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Life cycle assessment (LCA) of a novel solid-state recycling process for aluminum alloy AA6063 chips via direct hot rolling

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Abstract. Aluminum utilization has been growing in the last decades thanks to its high strength to weight ratio, corrosion resistance, excellent plasticity, and good weldability. Recently, unconventional processes have been developed for aluminum recycling, called Solid-State Recycling (SSR), by avoiding melting process, allow to save up to 85% of energy needed for secondary aluminum production. The aim of this study is to assess the environmental advantages of a novel recycling technique namely Direct Hot Rolling process. This innovative solid state recycling process will be evaluated for its eco-friendliness. The Life Cycle Assessment (LCA) analysis follows a gate-to-gate approach: collected chips coming from prior cutting process are cold pressed and subsequently hot and cold rolled to obtain the functional unit, defined as the sheet produced through Direct Rolling of 35g of AA6063 chips. Primary data come from direct measurements provided by an industry plant operating in aluminum production field and direct measurements taken during the experimental activity in laboratory. Secondary data were provided by studies available in literature and SimaPro® databases. This LCA comparison between two similar different routes for SSR through rolling suggests that the second one, Direct Hot Rolling + ARB technique, is more suitable to reduce the environmental impact of aluminum recycle industry. However, Accumulative Roll Bonding is considered a low productivity process for worldwide industries, considering the difficulty of automation and repeatability of the procedure.

Introduction

Aluminum has gained popularity due to its outstanding properties such as high strength-to-weight ratio, corrosion resistance, and formability and will reach about 180 million metric tons production in 2050 worldwide [1].

A significant innovation in this field is the development of Solid-State Recycling (SSR) methods to recycle aluminum. SSR omits the conventional melting step, potentially saving up to 85% of the energy typically used in recycling aluminum [2]. These methods involve common steps like cleaning, drying, compaction, and hot or cold plastic deformation, with the final stage varying based on the selected method. The last stage consisting of intense plastic deformation could be processes like direct extrusion[3,4], friction stir extrusion [5–7], friction stir consolidation [8,9], high pressure torsion [10], equal channel angular pressing [11,12] or accumulative roll bonding [13].

Solid-State Recycling is particularly effective in recycling aluminum chips, which are commonly produced in machining industries and traditionally recycled through melting, a process prone to high metal loss due to oxidation that occur during the melting step. SSR significantly reduces this loss by eliminating the need for melting [14].

Recent research has shown the effectiveness of various SSR techniques in recycling aluminum chips into functional products. Techniques like direct recycling extrusion and friction stir extrusion have successfully transformed chips into wires, tubes, and similar forms. The addition of reinforcing particles to chips has been shown to improve adhesion and mechanical properties after recycling [15]. Recycling aluminum is far more energy-efficient than producing it from raw materials, potentially saving up to 95% of energy and resulting in just 5% of the greenhouse gas emissions of primary production. Considering that primary aluminum production contributes about 1% of global greenhouse gas emissions [16], this reduction is significant. Furthermore, aluminum recycling conserves water and reduces waste, minimizing landfill usage.

There is, however, limited research on the environmental impact of SSR, particularly in the context of producing aluminum sheets [17,18]. This article introduces a novel approach, Direct Hot Rolling, for recycling aluminum chips into sheets. It evaluates the process's effectiveness in reducing waste and energy consumption and its impact on global warming potential and water usage. The paper also compares this technique to another studied by the authors, based on Accumulative Roll Bonding process [13], emphasizing its sustainability advantages. The paper is structured into sections, starting with a detailed description of the Direct Hot Rolling process, followed by a Life Cycle Assessment analysis, and concludes with research findings, contributing to sustainable aluminum recycling practices.

Experimental methods: the Direct Hot rolling process

In this paper, a widely used AA6063 Al-Mg-Si aluminum alloy was considered. The alloy was produced by Fonderie Pandolfo (Italy), the chemical composition (wt%) is reported in Table 1. The as-received billet material is characterized by an Ultimate Tensile Strength (UTS) of 186 MPa and 22% elongation. The chips were produced milling process without the use of lubricants to avoid any contamination of the chips.

