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Feasibility Study of Solid-State Recycling through Direct Hot Rolling of AA5754 Aluminum Chips for Automotive Applications

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Abstract. Recently, researchers have done a lot of efforts to develop new solid-state recycling processes, both experimentally and developing numerical models. This kind of process is energy-saving and environmentally friendly compared to the conventional aluminum recycling process because it avoids the melting step. The purpose of this study is to assess the feasibility of an innovative solid-state recycling process using direct hot rolling in a non-heat-treatable aluminum alloy for automotive applications. The chips made of AA5754 have been produced by turning a bar without the usage of lubricants and compacted with a 150 kN load; the compacted billets were treated at 400°C and directly hot rolled in several successive passes. Rolled samples are then analyzed in terms of Vickers microhardness and microstructure in both as-rolled and heat treatment conditions, this last was performed at 185°C simulating the process of paint-bake. The produced sheets exhibit an excellent consolidation and bonding between chips.

Introduction

The automotive industry is globally recognized for its technological advancement and innovation. Modified or newly designed aluminum alloys are being proposed as specific solutions, due to increasing economic and political pressure to reduce fuel consumption and CO_2 emissions, there has been a significant increase in efforts towards lightweight construction in automobiles [1]. Specifically, sheet applications for new lightweight structural parts and body-in-white construction are those of main interest. Major producers of semi-finished aluminum alloy products are making significant efforts to meet the primary requirements, which include sufficient strength, good formability, joining, high corrosion resistance, recyclability, and low material and fabricating costs [2]. The demand for aluminum in finished products has risen dramatically by 30 times since 1950, currently reaching 45 million tons per year. Experts forecast that this trend will persist, with demand expected to increase by 2-3 times the current levels by the year 2050. However, the production of aluminum accounts for 3.5% of the world's electricity usage and contributes to 1% of global CO_2 emissions. Meeting the target of reducing emissions by 50% by 2050 while accommodating the growing demand for aluminum will require a significant reduction of at least 75% in CO_2 emissions per ton of aluminum produced, which poses a daunting challenge [3]. The primary industry of aluminum presents a significant environmental challenge due to the high level of energy consumption and emissions associated with the Bayer and Hall-Héroult processes, mining exploitation and waste release, in particular red mud [4–6]. Secondary aluminum metallurgy is a well-established and widely used methodology that can significantly reduce the environmental impact of primary aluminum production, requiring only 5% of the total energy and reducing CO_2 emissions by 90% [7]. Recent estimates suggest that the quantity of recyclable aluminum will increase by more than double by 2050 [8]. Accordingly, in these years it has been studied how to recycle aluminum scrap, including both post-consumer and new scrap from working processes. To achieve further energy savings and optimize the recycling process, solid-state recycling (SSR) techniques have been proposed such as friction stir extrusion (FSE), friction stir consolidation (FSC), equal channel angular pressing (ECAP), and other severe plastic deformation processes (SPD) [9–11]. FSE is still in its early development stage due to a lack of literature on the subject and industrial competitiveness issues. Tang et al. [12] used FSE to create defect-free wires of aluminum AA2050 and AA2195 from machining chips, and they observed that the wires displayed a favorable combination of microhardness and bend ductility. El Mehtedi et al. [13,14] studied the feasibility of FSE process to produce defect-free wires of pure AA1090 and AA1099 aluminum chips. Other researchers studied FSE process of pure magnesium and AZ31 chips [15,16]. Baffari et al. [17] designed a prototype of a continuous FSE machine to make the process continuous. Other studies focus their attention on energy efficiency characterization to recycle aluminum alloy scraps by FSE [18,19]. FSC is a process similar to FSE with the exception of the die that doesn't have an extrusion channel. According to previous research papers concerned with solid-state recycling process, it allows obtaining energy saving with respect to the conventional remelting-based route [20] and mechanical properties comparable to the base material [21]. SPD is a commonly utilized method for creating materials with a fine-grained structure that enhances strength and fracture toughness [22]. ECAP is one of the common processes commonly used for SSR: there are only a few research papers that examine the combination of extrusion and ECAP process. Ying et al. [23] proved that the ECAP process led to a refinement in crystal grain size in the recycled specimens, and to an improvement in bonding thanks to the combination with hot extrusion. Also, Krolo et al. studied the effect of direct hot extrusion and ECAP at different temperatures to investigate the microhardness, electrical conductivity, and mechanical properties of recycled samples [24,25]. Hasse et al. [26,27] integrated an ECAP die into a conventional hot extrusion process to produce superior SSR samples.

