Solid state recycling operations for AA7075

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Abstract. Solid-state recycling offers a sustainable solution characterized by low energy consumption and heightened product efficiency compared to conventional melting-based methods. Among these, Friction Stir Extrusion processes emerge as an innovative and promising category within solid-state recycling, showcasing the ability to directly repurpose machining chips into solid products. However, as these processes primarily yield semi-finished products -typically in the form of wires, rods, or small billets- subsequent post-recycling forming processes become imperative for achieving net-shape or near-net-shape components. Consequently, a thorough evaluation of the mechanical properties of materials derived from solid-state processes is essential for ensuring the dependable design of process chains. This paper focuses on the calibration of constitutive parameters for raw materials obtained from aluminium chips within a novel process chain rooted in solid-state recycling operations. Cylindrical billets, resulting from friction stir consolidation (FSC), are tested in compressive conditions and investigated with respected of processing conditions to obtain ultra-fined grained materials through sever plastic deformation processes.

Introduction

The global aluminium industry faces the challenge of reducing carbon dioxide emissions and the greenhouse effect these emissions can have on global warming and climate change[1]. These emissions arise both directly from the production process and from the recycling process[2]. For aluminium alloy recycling, the traditional remelting recycling method usually results in re-oxidation of the metal, resulting in permanent loss of the metal. The remelting recycling process also generates higher energy consumption and recycling costs[3]. Solid State Recycling (SSR) process can avoid the remelting step and thus improve the recycling efficiency. Compared with conventional remelting recycling, direct conversion of aluminium and its alloy chips into compact specimens by extrusion leads to savings of 40% in materials, 26–31% in energy, and 16–60% in labour [4].

Friction Stir consolidation (FSC) is one of the SSR processes that has effectively recycled the metal chips into solid blocks, which can effectively reduce the impact on the environment during the recycling process. At the same time, compared with other SSR processes, FSC can provide more adequate oxide breaking and solidification effects[5].

The present study focuses on the calibration of constitutive parameters for raw materials obtained from aluminium chips within a novel process chain rooted in solid-state recycling operations. AA7075 alloy chips were friction stir consolidated into the shape of a billet, and subsequently respective billets were made into cylinders. The cylinders were subjected to compression testing, and the cut billets were subjected to microhardness testing. Finally, the thermal conditions in backward extrusion processes were investigated.

Application case

The application case refers to the cold impact backward extrusion of cans used to manufacture pressurized dispensers for cosmetic products. The typical manufacturing chain which counts several steps: (i) lubricant deposition on aluminium disks, by means a tumbling barrel that rotates at 16 RPM for 20 minutes in order to lubricate the external surface of the disks, (ii) impact extrusion of aluminium disks, (iii) trimming of the extruded cylinder because the extrusion process leaves the can slightly wavy at the top, washing and drying, (iv) internal and external spray coating, which is then cured in an oven in order to extend product life and preserve the integrity of the contents, (v) outside painting and printing and ending with (vi) edging and necking. The most severe step of the process chain is represented by the impact backward extrusion, since it exhibits the highest levels of pressure, temperature and surface expansion, which are particularly severe for the lubrication and the dies service life.

Materials

Specimens.

The starting material (as-received material) was AA7075 sheet with chemical composition listed in Table 1. The as -received material (see Fig. 1) is characterized by average values of 150 HV and 155 µm for hardness and grain size, respectively. The sheet was reduced into chips through milling operations with tool rotational speed of 1250 rpm, feed rate of 280 mm/min, and cutting depth of 1 mm. The selection of aluminum alloy AA 7xxx in the current studies was driven by its extensive use in the aerospace manufacturing industry where almost 90% of the input material turns into scrap [6]. In addition, AA7075 represents a class of wrought aluminum alloys with higher hardness value and relatively lower ductility. Thus, assessing the formability of AA7075 recycled billet can provide a better understanding to forecast quality of recycled billets with relatively good ductility such as AA6xxx, AA2xxx, and AA5xxx. This assessment can pave the way for transforming scrap materials into a value-added component for potential industrial applications.

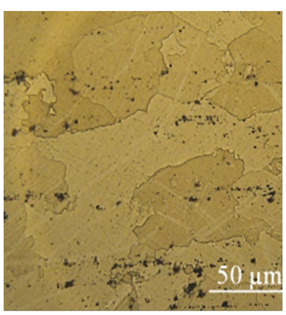

Fig. 1. *AA7075 as received.*

Table 1. *Nominal chemical composition of the AA7075.*

Al	Zn	O	Mg
88.07	5.07	2.60	42.25
Cu	**Cr**	**Fe**	**Mn**
1.76	0.2	0.03	0.02

Punch and dies.