Table 1 - Chemical composition of the alloy (wt.%).

Element	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
wt. %	0.585	0.231	0.027	0.030	0.489	0.007	0.007	0.033	0.018	Bal.

Figure 1 presents a schematic overview of the direct rolling process. The initial step in recycling is cold compaction. Here, 35 grams of chips are compacted under a load of 200 kN using a hydraulic press, resulting in dimensions of 30x60x9.5 mm^3. This achieves a density approximately 68% that of the as-cast material. Samples undergo a heat treatment (HT) for 6 hours at 570 °C in a Nabertherm N50 muffle furnace, followed by hot rolling (HR) at 490 °C with several consecutive passes, without the use of lubricants. These temperatures and the heat treatment duration are selected to mirror those used in industrial settings. The rolling machine employed in the experimental campaign is a BW200 two-high rolling mill, manufactured by Carl Wezel. The compacted chips are subjected to a rolling schedule comprising 7 hot rolling passes and a final cold rolling pass, resulting in a final sheet of 1 mm thick. To maintain the initial temperature of 490 °C, samples are returned to the furnace for 10 minutes after each rolling pass. The jagged borders of the samples, a result of rolling, must be trimmed. These trimmings, constituting approximately 10% of the mass, are scraps that need to be recycled again. This paper focuses on the environmental impact of the process, and therefore, will not discuss the properties of the recycled samples in detail. However, it is worth mentioning the most important tensile test mechanical data. When comparing recycled chips to the bulk material undergoing the same rolling schedule, the bulk material demonstrates an ultimate tensile strength of 218 MPa compared to 177 MPa for the recycled chips, with an elongation at break of 7.5 percent for the bulk material and 7 percent for the recycled chips.

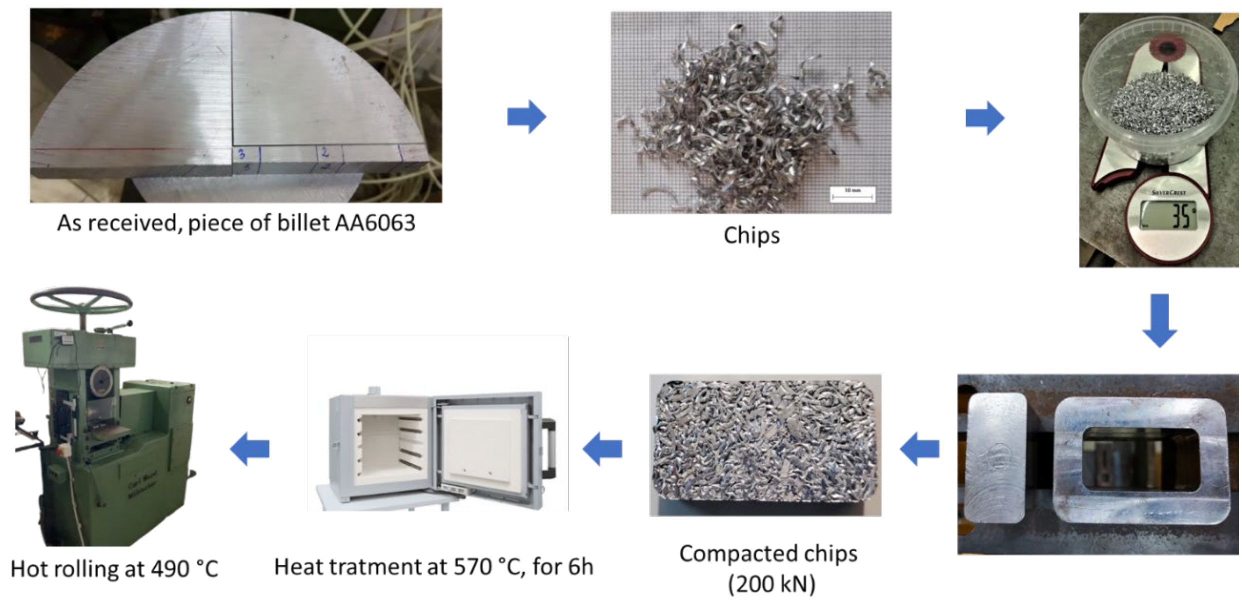

Figure 1 - Schematic representation of the Direct Rolling process.

