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Sustainability Study of a New Solid-State Aluminum Chips Recycling Process: A Life Cycle Assessment Approach

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Abstract: Nowadays, reducing greenhouse gas emissions in all human activities has become crucial. This article presents a life cycle assessment (LCA) investigation conducted to evaluate the environmental benefits of a newly developed solid-state recycling process for aluminum chips, involving two steps: direct rolling and accumulative roll bonding. A comparison was made between this process and two current industrial methods of recycling aluminum scraps to obtain wrought products, which involve melting, casting, and subsequent rolling. The LCA analysis considered a scenario where 50% of the total electric requirement was met by photovoltaic energy. The results of the study indicate that in all examined impact categories, direct rolling has a lower environmental footprint compared to both traditional recycling and twin-roll cast technology. These results suggest that this new solid-state recycling procedure has significant potential to replace environmentally harmful melting processes.

Keywords: solid state recycling; life cycle assessment; direct rolling; accumulative roll bonding; aluminum chips; circular economy

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1. Introduction

Aluminum is widely utilized across various industries, including transportation, construction, packaging, and electronics, due to its exceptional properties, such as strength, durability, conductivity, and lightweight nature [1]. The demand for aluminum in finished products has increased significantly over time, experiencing a 30-fold rise since 1950 and currently reaching an annual demand of 45 million tons. Experts predict that this upward trend will persist, estimating a 2–3 times increase in demand by 2050. However, achieving the target of reducing emissions by 50% by 2050 while meeting the growing demand for aluminum presents a formidable challenge [2], necessitating a reduction of at least 75% in production emissions [3].

The production of aluminum is energy-intensive and contributes to greenhouse gas emissions, thereby exacerbating climate change and environmental degradation. To address these negative impacts, aluminum recycling has emerged as a crucial solution. By exploring the recycling process, its associated benefits, and its role in reducing energy consumption and carbon emissions, we can gain a deeper understanding of how aluminum recycling contributes to environmental conservation and the establishment of a circular economy.

Aluminum recycling is vital for addressing the environmental challenges posed by primary aluminum production. The extraction of aluminum from bauxite ore involves energy-intensive processes, like the Bayer and Hall–Héroult processes, which lead to significant carbon dioxide emissions. Primary aluminum production alone is estimated to contribute around 1% of global greenhouse gas emissions [4]. Additionally, bauxite mining contributes to deforestation, biodiversity loss, and disruption of local ecosystems.

By contrast, aluminum recycling offers a sustainable alternative that greatly reduces the environmental impact associated with primary production. Recycling aluminum can save up to 95% [5] of the energy required for producing aluminum from raw materials, resulting in greenhouse gas emissions of just 5% compared to the primary process [6]. For example, primary production consumes approximately 45 kWh/kg and emits about 12 kg CO_2/kg, whereas secondary production through remelting of aluminum scrap consumes only 2.8 kWh/kg and generates emissions of approximately 0.6 kg CO_2/kg [7]. Recent estimates indicate that the amount of recyclable aluminum will double by 2050 [8]. Aluminum recycling offers environmental benefits beyond energy and emissions reduction. It also helps conserve water, as the recycling process requires significantly less water compared to primary production. Furthermore, recycling minimizes waste generation and reduces the need for landfill space, as aluminum products can be collected, sorted, and transformed into new items instead of being discarded. To further enhance the energy demand and emissions associated with the aluminum recycling process, researchers have explored innovative methods, such as solid-state recycling processes (SSR). These processes, which eliminate the melting stage, can reduce energy demand by 90% compared to conventional recycling processes [9]. While various processes exist, they typically involve certain steps, like comminution, cleaning, drying, cold chip compaction, and subsequent plastic deformation, depending on the specific process [10]. Examples of such processes include direct extrusion, friction stir extrusion (FSE), friction stir consolidation (FSC), equal channel angular pressing (ECAP), and other severe plastic deformation processes (SPD) [11–15].

There is limited availability of life cycle assessment (LCA) analysis for SSR. Only a few articles exist in the literature that focus on the environmental impact of processes, such as ECAP, FSE, and FSC. These studies mainly related to the extrusion or forging processes for the production billets, wires, and disks [16–19]. There is a noticeable lack of knowledge and research when it comes to solid state recycling for producing sheets for metal forming.

This article aimed to investigate the environmental impact of a new aluminum chip recycling technique, for aluminum sheet production, through an LCA analysis, namely DR + ARB (direct rolling and accumulative roll bonding). The technique involves two steps: direct hot rolling (DR) of cold compacted chips to produce the mother sheet, and accumulative roll bonding (ARB). The aim is to demonstrate the capability of this process in meeting the aluminum industry's waste reduction and energy consumption goals while exploring eco-friendly methods for aluminum scrap processing and recycling. Additionally, the study assesses the impact of DR + ARB on various categories, such as global warming potential, ozone formation, human health, terrestrial ecotoxicity, and water consumption. A comparison between traditional recycling methods (based on melting process) and secondary metallurgy is also conducted. Overall, this research contributes to the advancement of sustainable practices in the aluminum industry and the development of environmentally friendly recycling approaches.

This paper is organized as follows: DR and ARB processes are presented in Section 2. Section 3 contains and discusses the LCA analysis. Finally, Section 4 concludes the research.

2. DR and ARB Process

The process of direct hot rolling DR and accumulative roll bonding ARB to recycle aluminum is a novel process that was studied for the first time by the present authors on a laboratory scale. The process is tested on AA6063 aluminum alloy. In accordance with the standard specification ASTM B221, the AA6063 is an Al-Mg-Si heat treatable aluminum alloy.

The chips were produced by milling a billet of AA6063, manufactured by hydro spa, without the use of any lubricants to avoid contamination. Afterwards, 35 g of AA6063 compacted chips were directly hot rolled at 550 °C with seven rolling passes. The rolling parameters, in terms of temperature and reduction rate, were chosen based on a previous study [20]. Starting from a thickness of 10.5 mm for the compacted chips, the objective was to obtain a final flat sheet with a thickness of 1.5 mm, which is typically used in automotive applications. Subsequently, two ARB cycles were applied to improve the mechanical properties, specifically the ultimate tensile strength and the elongation at break.