The tool steel used for the punches is the EN HS 6-5-2 alloyed steel, commercially available with the name of Böhler S600 (see the chemical composition in **Table 2**).

The steel was thermally treated, in order to obtain a surface hardness of 62 (±1.5) HRC. The punches were machined to obtain a final surface roughness S_a of 1.735 (±0.001) µm. In the case of the die, the tool steel is the EN X37CrMoV51KU, commercially available with the name of Böhler W300 (see the chemical composition in **Table 2**).

The die steel was thermally treated, to obtain a surface hardness of 54 (±1.5) HRC. The final surface roughness Sa is equal to 0.563 (±0.001) µm. **Figure. 2** shows the tools surface and metal disc non coated in the as-delivered conditions.

Table 1. *Chemical composition of the tools grade.*

	C	Mn	Si	Cr	Mo	V	W
S600	0.9	-	-	4.1	5.0	1.8	6.2
W300	0.4	0.4	1.1	5	1.3	0.4	-

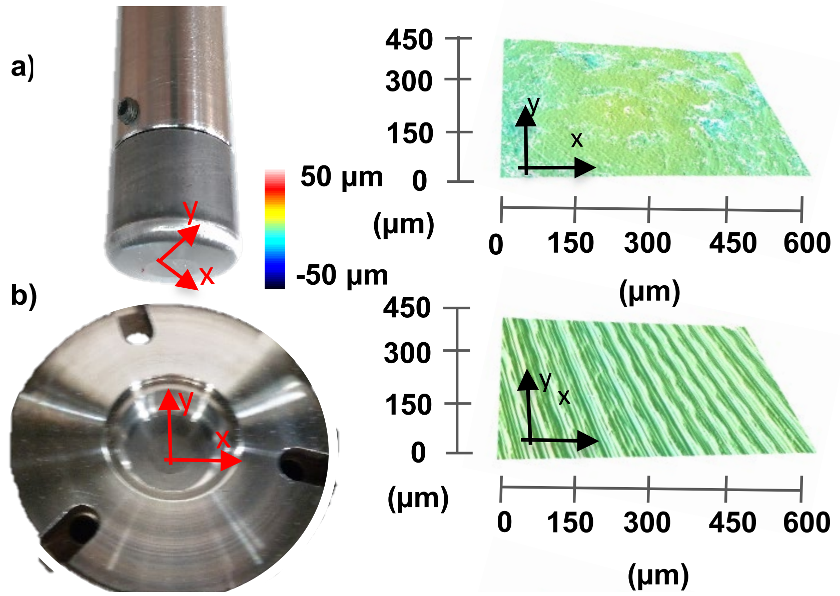

Fig. 2. *Surface topography of: a) the punch and b) the die.*

Experimental
Test specimens production.
The cleaning operation of the chips was performed by submerging them in acetone for 30 minutes. Then 15 g of input chip mass was loaded in a cylindrical die with a nominal diameter of 25.4 mm and then compacted at 5 kN force by a H13 steel cylindrical tool with a 25 mm diameter. The die and pressing tool system was integrated with ESAB-LEGIO (Fig. 3), a dedicated friction stir welding machine. Finally, the chips were consolidated at 20 kN with a high tool rotational speed of 1500 rpm, a processing time of 60 s and by adding the material in a single step, which means that the chips are consolidated in a single run [7].

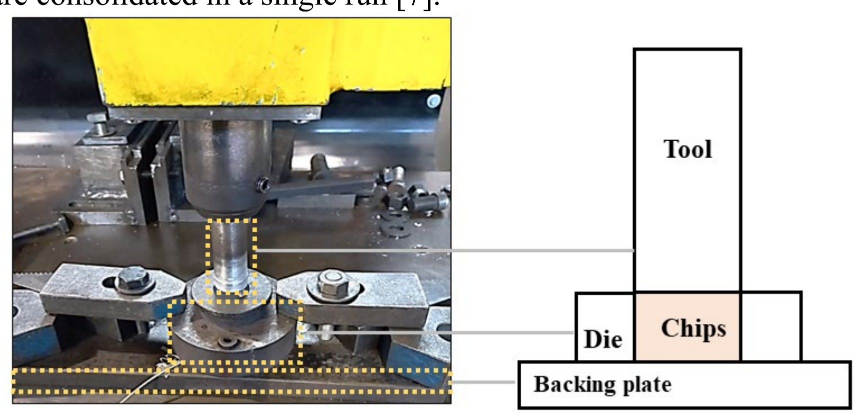

Fig. 3. *Experimental setup and process schematic of FSC process*

Compression tests for material characterization.
Cylindrical samples for compression tests, having a diameter of 6 mm and a height of 8 mm, were obtained from stirred billets. Compression tests were performed on a Gleeble™ 3800 machine. The tests were carried out at 100°C, 200°C, and 300°C and a constant strain rate 1 s^{-1}. The result as is shown at Fig. 4.