Miscellaneous methods that include rolling have been investigated by few authors. Suzuki et al. [28] employed hot rolling as the second step in the SSR process after extruding chips, while Chiba et al. [29] investigated the possibility of recycling chips through cold extrusion followed by cold rolling.

In another study, Allwood et al. [30] investigated the potential of cold bonding through forging, rolling, or extrusion processes, performed independently. Their results showed that bonding could occur with sufficient strain, but some voids may remain.

To the authors' best knowledge, this should be the first paper to propose a new technique that involves only direct hot rolling of compacted chips of AA5754, without any preceding processes. Rolling was chosen as a promising method since it represents one of the main working processes and it is used in the production of many automotive components. This paper aims to achieve two main objectives. The first objective is to investigate the microstructure of the recycled samples, and on the other hand, to analyze the microhardness of the AA5754 alloy before and after a heat treatment that simulates the paint-bake process, which is commonly used in the automotive industry.

Experimental Procedures

The chips were produced by turning a bar of AA5754 aluminum alloy without the use of lubricants. The nominal chemical composition of the studied alloy is reported in Table 1.

Table 1. Chemical composition of the alloy.

	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
Elements (wt.%)	<0.40	<0.40	<0.10	<0.50	2,90	<0.20	<0.15	<0.30	bal.

Afterward, the chips were cold compacted in a circular mold with a force of 150 kN and then underwent a two-hour heat treatment at 400°C in a muffle furnace. The resulting discs have a diameter of 40 mm and a thickness of 9 mm. Subsequently, the compacted chips were hot rolled (HR) at 400°C for 6 passes, without the use of lubricants. The rolling machine is a two-high-rolling mill “BW200”, manufactured by Carl Wezel, characterized by a 130 mm roll diameter and a constant rotational speed of 52 rpm. A schematic overview of the process is reported in Fig.1. The specimen returns to the furnace for 10 minutes after each pass to restore the initial temperature. The final thickness is achieved through a last cold rolling (CR) pass. A detailed breakdown of all the rolling passes is provided in Table 2.

Fig. 1. Schematic overview of the process.

Afterwards, the jagged borders of the samples were cut, and some samples underwent heat treatment (HT) at 185°C for 20 minutes to simulate the paint-baking process applied in the automotive industry. The temperature was measured on the surface of the samples using a K thermocouple-type and a Portable Digital Thermometer, TASI-8620.

Table 2. Detailed rolling schedules.

	HR passes						CR
Pass number	1	2	3	4	5	6	7
Thickness (mm)	9	5	4	2.5	1.75	1.25	0.8
True strain		0.6	0.2	0.5	0.4	0.3	0.4

Vickers Microhardness was assessed under two conditions: as rolled and after heat treatment (HT), using a Shimadzu Microhardness Tester, type M, with a load of 200 gf. A minimum of six measurements were taken for each condition after grinding the surface of every sample with 2500-grit paper. Hardness was measured in both the cross-section and the rolling direction section of all samples, as well as on the surface of each sample. Micrographs were carried out for both conditions, as rolled and after HT, under polarized light using a light microscope (Olympus BX53M) equipped with an Olympus UC90 camera. To reveal the grain microstructure, the samples were electropolished with H_3PO_4 at 75°C and then etched with Barker’s reagent at 15 volts for 30s.