The process scheme is illustrated in Figure 1. The ARB process, initially studied by Saito et al. [21] in 1998, is a relatively new technique aimed at producing an ultra-fine grain microstructure through severe plastic deformation (SPD). In this process, a sheet is cut in half lengthwise to obtain two strips, which are then surface polished, such as through wire brushing. The polished strips are stacked together and hot rolled down to 50% of their original thicknesses. The resulting sheet maintains the same thickness as the original sheet. This cycle is repeated multiple times. The purpose of this paper is to evaluate the environmental impact of the DR + ARB process compared to two traditional industrial processes of remelting of aluminum scraps using a life cycle assessment (LCA) approach. Therefore, no discussion about the mechanical properties will be presented in this paper.

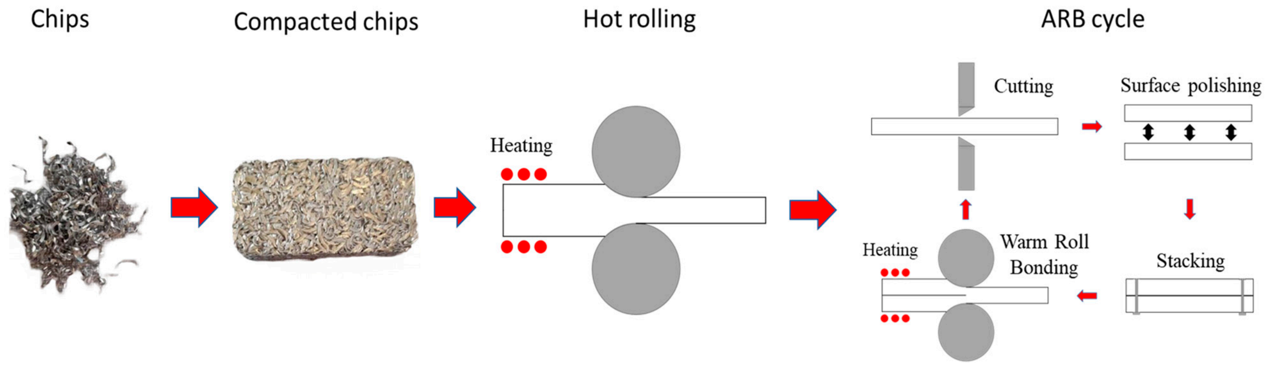

Figure 1. Schematic representation of the process (source: authors' elaboration).

3. LCA Analysis

In the first part of this section (Section 3.1), the impact of the new SSR process is analyzed using a gate-to-gate LCA analysis. In the second part (Section 3.2), the SSR process is compared with two of the main aluminum recycling industrial processes for sheet production, namely traditional recycling and the twin roll cast processes.

3.1. LCA of Direct Hot Rolling as the SSR Process

This section describes the process of conducting a LCA for DR + ARB as a solid-state recycling method for aluminum chips in the present workpaper. It begins with an explanation of the parameters and settings used in the SimaPro® 9.4 software. Subsequently, the following paragraphs will outline the assumptions, methods, and databases utilized in this analysis. The LCA can be divided into four interconnected phases, as follows:

- Goal and scope definition.
- Life cycle inventory (LCI) analysis.
- Life cycle impact assessment (LCIA).
- Interpretation of results.

3.1.1. Goal and Scope Definition

In this step, the approach to be pursued is established, and all life cycle phases of the studied process are identified. The functional unit serves as the reference for all assessments conducted, and both input and output data are normalized based on this unit. The selection and identification of impact categories should align with the established objectives and represent the comprehensive global effects of the studied system on the environment. The aim of performed LCA is to investigate the environmental impact, in terms of CO_2 emissions and global warming potential, of direct rolling and ARB as a new SSR technique applied to aluminum chip recycling. The goal is to demonstrate the viability and suitability of this process in accordance with the needs of the aluminum industry, which include waste reduction, energy saving, and the development of environmentally friendly methods for recycling aluminum scrap. The reported LCA focuses on the production of an aluminum sheet through a rolling procedure starting from a 35 g sample of chips. This analysis follows a gate-to-gate approach, where collected chips obtained from prior machining processes are cold pressed and subsequently hot rolled to achieve the desired final product (Figure 2). The functional unit in this process refers to the aluminum sheet produced through different steps (Figure 1). Initially, 35 g of aluminum chips derived from the machining processes, such as milling, drilling, and turning are pressed at room temperature to create a compact filleted rectangular sample. Once the cold compaction is completed, the resulting sample undergoes hot rolling at a temperature of 550 °C. This process transforms the compacted chip sample into a sheet with a thickness of 1.5 mm. To further enhance the mechanical properties of the sheet, an additional step called accumulative roll bonding is performed. This bonding process takes place at 450 °C and is carried out in two separate passes.

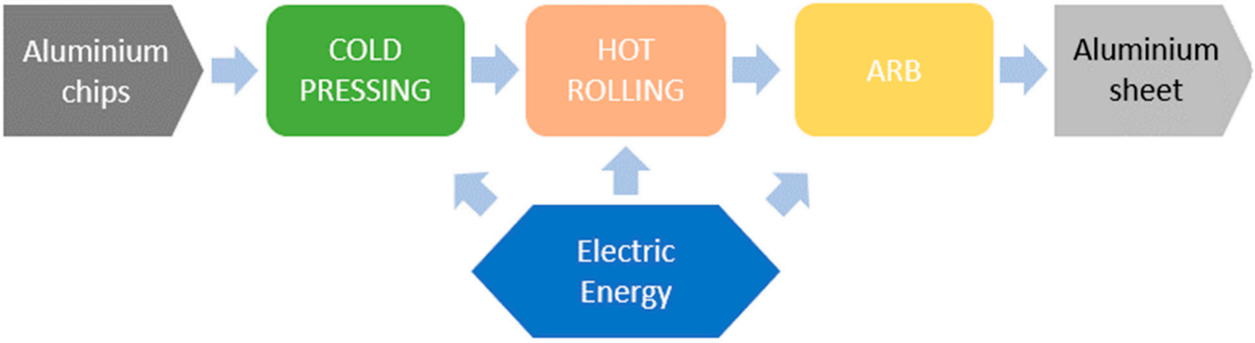

Figure 2. Schematic diagram of the SSR process analyzed in this study (source: authors' elaboration).

