower mechanical property in these zones.

The hardness results for the magnesium case study are visible in Fig. 4 going into detail for 30s (Fig. 4c) and 60s (Fig. 4d) trends.

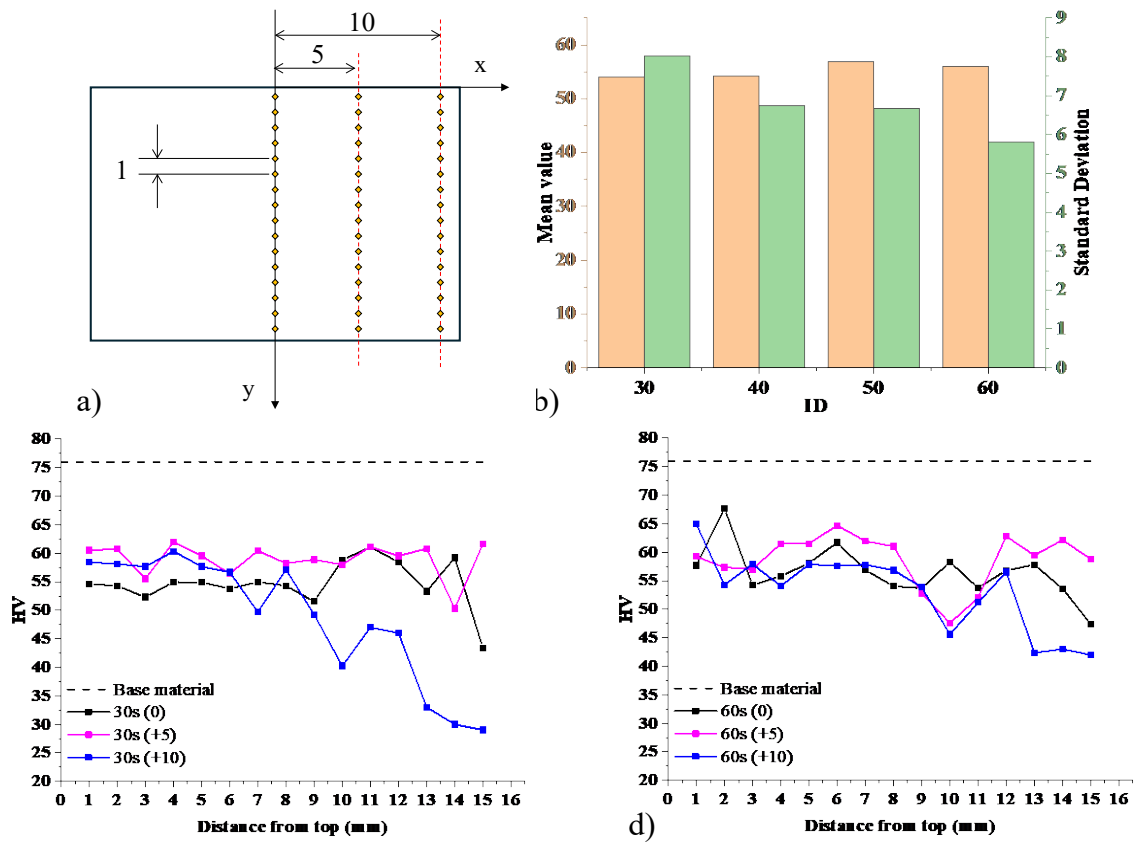


Figure 4 – a) Schematic representation of hardness indentation; b) Mean values and standard deviation of the billets' cross section, from the top (0mm) to the bottom (15mm) for 30s, 40s, 50s, and 60s; Hardness trends compared to base material for c) 30s, and d) 60 specimens

From the results reported in Fig. 4 it is possible to state that the processing time does not affect the hardness average, on the other hand it is possible to observe that standard deviation decreases with increasing the processing time. The better standard deviation value for EXP 4 is due to the better consolidation at the bottom region of the billet, close to the bottom corner.