Results and Discussions

Fig. 2 shows the produced samples starting from the compacted chips, after hot rolling, and after cold rolling. Vickers microhardness has been measured in the as-rolled sample, and on the same sample after the heat treatment at 185°C that simulates the paint bake. The measurements were performed on the same sample for each condition to reduce the variability of the measurements, as the process itself is highly variable depending on the original recycled material. Nevertheless, for each condition, there is a lot of variability in the values of the microhardness as is possible to see in Table 3. The HV_{200} mean value on the cross-section is around 80 HV while it’s higher in the rolling direction (RD) with 88 HV. On the surface, the hardness is considerably high reaching 104 HV_{200}. The increase in hardness is affected by the oxide present on the surface and by the strengthening effect due to the roll friction effects, which lead to a greater hardness near the surface rather than in the middle of the sheet’s thickness. After heat treatment, the hardness decreases in all zones except for the cross-section where the mean value stays constant as shown in Fig. 3.

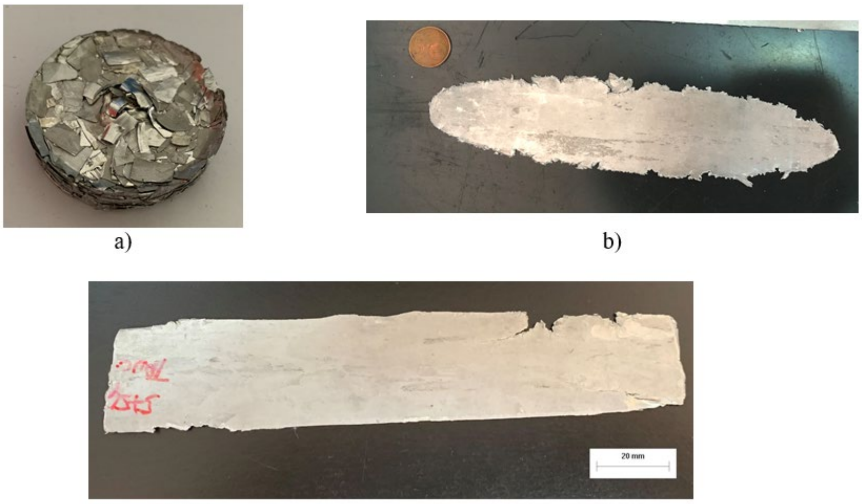


Fig. 2. a) Compacted chips before recycling, b) sample after 4 passes hot rolling, c) sheet after cold rolling.

In Figs. 4 and 5, it is possible to observe the microstructures of the recycled sheet samples. The length of the markers in the figures is represented by the entire length of the white box. They appear like a very layered microstructure due to the characteristic of the original material and oriented along the rolling direction. The recrystallization of the grains could be stacked by the presence of oxide around the original chips. It is characterized by higher elongated grains in the RD with respect to the cross-section. The heat treatment appears to not affect the shape of the grains. Each layer is separated and adorned by the oxide that is present on the surface of the original chips. It is shown by several authors that bonding occurs between chips if the oxide layer is broken during plastic deformation. For example, Suzuki et al. [28] have increased the bonding between chips after extrusion, with the usage of differential speed rolling, increasing also the mechanical properties and the corrosion resistance.

Table 3. HV_{200} measured on different zones of the sample, and in different conditions.

	HV_{200} of recycled-chips			HV_{200} of recycled-chips after HT		
	CROSS	RD	SURF	CROSS	RD	SURF
Mean	79.2	88.2	104.2	79.2	85.0	97.6
St. dev.	5.6	6.5	4.8	3.6	7.7	5.1