Based on the conducted experimental study and to the obtained results, the reported procedure demonstrates the ability to achieve of the best mechanical properties, specifically in terms of ultimate tensile strength (UTS) and percentage elongation at break, for the recycled chip samples subjected to the rolling process. It is worth noting that chip treatment, including annealing or cleaning, may be required before the pressing step to remove any lubricant or oil residues. However, it is important to note that this specific step was not considered within the scope of this study, as it is a common requirement for various chip recycling processes.

3.1.2. LCI

The life cycle inventory (LCI) step is crucial for defining the material and energy flows within the different unit processes of the system. The inventory data used in this study were calculated according to both primary and secondary data sources. Primary data were obtained from direct measurements provided by an industry plant operating in an aluminum production field sited in the center of Italy, as well as measurements taken during the experimental activities in the laboratory. Secondary data were provided from studies available in the literature and databases available in the SimaPro® software. During life cycle inventory analysis, the quantities of materials and energy required as inputs or flows for the selected process are determined. The main steps of the DR process include the tooling phase, which involves the production of the steel die used for compacting the material, the raw materials phase, which encompasses the collection and preparation of aluminum chips, and the manufacturing phase, which follows the sequence of processes necessary to produce the desired functional unit.

The impact of manufacturing machines, such as hydraulic press and rolling mills, is considered negligible, as their service lives significantly exceed the temporal boundaries of the production of the functional unit [22].

For the LCI analysis, it was necessary to divide the system into unit processes and quantify the corresponding flows of inputs and outputs. The first process considered is cold pressing, which is performed using a hydraulic press. The input flows for this process are aluminum chips and electricity to power supply the press, while the output is a compacted sample the same as the ones produced in the reported experimental part.

The manufacturing of the steel die for pressing was also included in this process, requiring additional inputs, such as electricity to power the milling machine. Additionally, steel scrap is generated as a solid residue of the process. The energy required for cold pressing was evaluated by considering the applied pressure (p) and the contact surface area (A) of the aluminum chips during the compaction process, using the following relationship:

$$E_{press} = pA\delta\frac{1}{\eta} \quad (1)$$

where δ is the total thickness reduction during pressing and η is the electro-mechanical efficiency.

The production of the steel die used for cold pressing was also considered. The electric consumption was estimated according to the results of Priarone et al. [23]. The amount of steel chips produced as solid waste from milling was calculated according to geometrical considerations. The reference dataset for electricity was electricity, high voltage, IT, and APOS S, and for steel chip waste the dataset was scrap steel (Europe without Switzerland), market for scrap steel, and APOS S.

The second process is direct rolling (hot rolling), which is performed by preheating the sample for 10 min at a selected temperature of 550 °C. The compacted sample produced in the previous process serves as one input for this process. The second input is the electric energy required for the rolling mill, measured in the referenced industrial plant. Additionally, thermal energy for heating the samples at 550 °C is needed. In this analysis, the scenario assumes the use of a muffle furnace that requires electrical energy from the electrical grid. Another input is water for cooling during the hot rolling procedure, estimated according to [24]. The only output of this process should be the hot rolled sheet. However, a metal loss of 10% was considered during the hot rolling process, and it was reported as solid waste in the outputs. The quantity of electrical energy required to heat the aluminum compacted sample to 550 °C was estimated according to the industrial procedure and primary data. The reference dataset for electricity consumption is electricity, high voltage, IT, and APOS S, while for cooling water, the dataset of water, cooling, unspecified natural origin, and IT was selected.

The last process is accumulative roll bonding, performed after preheating the stacked sheets at 450 °C for 10 min. The experimental procedures are reported in [25]. The material input for this process is the hot rolled sheet produced in the previous step. Another input required for this process is the electrical energy needed for preheating, both in the muffle furnace and for the rolling mill. The calculated values for energy consumption come from the same sources used for the previous process, hot rolling, which includes direct measurement in the industrial plant of roll engines and the thermal energy required for heating the material. The product of this process is the functional unit, reported as the 31.5 g aluminum sheet with a thickness of 1.6 mm, obtained after two ARB cycles. The energy consumption of cutting and brushing operations is neglected in this analysis. The reference dataset for electricity consumption is electricity, high voltage, IT, and APOS S. Input and output flows are reported in Table 1.

Table 1. Input and output flows of DR + ARB process (source: authors' elaboration).

Cold Pressing			**DR**			**ARB**		
INPUTS	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**
Chips	35	g	Compacted chips	35	g	HR sheet	31.5	G
Electric energy (press)	0.0017	MJ	Electric energy (heat)	0.032	MJ	Electric energy (heat)	0.023	MJ
Electric energy (milling)	0.006	MJ	Electric energy (roll)	0.018	MJ	Electric energy (roll)	0.005	MJ
			Water (cooling)	4.73×10^{-5}	m^3			
OUTPUTS	Quantity	Unit	OUTPUTS	Quantity	Unit	OUTPUTS	Quantity	Unit
Compacted chips	35	g	HR sheet	31.5	g	ARB sheet	31.5	G
Steel chips	405	g	Aluminum scrap	3.5	g			

3.1.3. LCIA

LCIA is the final operative phase, which consists of choosing the analysis method and representing the most significant results.

In this analysis, the IMPACT 2002+ v2.15 LCIA method was used, and 15 impact categories were selected, including ozone layer depletion, global warming, mineral extraction, aquatic acidification, land occupation, and terrestrial ecotoxicity. Four damage categories were chosen: human health (HH), ecosystem quality (EQ), climate change (CC), and resources (R).

The graph in Figure 3 displays the results for the impact categories. In most of the selected categories, the DR process has the highest environmental impact. When examining the global warming category, the hot rolling process contributes approximately 0.006 kg CO_2 eq. of greenhouse gas emissions. In comparison, the cold pressing process emits approximately 0.004 kg CO_2 eq., while the ARB (accumulative roll bonding) process yields around 0.003 kg CO_2 eq. of emissions. These values highlight the relative differences in carbon dioxide equivalent emissions associated with each of these manufacturing processes. Due to the production of steel scrap during the tooling phase, which is considered as a solid waste released into the environment, cold pressing has the highest impact in terms of terrestrial ecotoxicity and ozone layer depletion.