Life Cycle Assessment (LCA) Analysis

In order to evaluate environmental benefits of the investigated Direct Rolling process, a LCA analysis was performed with SimaPro® software. Next paragraphs indicate all assumptions, methods and reference databases used in the analysis.

Introduction to LCA

Life Cycle Assessment can be distinguished of four connected phases. First phase is the goal and scope definition: the aim of this analysis is to evaluate the environmental impact of the SSR process discussed in this study. The goal is to demonstrate the viability and suitability of this technique according to the exigence, from aluminum industry, of the reduction of wastes and energy consumptions, and the purpose of development for new ecological ways in aluminum scrap recycle. This analysis follows a gate-to-gate approach: collected chips coming from prior cutting process are cold pressed and subsequently hot and cold rolled to obtain the functional unit, defined as the sheet produced through Direct Rolling of 35 g AA6063 chips.

Second phase is Life Cycle Inventory (LCI) analysis: material and energy flows of the different unit processes are defined in this phase. Primary data come from direct measurements provided by an industry plant operating in aluminum production field and direct measurements taken during the experimental activity in laboratory. Secondary data were provided by studies available in literature and SimaPro® software databases. The first unit process is Cold pressing, and its input flows are aluminum chips and electricity to feed the press, and the output is the compacted sample. In this process, the manufacturing of the steel die for pressing was included. Therefore, further input is electricity for feed the milling machine, and steel scrap is also an output as solid residue of the process. The electricity usage was determined based on the findings of Priarone et al. [19]. The quantity of steel chips produced as solid waste from milling was estimated through geometric analysis. The energy needed for cold pressing was assessed by taking into account the pressure applied and the surface area of contact of the aluminum chips during the compaction process, according to Eq. 1.

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

where p is the applied pressure (40 MPa), A is the contact area, δ is the total thickness reduction during pressing and η the electro-mechanical efficiency (0.76 is assumed as a reasonable value).

The dataset for electricity in SimaPro® was Electricity, high voltage, IT, APOS S and for steel chips waste was Scrap steel {Europe without Switzerland}, market for scrap steel, APOS S.

The second unit process is Hot Rolling, which input is the compacted sample. Further input is electric energy required for rolling mill (provided by the referenced industrial plant). In addition, thermal energy is required to heat the samples for HT to 570°C for 6 hours and then (after cooling) to heat them again to the rolling temperature at 490°C, and is considered as the electricity required by the muffle furnace. Electric energy required for muffle furnace was calculated according to the industrial procedure. In the hot rolling process, water is used for cooling, as specified in reference [20]. The resulting product is a hot rolled sheet. Additionally, a metal loss of 10% was considered during this process to remove the jagged border, which is classified as solid waste in the output data. The reference dataset for electricity consumption is Electricity, high voltage, IT, APOS S, while for cooling water the dataset Water, cooling, unspecified natural origin, IT was selected.

The third process is Cold Rolling, performed in one pass to reduce the sheet thickness from 1.5 mm to 1.0 mm. Electric energy is required for rolling machine and it was calculated in the referenced industrial plant. Table 2 presents both primary and secondary data for the Life Cycle Assessment (LCA) of the Direct Rolling process.

Table 2 – Input and output flows for the three steps of investigated Direct Rolling process.

Cold pressing			**Hot Rolling**			**Cold Rolling**		
INPUTS	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**
Chips	35	g	Compacted chips	35	g	HR sheet	31.5	g
Electric energy (pressing)	0.0017	MJ	Electric energy (heating)	0.0631	MJ	Electric energy (rolling)	0.0091	MJ
Electric energy (milling)	0.0061	MJ	Electric energy (rolling)	0.0176	MJ			
			Water (cooling)	$4.732 \cdot 10^{-5}$	m^3			
OUTPUTS	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**
Compacted chips	35	g	HR sheet	31.5	g	CR1.0 sheet	31.5	g
Steel chips	405	g	Aluminum scrap	3.5	g			

The third phase of LCA analysis is Life Cycle Impact Assessment (LCIA), and the fourth and last phase is Results analysis. These steps are described in next paragraph.