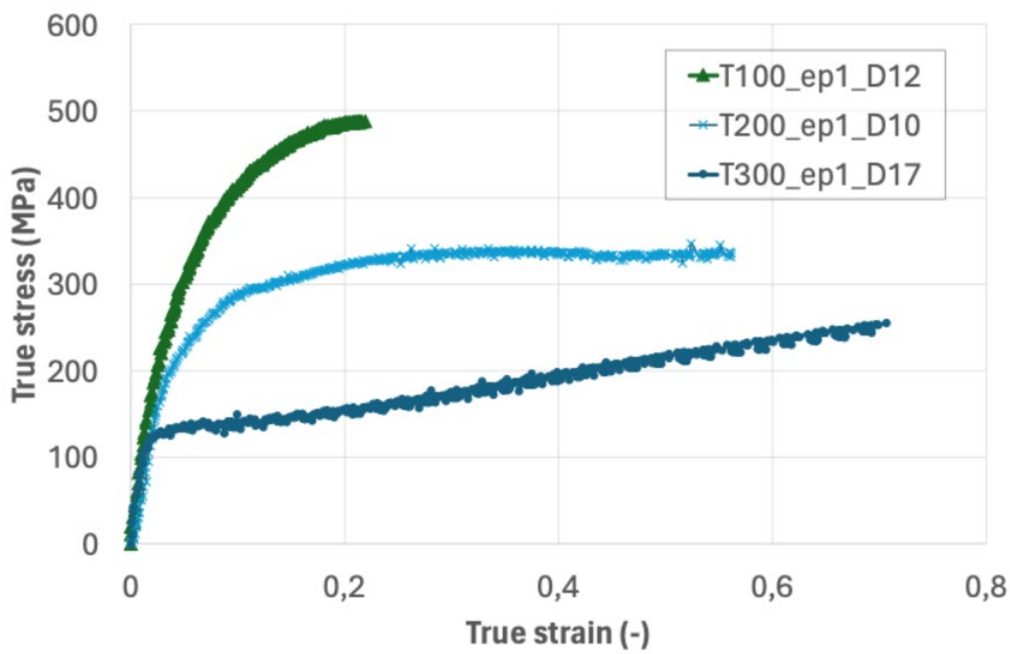

Fig. 4. *Compression test at different temperatures.*

Hardness tests.
Hardness (HV) measurements were carried out to assess uniformity of the mechanical properties in the manufactured sample. The hardness was evaluated by the Vickers hardness test. A load of 49 N (5 kg) was applied for a dwell time of 15 s along four loci along the cylindrical direction, i.e. at radius, r = 0 mm (L0), 6.5 mm, 9 mm, and 12.25 mm (L1, L2, and L3, respectively) as illustrated in Fig. 5. A constant pitch of 0.5 mm was set for the load points on each line. The highest hardness was shown by the central and top parts of the billet. The hardness values decrease as moving from centre to the edge (external surface). The bottom part exhibited the lowest hardness was values. The hardness of the whole section of the billet has been represented in Fig. 5. This gradation in hardness is caused by the process mechanics of the FSC process [8].

Axial distribution of hardness: The rotating tool is considered the hub of the heat. Maximum heat is gained by the top surface, and sound bonding is developed between the layers of the chips, and therefore, the top surface has high hardness. The intensity of the heat reaching the bottom surface is quite low and is not sufficient to cause a full solid bonding of the layers of the chip at the bottom, and thereby, an unconsolidated zone was observed at the bottom of the billet with a relatively low hardness value [7].

For radial hardness distribution: The hardness also follows a decreasing trend along the radial direction. It decreased from the central line to the line near the external surface [9]. L1 and L2 measuring loci, show a similar trend to L0 one but a slightly late drop occurred at L1 due to occurring material flow [10]. In turn, L3 shows an earlier drop in hardness value due to the upward movement of the bottom material at that radius.