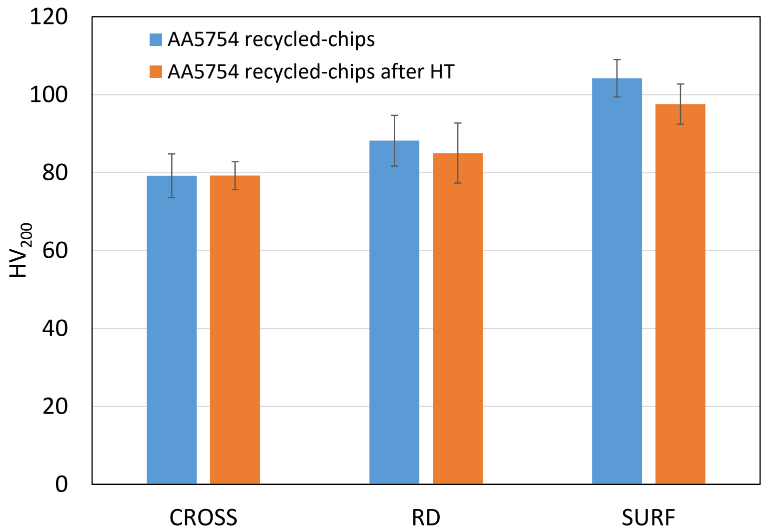
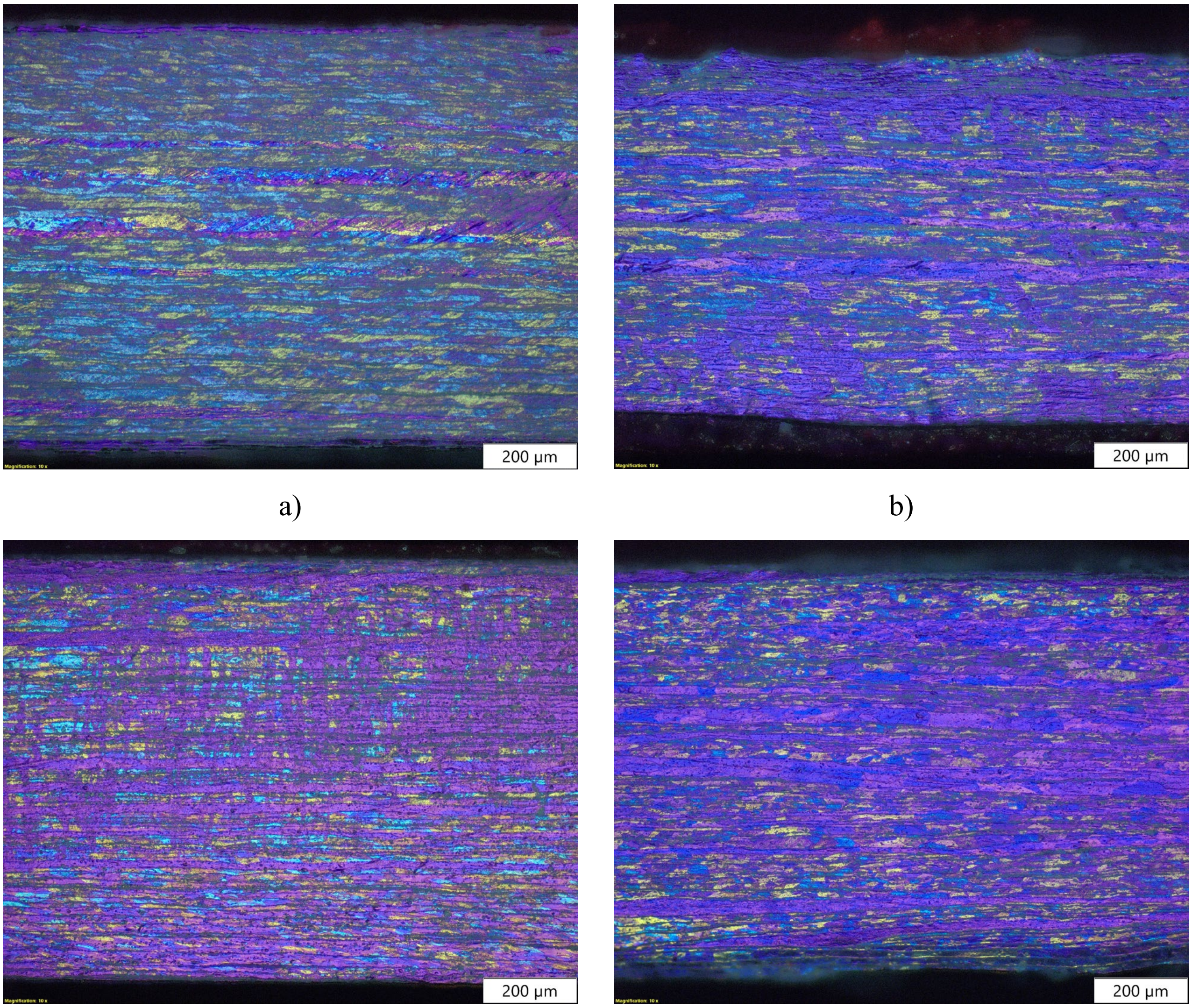