LCIA and results

In LCIA analysis, the IMPACT 2002+ method was selected. Characterization analysis shows the impact of the three-unit processes on different impact categories, like Ozone layer depletion, Global warming potential, Terrestrial ecotoxicity, Mineral extraction and others (Figure 2). Hot Rolling process has the highest impact for the most of categories, due to high energy requirement of the muffle furnace for preheating the sample. Electric energy database is referred to the national country mix, and fossil sources like carbon and natural gas plants are considered with their impact on environment. Cold pressing has high impact in some categories like Respiratory organics and Respiratory inorganics, and the reason is the pollution of solid wastes produced during the steel die manufacturing. Cold Rolling has a minor impact on all categories.

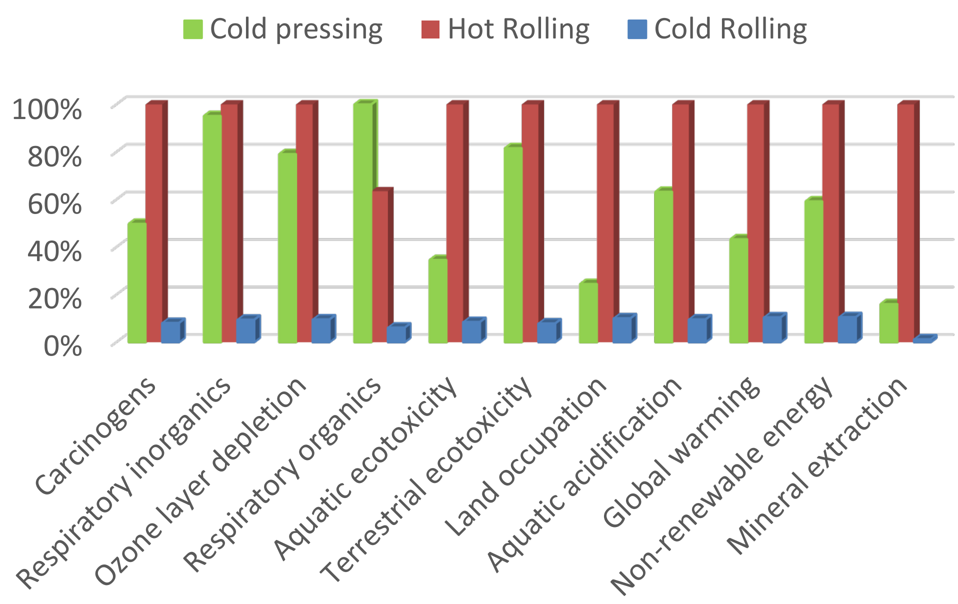

Figure 2 – Impact categories for the three-unit processes of Direct Rolling.

Damage analysis allows to understand the impact of each unit process on Human health, Climate change, Resources and Ecosystem quality (Figure 3). For the four environmental damage categories, Hot Rolling has the highest impact as energetic requirement is higher than Cold pressing and Cold Rolling: land occupation, CO2 emissions and environmental pollution due to non-renewable sources are very important factors in this analysis. Cold pressing has high impact in Human Health category because of the pollution and the negative effects of steel scrap produced in the tooling phase.