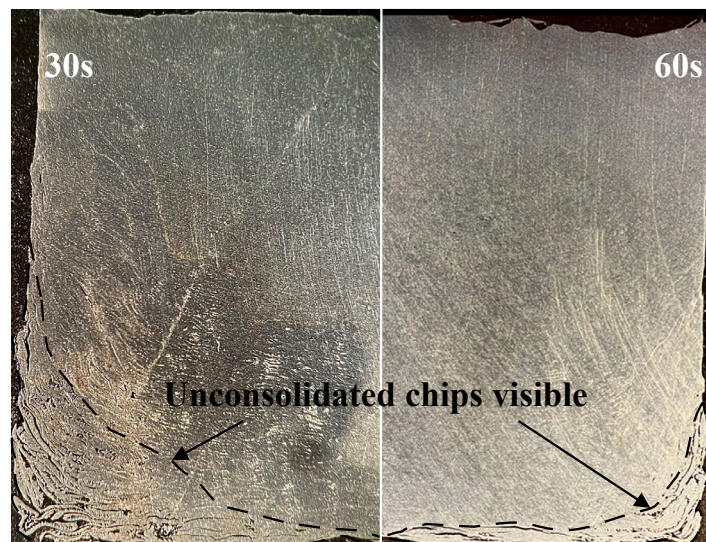


Figure 5 – Macroscopic analysis of cross sections for the 30s (left) and 60s (right)

This is also highlighted in Fig. 4c and 4d, where it is clear that the outer region of the billet of EXP 1 (30s) is less consolidated at the bottom as a drop in hardness occurs. Such drop is instead much more limited when Fig. 4 d is analyzed. This detail is shown in Fig. 5, where a macroscopic analysis of the surface of the billets is presented in order to investigate the consolidation occurrence for the case study 30s and 60s. In this figure the areas unconsolidated are highlighted, in these regions porosity and unconsolidated chips are clearly visible, such region is limited in the 60s case.

Lastly, the consolidated billet production was coupled with electrical energy consumption recording for each case study. A typical Power trend for the consolidation of a 60s billet is reported in Fig. 6, where the six main phases are highlighted in different colors.

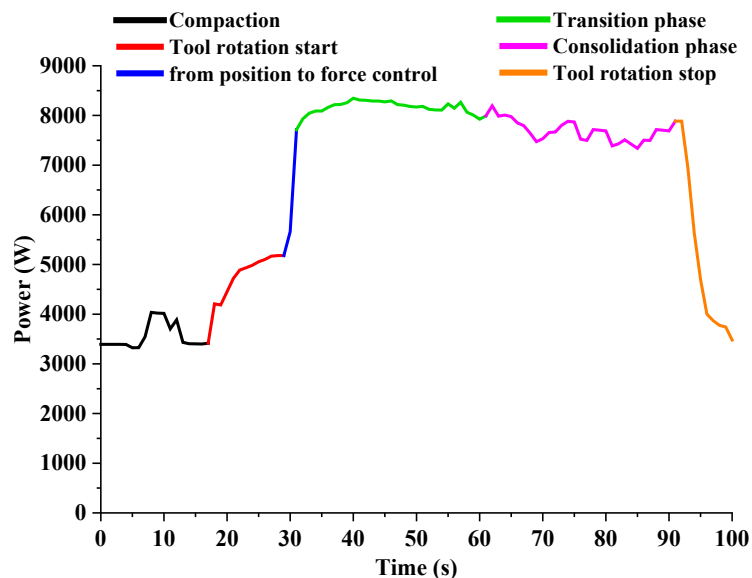


Figure 6 – Electric power trend of FSC process for 60s case study

To determine the energy required by the process, the compaction phase was disregarded, as it is a non-productive stage. However, this phase should be taken into account when considering an industrial case.

Table 2 – Energy data for the FSC of AZ31B magnesium alloy

Exp ID	Transition phase [kWh]	Consolidation phase [kWh]	Total energy demand of FSC process [kWh]
Exp 1	0.065	-	0.065
Exp 2	0.065	0.025	0.090
Exp 3	0.065	0.045	0.110
Exp 4	0.065	0.066	0.131

Considering the case study Exp 4, the embodied energy of the FSC process is 73.1 MJ/kg, 27% higher than the embodied energy associated with the conventional recycling process (57.7 MJ/kg). To determine the Primary Energy Demand of the FSC process, the energy recorded during the process is divided by an average efficiency factor of 0.43, considering the energy mix of Italy. This value was obtained from the EcoInvent database. To assess the sustainability of the FSC process, a comparison in terms of Primary Energy Demand was conducted with the traditional recycling process (remelting). The data required for the comparative analysis were obtained from a literature review (Table 3).