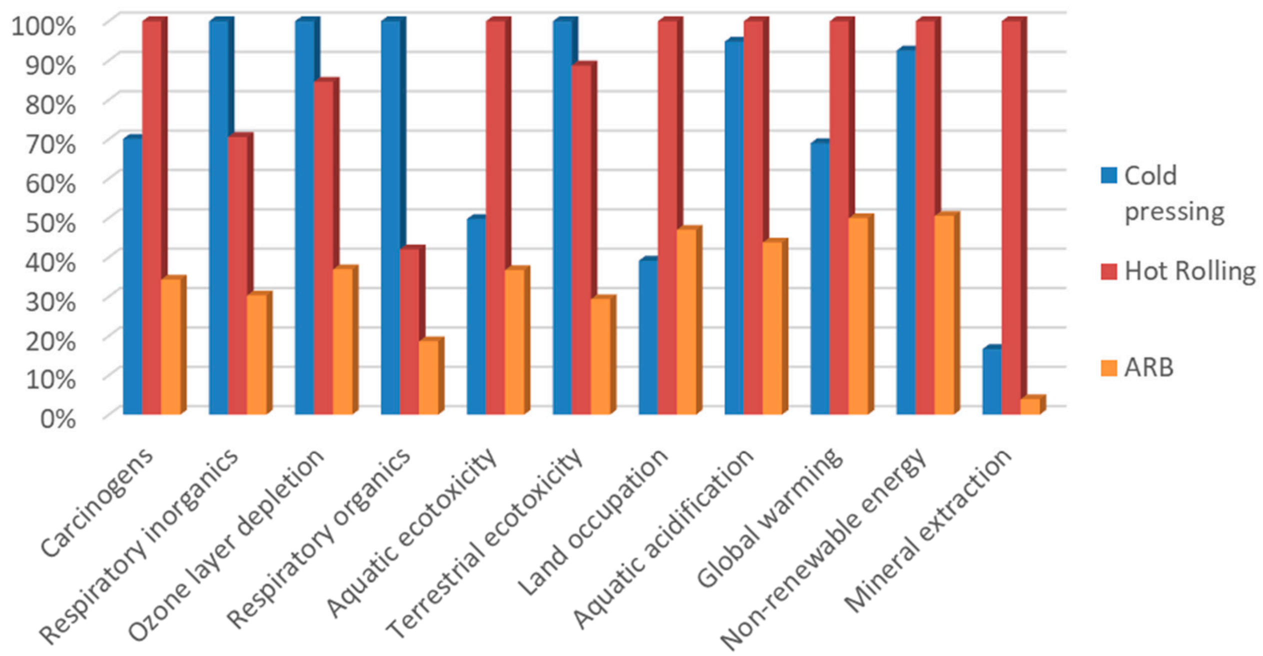

Figure 3. Impact categories analysis for direct rolling process (source: authors' elaboration).

Hot rolling has the highest impact in three of the four damage categories considered in this method (Figure 4).

The high impact of the cold pressing process is related to the generation of steel scrap during the milling operations involved in manufacturing the steel die used for compacting aluminum chips. Considering that the same die, once produced, can be utilized multiple times, this operation can be excluded in the LCIA of the DR process. The results of damage categories, excluding the tooling phase from the cold pressing step, are presented in Figure 5.

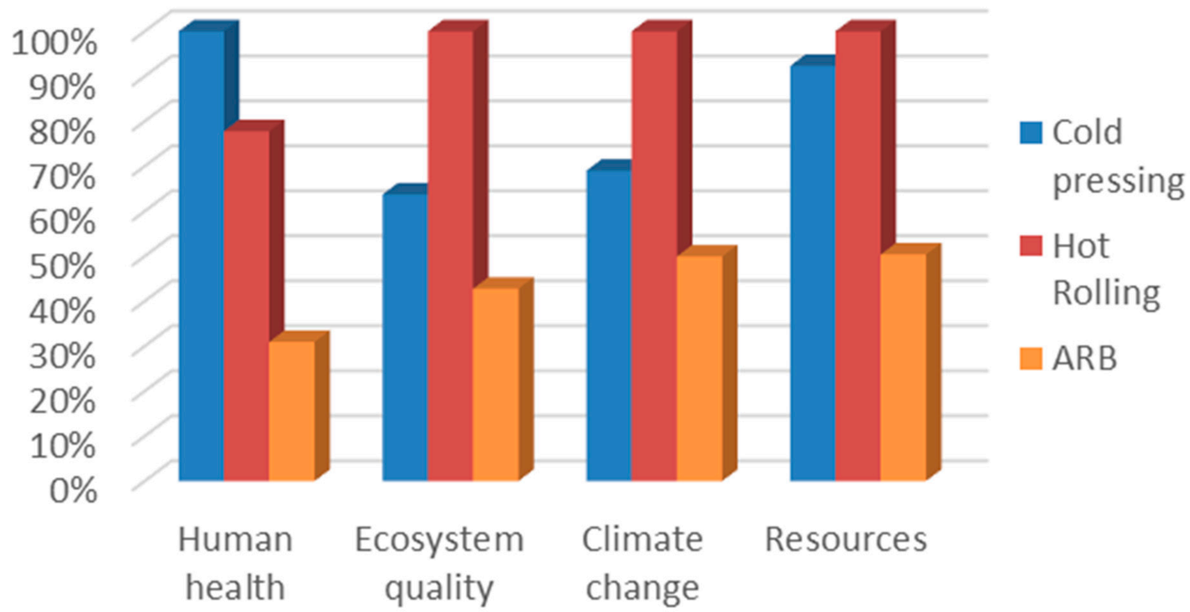

Figure 4. Damage categories analysis for DR + ARB process (source: authors' elaboration).