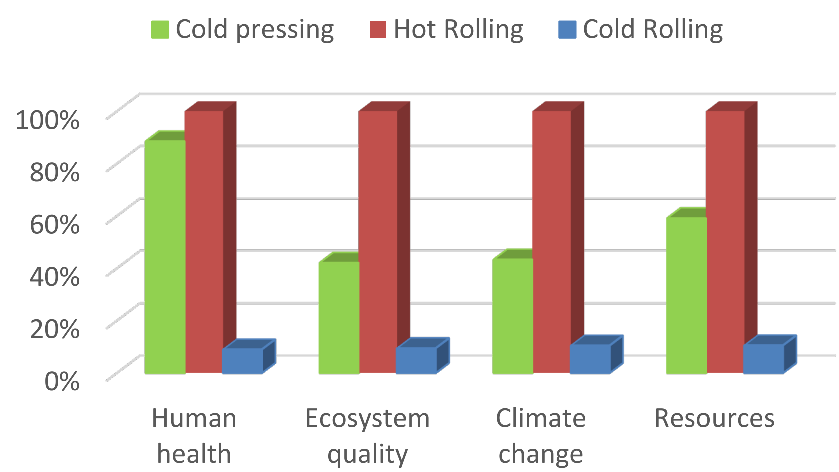

Figure 3 – Damage categories for the three-unit process of Direct Rolling.

Once produced, the steel die could be used several times before it gets damaged. Thus, excluding the tooling phase from the impact analysis the results change. In this case, Cold pressing has the lowest impact in all categories and Hot Rolling, due to high energetic requirements for heat treatment and heat during rolling, has the highest impact (Figure 4).

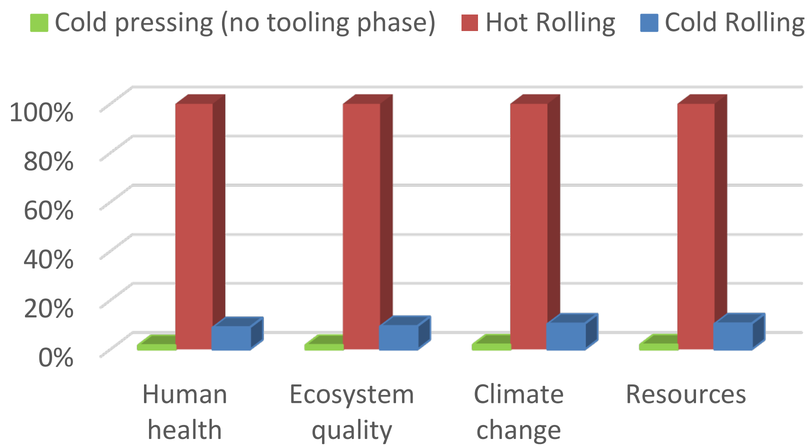

Figure 4 – Damage categories without the tooling phase.

The dataset considered for electricity needed in Cold pressing, Hot Rolling and Cold Rolling, is referred to Italian electricity mix based on reports and data published in 2016 by IEA World Energy Statistics and Balances and available in the Ecoinvent database. Major energetic sources are natural gas and carbon fossil plants, therefore environmental impact of the Direct Rolling process is higher because of emissions and pollution related to the electric energy demand. A completer, and more interesting overview, was produced by replicating the same LCA analysis, this time considering the energetic requirement satisfied by national country mix for 50% and by photovoltaic energy for the other 50%, and another case with the 100% of electricity requirement satisfied by photovoltaic (PHV) energy. The reference dataset of photovoltaic energy procurement in SimaPro® was Electricity, low voltage {IT}, photovoltaic open ground installation.

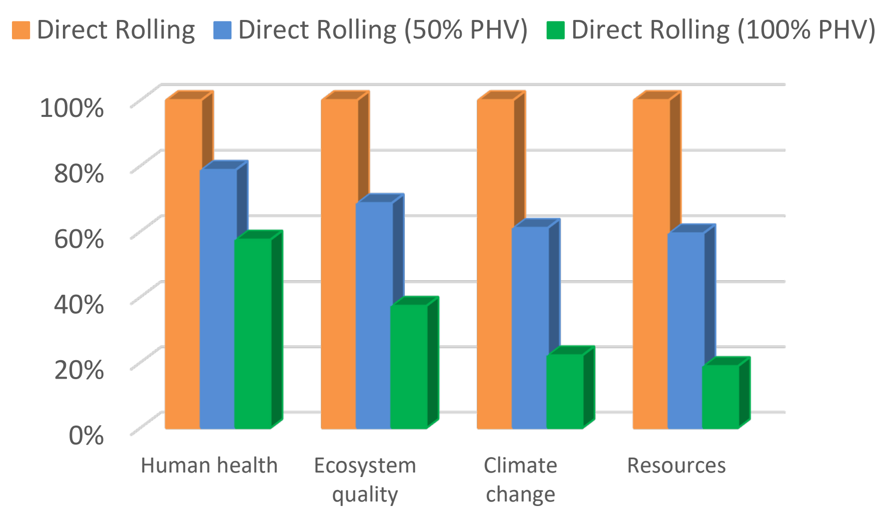

Figure 5 – LCA comparison with 50% and 100% of electric requirement satisfied by photovoltaic energy.