Fig. 3. Vickers microhardness (HV_{200}) measured on samples.



a) b)

c) d)

Fig. 4. Optical micrograph of the samples, a) Recycled chips in the RD, b) recycled chips in the RD after HT; c) Recycled chips in the cross section; d) Recycled chips in the cross section after HT.

According to Zhang et al. [31], the oxide layers inhibit the recrystallization of the α-Al grains during the recycling process in AA6061 alloy, resulting in a different microstructure in the recycled samples. Consequently, lower mechanical properties are obtained in the recycled samples, which are also attributed to the lack of Mg from the original composition of the alloy caused by the oxidation reaction.

The mechanical properties of the recycled sheets, in terms of microhardness, are comparable to those obtained by the combination of heat treatment, friction stir welded, and cold rolled sheets [32]. Thus, this indicates the excellent bonding of the chips after the direct hot-rolling process demonstrated in this study.

In Fig. 6, it is possible to observe the oxide layer that separates each layer. It is broken into numerous parts, meaning that bonding occurs. Moreover, with higher magnification, it is not possible to see any difference among the as-rolled condition and after the heat treatment.

Chino et al. [33] used a 1600:1 extrusion ratio to achieve a uniform dispersion of oxide layers around the chips, which ideally translates to a real strain of 7.4. In rolling processes, high deformation is not typically undergone; the maximum deformation experienced in this case, according to the rolling schedule in Table 2, has been 0.6 during the initial rolling pass, leading to a total real strain of 2.4 from the initial thickness to the final pass. However, it is noticeable that the oxide layer around the chips has broken at several points, revealing some continuity in the matrix of the aluminum alloy.