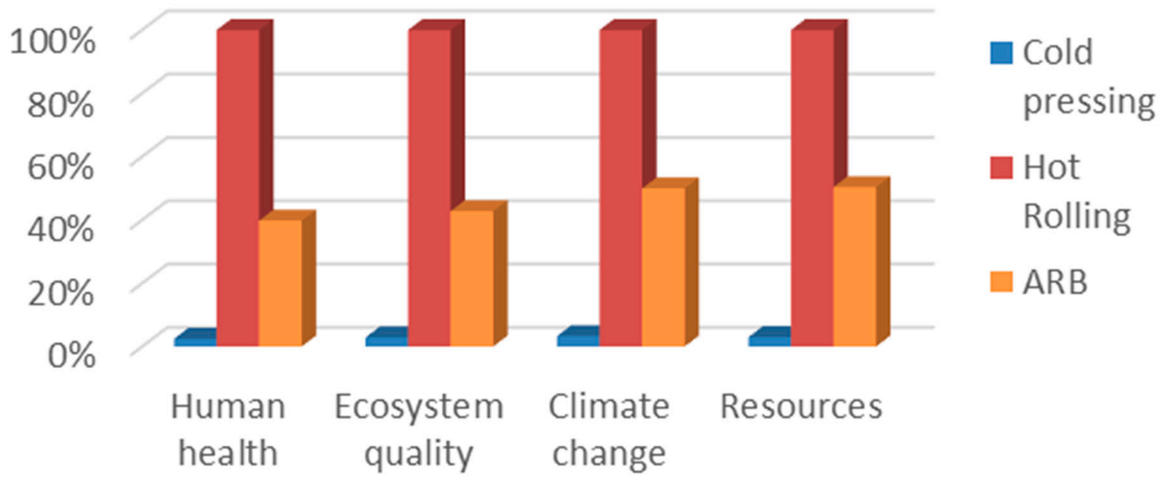

Figure 5. Damage categories without tooling phase (source: authors' elaboration).

3.2. Comparison between SSR and Industrial Remelting Routes

The previously conducted LCA for DR as a solid-state recycling process for aluminum chips was undertaken to enable a comparison with the traditional method of scrap recycling commonly employed by industries. The objective was to evaluate energy consumption and environmental damage considering different impact categories, and to determine if DR as an SSR method can introduce significant benefits over the conventional recycling route.

The conventional aluminum recycling process consists of different operations. It begins with scrap collection, followed by scrap beneficiation, melting, metal refinement and purification, ingot casting, and rolling to the final desired thickness. The melting phase is particularly energy-intensive as it requires reaching the melting temperature of the alloy. Subsequently, the liquid alloy is cast into ingots and undergoes hot rolling to achieve the desired thickness. It is typical for flat sheets to be produced from these large ingots.

An alternative route to cast aluminum alloy is the twin roll casting process, where the liquid is directly cast into sheets measuring 6 or 7 mm in thickness. This procedure eliminates the need for hot rolling, allowing for direct cold rolling of the material. A heat treatment after twin roll casting is sometimes necessary to homogenize the alloys' composition. Figure 6 reported the process diagram for both twin roll casting and the casting of ingots. By comparing these two casting methods, a comprehensive assessment can be conducted to ascertain their respective advantages and drawbacks in terms of energy consumption, environmental impact, and overall sustainability.