Hot extrusion material yield, oil removal, drying, and compaction were found into DLR report [22], [23], and paper from Cooper [24]. Remelting and primary production demand of AZ31B were found by CES Edupack [25].

*Table 3 – Main Life Cycle Inventory data*

	Primary specific energy [MJ/kg]	Reference
Oil removal & drying	8.1	[24, 26]
FSC	73.1	Experimentally measured
Compaction	0.792	[25]
Remelting	57.7	[27]
Primary production AZ31B	393	[27]
Hot extrusion	2.16	[24, 25]

In Fig. 7, the analyzed recycling routes highlight the contribution of each process step/factor to the total demand, as reported by the developed comparative analysis for a functional unit of 15g or magnesium billet.

The FSC process outperforms the traditional process. This significant difference is primarily attributed to permanent losses, which account for 36.4% of the process's impact.

Additionally, the FSC process is more advantageous as it enables the production of a final product in a single step, whereas the traditional process would require additional intermediate steps to achieve the same result.

### **Conclusion**

The Friction Stir Consolidation process was performed to explore the capability of the friction stir consolidation technique to turn magnesium chips into consolidated billet. Four samples were well produced considering four different consolidation times, to assess the effect of the time process on the magnesium billets, and the following conclusion were drawn:

- The friction stir consolidation process successfully produced consolidated billet. The billet obtained at 60 seconds process time is the one having the highest consolidation level
- The hardness of the consolidated billet for each process window decreases from the top to the bottom of the cross-section, especially in the outer regions. Despite the hardness has a decreasing trend, the maximum value is less than the base material
- The numerical simulation has successfully represented the FSC process for the AZ31B and helps to motivate the hardness evolution along the billet cross section
- The energy consumption analysis shows that the transition phase has a high impact compared to the consolidation phase. A first primary energy demand comparative analysis proved that FSC can enable significant environmental impact reduction with respect to remelting-based routes

Further work will concern a deeper study of the consolidation bonding occurrence by means of the implementation on solid bonding criteria already developed by the authors [26]. Moreover, a full LCA analysis will be developed, and the study will be extended to Friction Stir Extrusion processes.

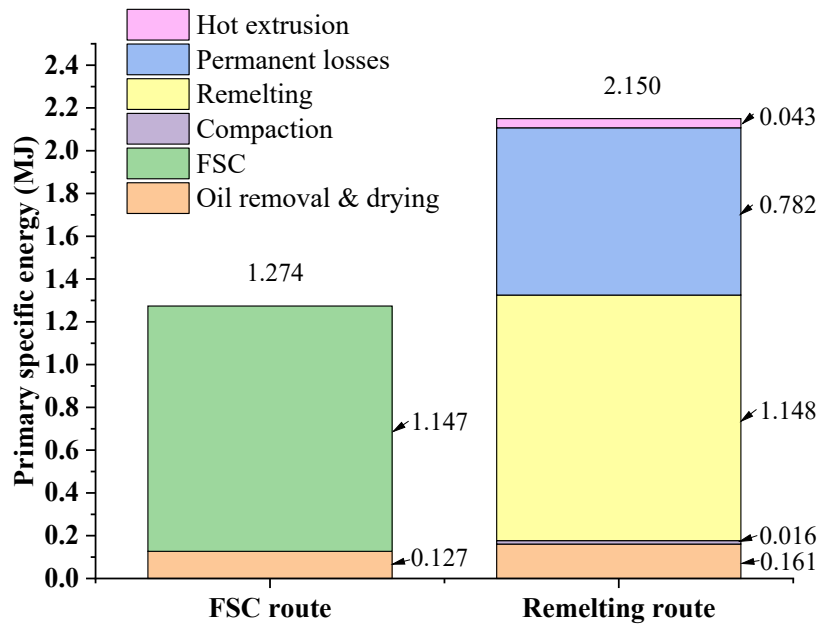


Figure 7 – Primary specific energy demands of the analyzed recycling routes

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