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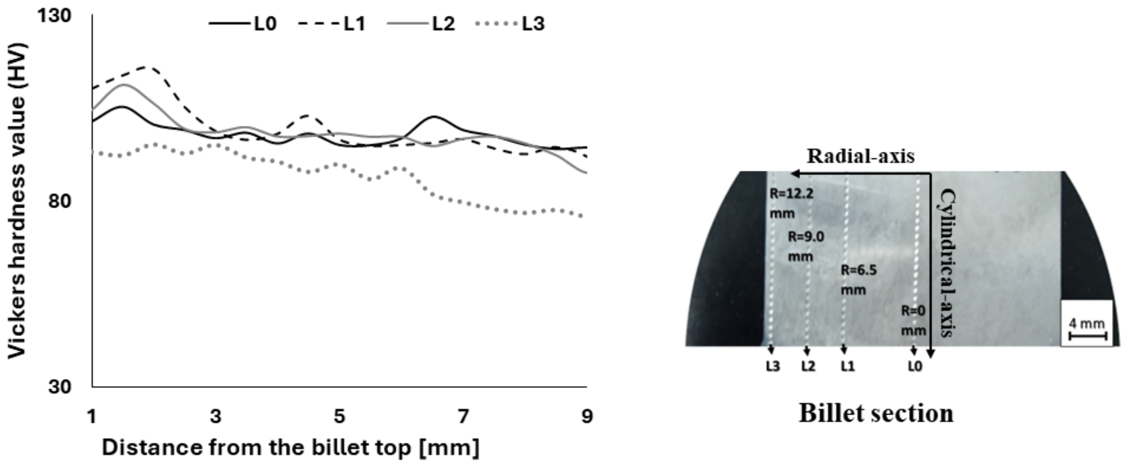

***Fig 5.** Material hardness along the FSC billet section*

FE model

The FE software Deform 3D was used to simulate the impact extrusion process, using the Optimizer Tool embedded in the software suite for the inverse analysis. By means of the algorithm, the user can submit the forming problem directly to the software application, by choosing the criteria to be optimized and the variables to be modified. On this basis, the difference between the values of extrusion forces, recorded in the experimental tests and obtained from FE simulations respectively, was selected as objective function to be minimized, choosing the friction factor *m* according to the Tresca model as the parameter governing the convergence. The flow stress model used in the simulations was the Hansel-Spittel (H-S) equation, to take into account the effects of the temperature due to the adiabatic heating during the deformations:

$$\sigma = A \cdot e^{m_1 T} \cdot \varepsilon^{m_2} \cdot \dot{\varepsilon}^{m_3} e^{m_4/\varepsilon} \qquad (1)$$

where σ is the material trues stress, ε the material equivalent true strain, $\dot{\varepsilon}$ the equivalent material strain rate, T the temperature and A, m_1, m_2, m_3, m_4 the constitutive parameters. The flow stress was investigated in the same range of temperatures and strain rates of the industrial process. Through a nonlinear regression analysis, the constants of the H-S equation were calculated to be implemented in the FE code. The simulations were reproduced under the conditions of **Table 4**.

***Table 4:** The mail process parameters used for the simulation and constitutive parameters for the material.*

Temperature [°C]			20, 100, 200	
Strain [-]			1	
Strain rate [s^{-1}]			1	
A	**m$_1$**	**m$_2$**	**m$_3$**	**m$_4$**
1309,03998	-0,00545	0,26205	0,00280	-0,00091

Punch, die and backing plate were modelled rigid bodies with a mesh size of 15000 elements while the FSC recycled billet was considered a plastic object of 35000 elements as shown in Fig. 6. Three different numerical simulations at punch speeds of 50 mm/s, 100 mm/s, and 200 mm/s, each with a total punch displacement of 7.5 mm, were performed under a constant friction coefficient of 0.1 and a heat transfer coefficient of 11 N/sec/mm/°C. A clearance of 2.5 mm was maintained between the punch and die for the billet extrusion.

To compare the influence of punch speed on the final state of the extruded billet, temperature profiles for all three simulations were compared specifically along the trajectory comprising 20 points from "A" to "B" as illustrated in Fig. 7. The trajectory was taken along the section of the billet, starting from the centre of the external wall of the billet "A" and completed at centre of the billet bottom surface. The results showed that higher punch speed led to impart higher temperature (Fig.7)