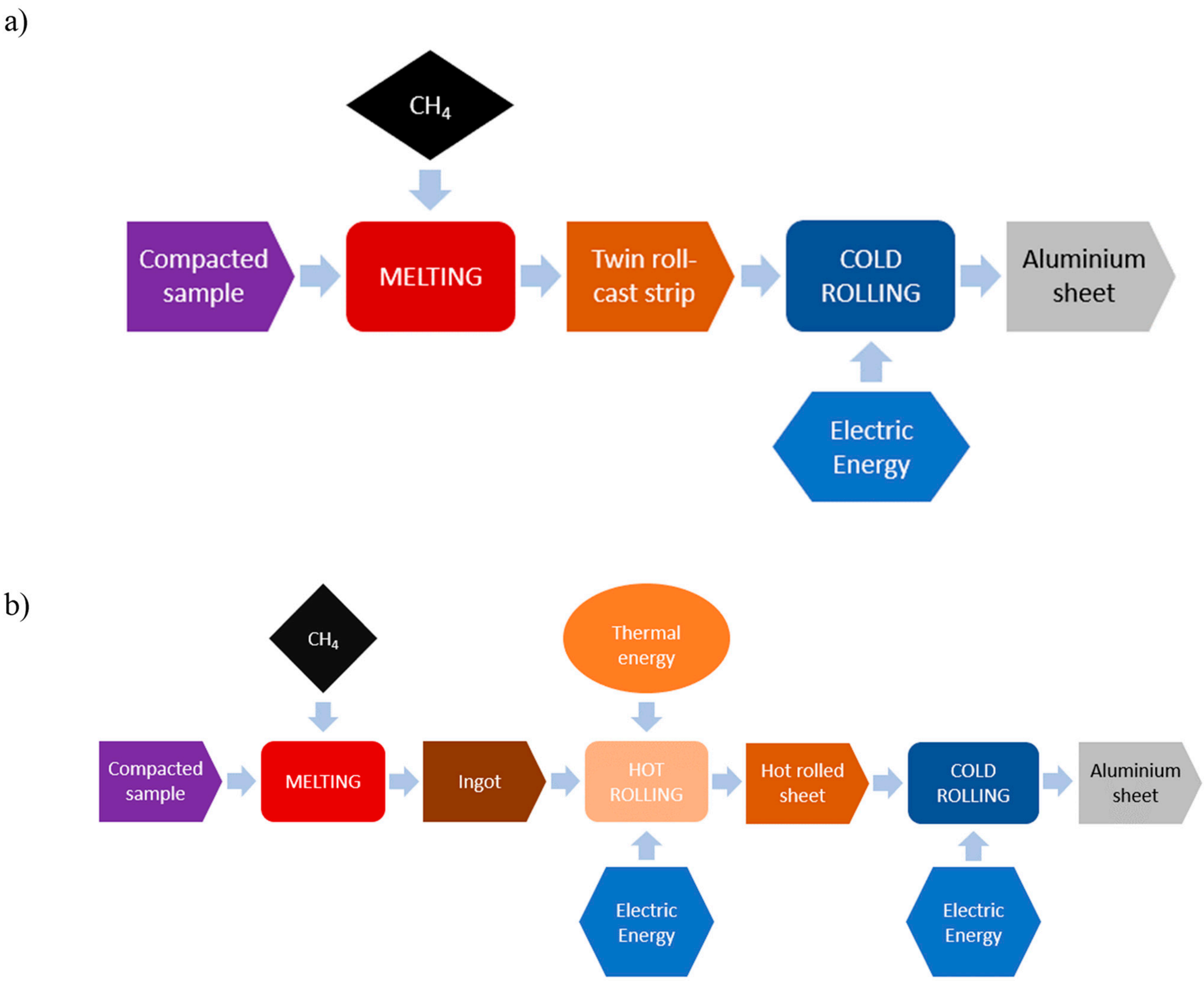

Figure 6. Schematic representation of each step and energy flows of the secondary remelting processes. (**a**) Twin roll casting and (**b**) casting of ingots followed by hot and cold rolling (source: authors' elaboration).

The functional unit in this analysis is an aluminum sheet weighing 0.9 kg, produced using recycled chips. The comparison involves the following three different processes:

- Traditional Recycling.
- Twin Roll Cast.
- DR + ARB.

It is important to note that cold pressing is a common step in all three processes. However, for the purpose of this analysis, it has been excluded in order to focus on the comparison of the remaining steps and their respective impacts.

Traditional recycling consists of three steps, as outlined in Table 2. These three steps are as follows:

- Melting: This initial step takes the cold-pressed sample obtained from the aluminum chips as its material input. The process requires additional inputs, such as thermal energy sourced from natural gas, and water used for dross treatment. Considering that in secondary aluminum production, there is a typical metal loss of approximately 20–45%, a total loss of 35% was assumed for this step. To obtain a cast ingot of 1 kg as input for the subsequent rolling process, the mass of compacted chips required was determined to be 1.54 kg. The material output of this step is the aluminum cast ingot, which represents the input for next step, while emissions into the air and water are additional outputs.

- Hot rolling: The cast ingot obtained from the melting stage serves as the primary input for this step. It requires electricity for both the reheating furnace and the rolling machine. The main output is the hot rolled sheet, which is prepared for subsequent cold rolling. Furthermore, considering a 10% material loss during the process, the aluminum residues are also considered as output waste.
- Cold rolling: This final step is carried out to reduce the thickness of the hot rolled sheet to the desired measurement, which, in this analysis, is determined to be 1.6 mm based on experimental procedures conducted in the laboratory. The inputs for this step include the hot rolled sheet, electricity for the rolling machine, and kerosene, which is employed as both a coolant and a lubricant. The output of this step is the cold rolled sheet, with any material loss during this particular process considered negligible.

Table 2. Input and output flows of traditional recycling (source: authors' elaboration).

Melting			Hot Rolling			Cold Rolling		
INPUTS	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**
Compacted chips	1.538	kg	Cast ingot	1	kg	HR sheet	0.9	kg
Thermal energy (CH4)	8.442	MJ	Electric energy (heat)	1.08	MJ	Electric energy (roll)	0.259	MJ
Water	1.79×10^{-6}	m^3	Electric energy (roll)	0.72	MJ	Kerosene	0.042	kg
			Water (cooling)	0.0014	m^3			
OUTPUTS	Quantity	Unit	OUTPUTS	Quantity	Unit	OUTPUTS	Quantity	Unit
Cast ingot	1	kg	HR sheet	0.9	kg	CR sheet	0.9	kg
Emissions to air			Aluminum scrap	0.1	kg			
Emissions to water								

The thermal energy required for the melting phase was determined through direct measurements taken at the industrial plant, considering the amount of chips introduced into the furnace. The dataset in SimaPro® was heat, district or industrial, natural gas, RER, and APOS S. Water consumption during melting for dross treatment was estimated according to [26], and the reference dataset used was water, cooling, unspecified natural origin, IT. For the hot rolling process, the electricity and water consumptions were selected from the same dataset previously utilized for the direct rolling process. The amount of kerosene was calculated by direct measurements in the industrial plant, and the reference dataset was kerosene (Europe without Switzerland), market for, and APOS S. Emissions released into air and water were selected based on the Ecoinvent 3.1 Database (secondary aluminum data).

The twin roll cast process consists of two steps, as reported in Table 3. These two steps are as follows:

- Melting: This step is identical to the first stage of traditional recycling, involving the same inputs and outputs. The process begins with the melting of the material, and it shares the same inputs and outputs as the melting step of traditional recycling. Therefore, the datasets and sources utilized for traditional recycling's melting phase are also applicable to the twin roll cast process.
- Cold rolling: This step is comparable to the third stage of traditional recycling, with the same inputs and outputs. Similar to the cold rolling step in traditional recycling, the inputs and outputs remain unchanged. However, it is important to note that a total material loss of 10% was considered during this step for the twin roll cast process.

The datasets and sources, including both primary and secondary data, used for the flows in traditional recycling are also employed for the twin roll cast process. This ensures consistency and allows for a fair comparison between the two methods.

Traditional recycling results as the most pollutant process, exhibiting the highest impact across the majority of the selected categories. In contrast, the analysis of the twin roll cast process suggests that by avoiding the hot rolling step and the related energy consumption, it demonstrates a lower impact in all categories. Specifically, when examining the global warming potential (GWP), both traditional recycling and twin roll cast processes present a high impact, while the direct rolling SSR process has a minimum contribution. This discrepancy can be attributed to the high energy requirement for melting, which relies on natural gas consumption, and the emissions released into the air and water, including CO_2, NOx, N_2O, chlorides, fluorides, and particulate matter. These factors contribute to the overall impact in categories related to pollutant substances. It is important to note that the impact of the direct rolling SSR process varies across different categories. For instance, it demonstrates a high impact in certain categories, such as land occupation, aquatic and terrestrial ecotoxicity, and mineral extraction. However, it is crucial to contextualize these results. The high energy requirement for heating and the operation of the rolling mill during the hot rolling and ARB processes are based on the Italian energy mix provider, as available in the Ecoinvent database. Therefore, the results of impact categories are significantly influenced by geographic location and the respective energy production sources. In countries heavily reliant on fossil fuels, the impact of the DR process may be considerably higher. Considering all the categories depicted in Figure 7, the impact analysis strongly suggests that the novel experimental process presented in this study enables a substantial reduction in the environmental impact of the aluminum recycling process. Consequently, it represents a more favorable choice across the various categories considered in this analysis.