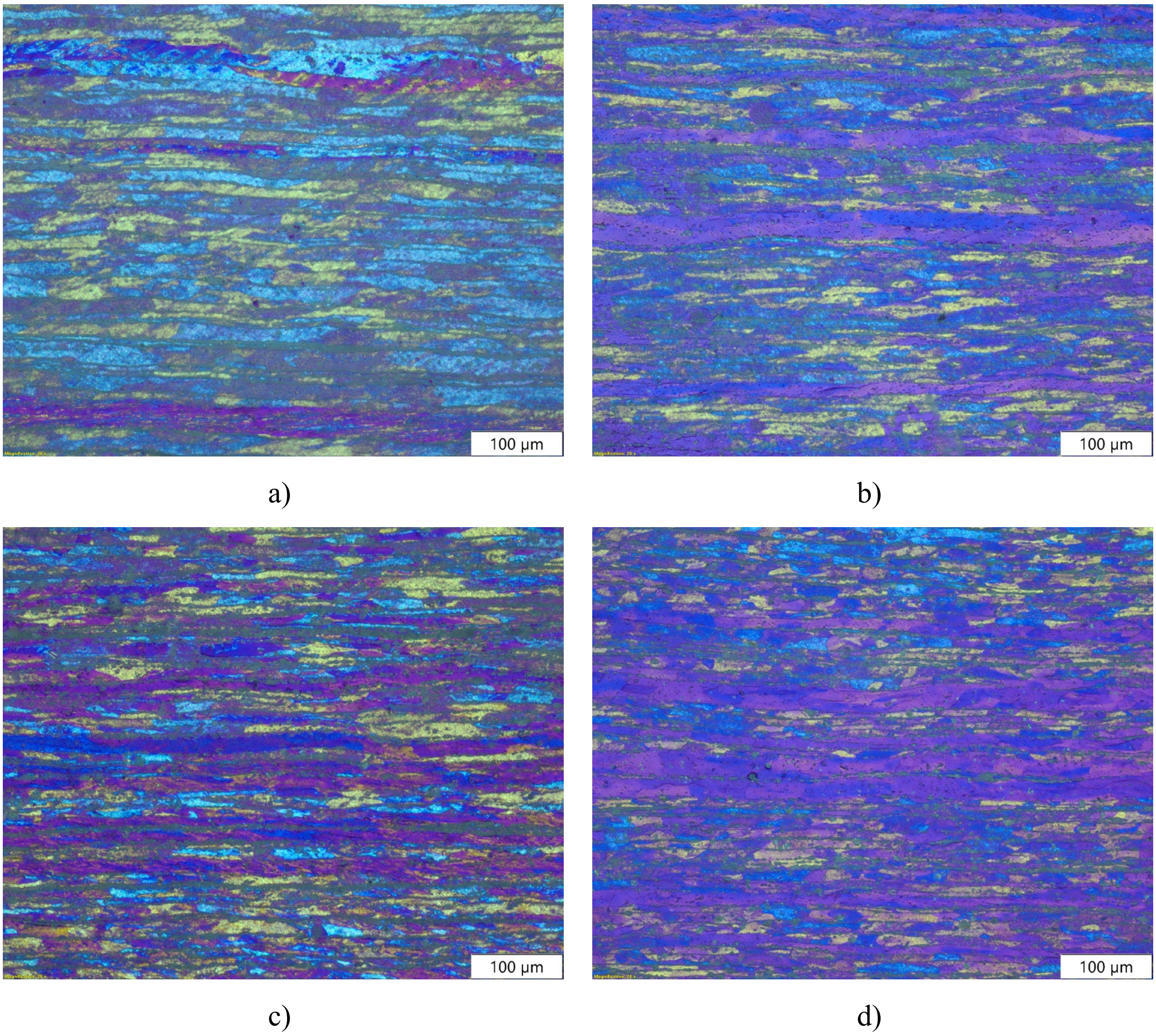
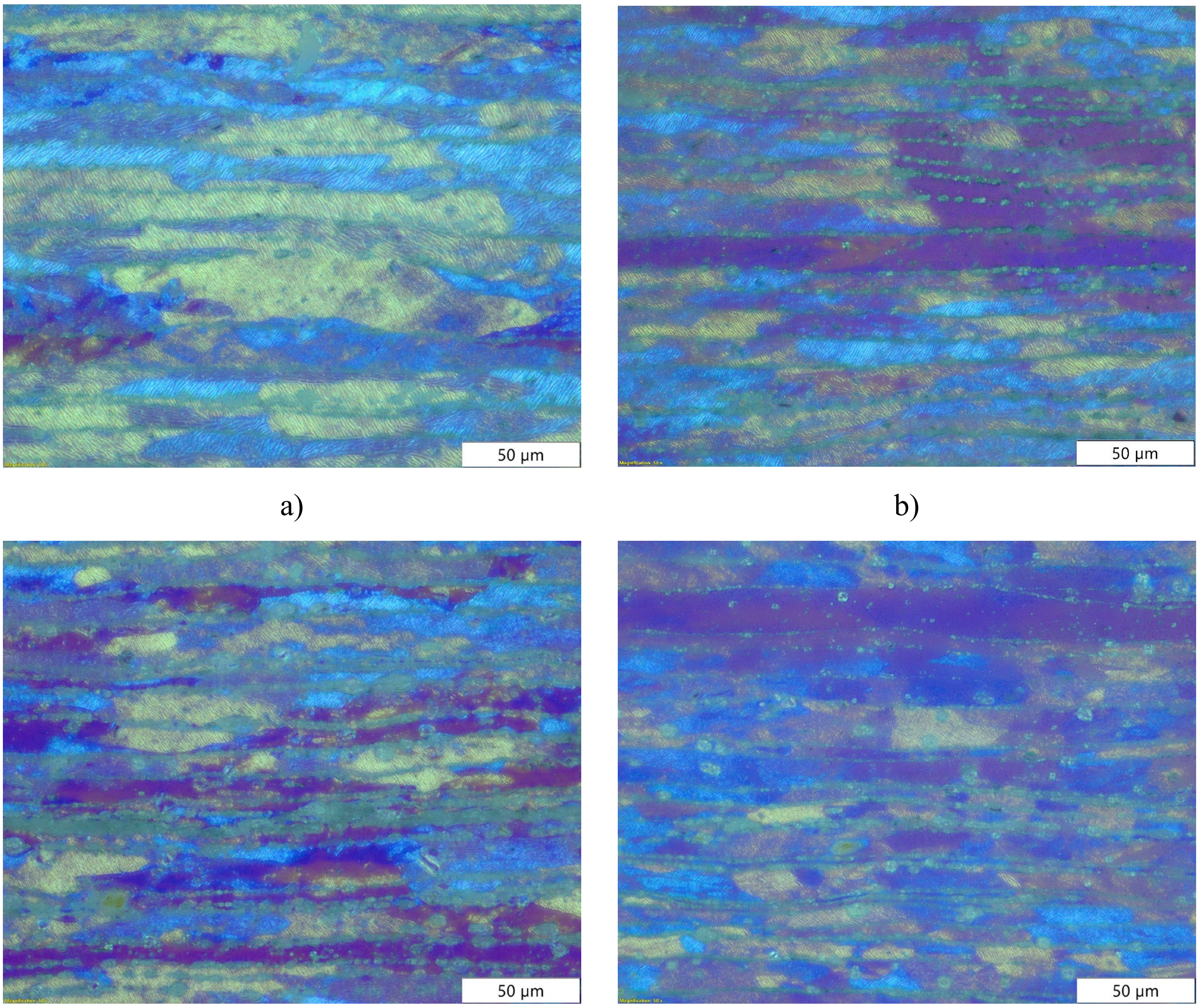