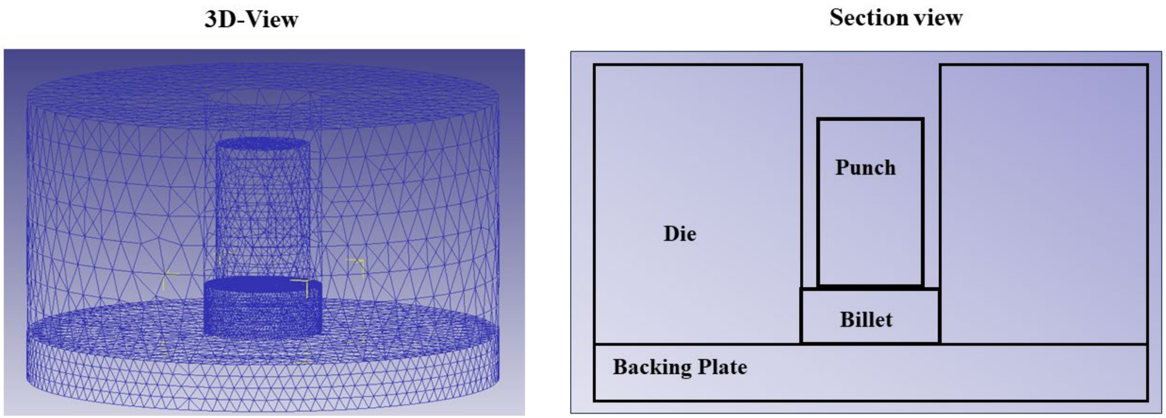

Fig. 6. *Numerical Model for extrusion process*

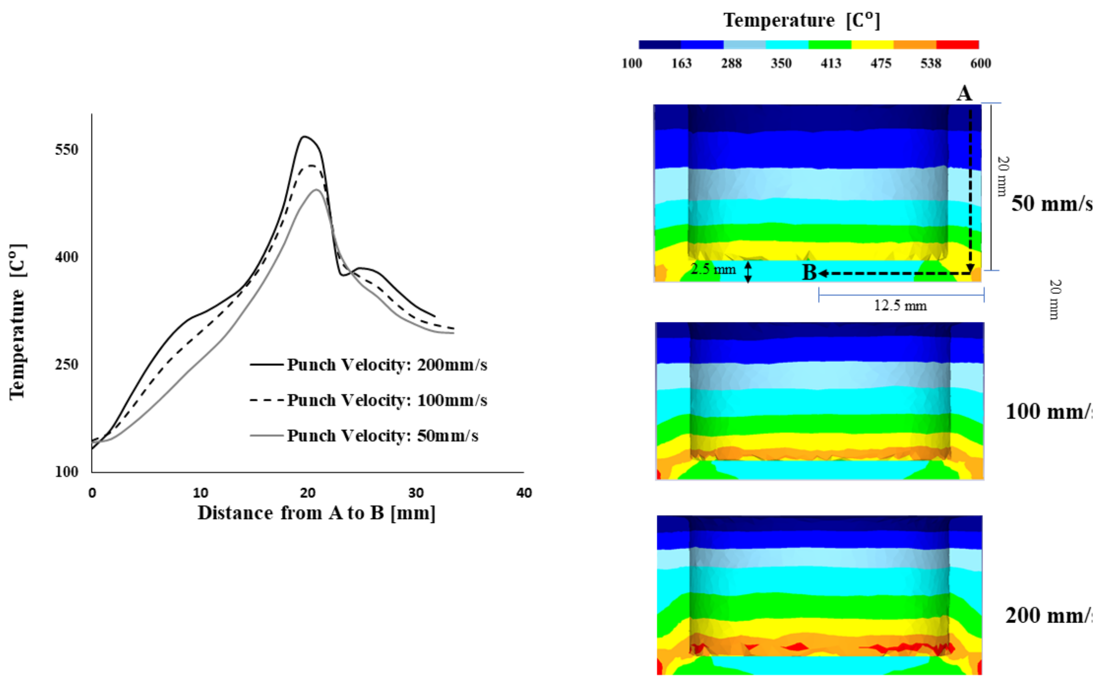

Fig. *7 Influence of punch speed on temperature of extruded profile*

Conclusions

The paper focuses on the calibration of constitutive parameters for raw materials obtained from aluminium chips within a novel process chain rooted in solid-state recycling operations. Cylindrical billets, resulting from friction stir consolidation, have been tested in compressive conditions and investigated with respected of processing conditions to obtain ultra-fined grained materials through sever plastic deformation processes. The description of the microstructural distribution has been described in previous studies [7]. The microstructure of the bottom part remained unaltered during the FSC process. Moving toward the top part of the billet, changes in microstructure (grain growth) and the improvement in billet quality (disappearance of defects) were noticed. Numerical models for the extrusion operation have been developed to assess the main process parameters, with particular regard to temperature since it might have a relevant influence on the microstructure of subsequent operations.

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