Table 3. Input and output flows of the twin roll cast recycling process (source: authors' elaboration).

Melting			Cold Rolling		
INPUTS	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**
Compacted chips	1.538	kg	Twin roll cast	1	kg
Thermal energy (CH4)	8.442	MJ	Electric energy (roll)	0.288	MJ
Water	$1.79 \cdot 10^{-6}$	m^3	Kerosene	0.042	kg
OUTPUTS	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**
Twin roll cast	1	kg	CR sheet	0.9	kg
Emissions to air			Aluminum scrap	0.1	kg
Emissions to water					

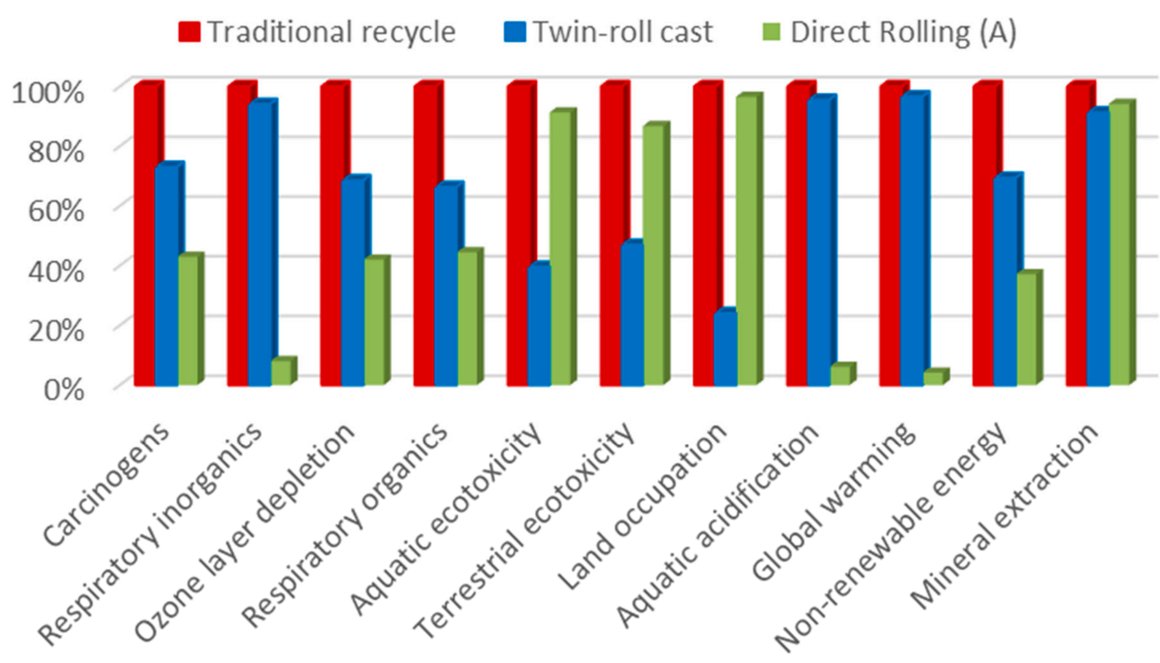

Figure 7. Impact categories comparison between melting and SSR processes (source: authors' elaboration).

The results obtained from the impact categories indicate a strong correlation between the background of the Italian national energy mix and the potential benefits of solid-state recycling (SSR) processes, like the proposed direct rolling (DR) method in this study. The dataset chosen as the electricity provider for both the hot rolling and ARB steps is based on the Italian electricity mix, using reports and data published in 2016 by IEA World Energy Statistics and Balances, as accessible in the Ecoinvent database.

During the conducted LCA investigation, it was intriguing to assess the advantages of the DR process in different scenarios, particularly when considering renewable energy sources for electricity requirements.

To achieve this, a comparison was made between the previously examined scenario, referred to as DR (A) based on the Italian electricity mix, and a greener scenario, termed DR (B), which incorporated the contribution of renewable energy. In the case of DR (B), it was assumed that 50% of the electricity was provided by photovoltaic plants, utilizing the dataset electricity, low voltage (IT), and photovoltaic open ground installation. The results of this comparison are presented in Figure 8.

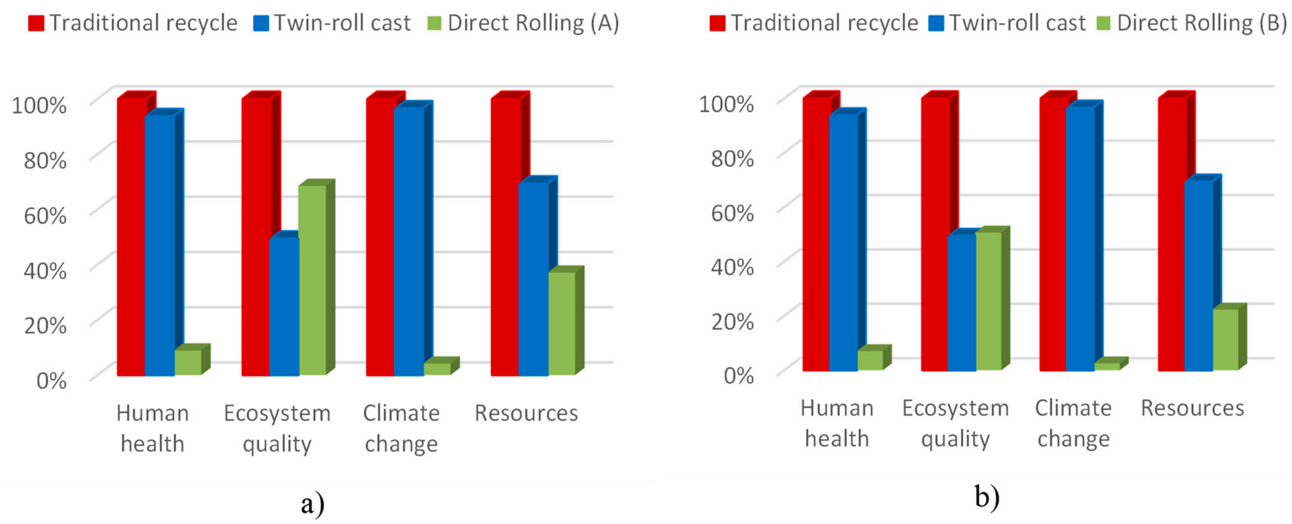

Figure 8. Damage categories analysis with two SSR scenarios: (**a**) 100% from electric grid; (**b**) 50% from photovoltaic plants (source: authors' elaboration).