Fig. 5. Optical micrograph of the samples, a) Recycled chips in the RD, b) recycled chips in the RD after HT; c) Recycled chips in the cross section; d) Recycled chips in the cross section after HT.



a) b)

c) d)

Fig. 6. Optical micrograph of the samples, a) Recycled chips in the RD, b) recycled chips in the RD after HT; c) Recycled chips in the cross section; d) Recycled chips in the cross section after HT.

Conclusions

Solid-state recycling processes have been receiving considerable attention from researchers due to their energy-saving and environmentally friendly attributes. This study aimed to evaluate the feasibility of a new solid-state recycling process involving direct hot rolling of AA5754 chips, a commonly used alloy in automotive applications. The results demonstrate the successful transformation of chips into rolled sheets.

To summarize, the results presented in this paper indicate that:

- recycling methods employing direct hot rolling produce jagged edges that require refiling, resulting in the generation of scraps that need further recycling; hence, additional research is necessary to optimize the process and minimize waste;
- microstructures show different textures compared to typical 5xxx aluminum sheets in the as-rolled condition; chips-recycled samples display a layered microstructure, with oxide seeming to separate each layer. At higher magnification, the oxide layer appears broken at various points, indicating excellent bonding between chips.
- microhardness measurements conducted across different zones of the sample, both in the as-rolled condition and after simulating the paint bake process via heat treatment, demonstrate

slight variability along the sheets' sections. The Surface and rolling direction exhibit higher hardness, while the cross-section displays lower values;
- microhardness decreases after heat treatment on the surface and in the rolling direction of the sample but remains constant in the cross-section.

In conclusion, this innovative recycling process shows promising potential, though this is just a first study. Subsequent studies will involve SEM analysis.

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