The analysis reveals a notable trend: the DR process demonstrates superior performance across all categories, with one exception—ecosystem quality, where it exhibits a higher impact than the twin roll cast process (Figure 8a). However, this dynamic changes when Scenario B is taken into account. The adoption of Scenario B brings about a significant reduction in the impact across all categories within the DR process. Remarkably, the ecosystem quality metric becomes comparable to that of the twin roll cast process (Figure 8b). These findings highlight the potential for mitigating the environmental impact associated with ecosystem quality through the implementation of greener practices within the DR process. Thus, by considering alternative scenarios and embracing more sustainable approaches, the DR process can be further optimized to align with the twin roll cast process in terms of ecosystem quality.

The comparison between these two scenarios provides valuable insights into the potential environmental benefits of adopting renewable energy sources in the DR process, further contributing to the overall sustainability and reduced environmental impact of aluminum recycling.

Figure 9 presents the environmental burden for the medium scenario according to the midpoint impact categories with labelling for the four most important ones. The assessment of damage and the analysis of the single-score metric reveal remarkable benefits across all the considered categories. These results hold immense significance and strongly indicate that in a future scenario characterized by a greener and more renewable energy landscape, the advantages offered by the DR technique as an SSR method will be significant. The implications of these findings are far-reaching, suggesting that as we move towards a future characterized by greener and more sustainable practices, the advantages brought forth by the DR process as an SSR technique will be even more pronounced. These breakthroughs open up new possibilities for the industrial development of SSR processes as environmentally benign alternatives to the current melting-based practices. Embracing these advancements in aluminum recycling can contribute to an overall reduction in environmental impacts, paving the way for a more sustainable and environmentally conscious industry.

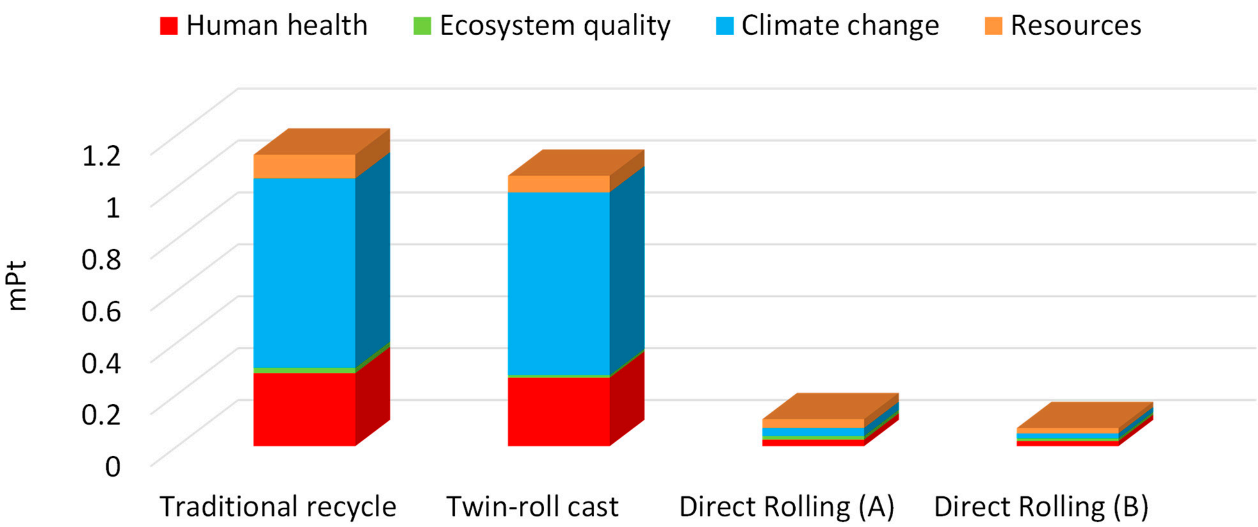

Figure 9. Single-score analysis for melting and SSR processes (source: authors' elaboration).

4. Conclusions

In this article, an LCA investigation was conducted to evaluate the environmental benefits of the newly developed DR + ARB process for the solid-state recycling of aluminum chips. The process consists of three elementary steps: cold pressing, hot rolling, and ARB. It was compared to the current industrial process for recycling aluminum chips, which involves the melting, casting, and subsequent rolling of aluminum scrap. The melting step is highly polluting due to emissions released into the air and water. The DR process relies on electric energy for both the preheating of the material and the rolling procedure. The source of the electric energy is a critical factor to consider in this analysis, particularly when taking into account the proportion of non-renewable sources in electricity generation. In this LCA analysis, a greener scenario was considered, where 50% of the total electric requirement was sourced from photovoltaic energy. The results indicate that the DR process demonstrates a lower environmental impact across all impact categories when compared to traditional and twin-roll cast recycling technologies. Specifically, in terms of climate change, the proposed new SSR process accounts for less than 10% of the total damage. These findings strongly suggest that the novel SSR procedure holds significant potential to replace the melting-based process and enhance the environmental benefits for the circular economy of aluminum sheet production.

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Nomenclature

LCA	Life cycle assessment
FSE	Friction stir extrusion
FSC	Friction stir consolidation
ECAP	Equal channel angular pressing
SPD	Severe plastic deformation
DR	Direct rolling process
ARB	Accumulative roll bonding process
DR + ARB	Direct rolling process followed by accumulative roll bonding
SSR	Solid state recycling
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
UTS	Ultimate tensile strength

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