This analysis is more compatible with a greener and eco-friendly scenario of modern industrial plants. Direct Rolling technique avoids the production of wastes and emissions typical of melting processes. The case with 50% of electric requirement provided by photovoltaic energy produces a better and more eco-friendly scenario, leading to an overall reduction of pollution and emissions of this SSR process (Figure 5). The case with 100% of electricity provided by PHV plant could be considered as the perfectly eco-sustainable scenario in the circular economy philosophy.

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Comparison with Direct Hot Rolling + ARB technique

Another study published by the authors [13] investigated another SSR procedure, indicated as Direct Hot Rolling + ARB technique. The sample produced by cold pressing 35 g of AA6063 chips has been hot rolled at 550 °C to obtain 1.5 mm thick sheet and subsequently Accumulative Roll Bonding has been performed at 450 °C in two steps. During the ARB process, two sheets are cleaned and stacked together, then passed through a rolling mill, usually at elevated temperatures, with a reduction of 50% in thickness. After the first pass through the rolling mill, the bonded sheets, which have been reduced in thickness, are typically cut in half, and then stacked again. In this way, the rolling, cutting and stacking process can be repeated several times [21]. In this process, after Cold pressing the compacted chips underwent directly to Hot Rolling without any heat treatment. This procedure allowed to obtain a 1.5 mm thick sheet with high mechanical properties and a LCA comparison with melting recycle stated this novel SSR process could highly reduce environmental impact of aluminum recycle industry. A comparison between the Direct Hot Rolling + ARB procedure and the Direct Hot Rolling procedure described in this paper is reported in this paragraph.

Although the two methods differ, they are interesting to compare in a Life Cycle Assessment (LCA) for environmental impact. The first method, direct hot rolling, includes a single heat treatment (HT), followed by seven hot rolling steps (HR) passes and one step cold rolling (CR) pass. The second method combines direct hot rolling (without HT) with Accumulative Roll Bonding (ARB). It involves seven HR passes at 550 °C and then two ARB cycles at 450 °C. This comparison aims to determine which SSR route has the least environmental impact. The functional unit in both cases is the aluminum sheet produced by rolling 35 g of AA6063 compacted chips. Direct Hot Rolling + ARB input and output flows are reported in Table 3. Cold pressing step is common to both processes.

An overview of damage categories is reported in Figure 6. Direct Rolling has the highest impact in all categories, and the reason is the amount of heat necessary to both early heat treatment and heating during Hot Rolling. The higher the energetic demand, the higher the overall impact. Direct Hot Rolling + ARB procedure avoids the heat treatment step, and enhances the eco-sustainability of this SSR route, avoiding the surplus energetic demand for heat treating the compacted samples.

Table 3 – Direct Hot Rolling + ARB input and output flows.

Hot Rolling			**ARB**		
INPUTS	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**
Compacted chips	35	g	HR sheet	31.5	g
Electric energy (heating)	0.0315	MJ	Electric energy (heating)	0.0227	MJ
Electric energy (rolling)	0.0176	MJ	Electric energy (rolling)	0.0050	MJ
Water (cooling)	$4.732 \cdot 10^{-5}$	m^3			
OUTPUTS	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**
HR sheet	31.5	g	ARB2 sheet	31.5	g
Aluminum scrap	3.5	g			

This LCA comparison between two similar different routes for SSR through rolling suggests that the second one, Direct Hot Rolling + ARB technique, is more suitable to reduce the environmental impact of aluminum recycle industry. However, Accumulative Roll Bonding is considered a low productivity process for worldwide industries, considering the difficulty of automation and repeatability of the procedure.

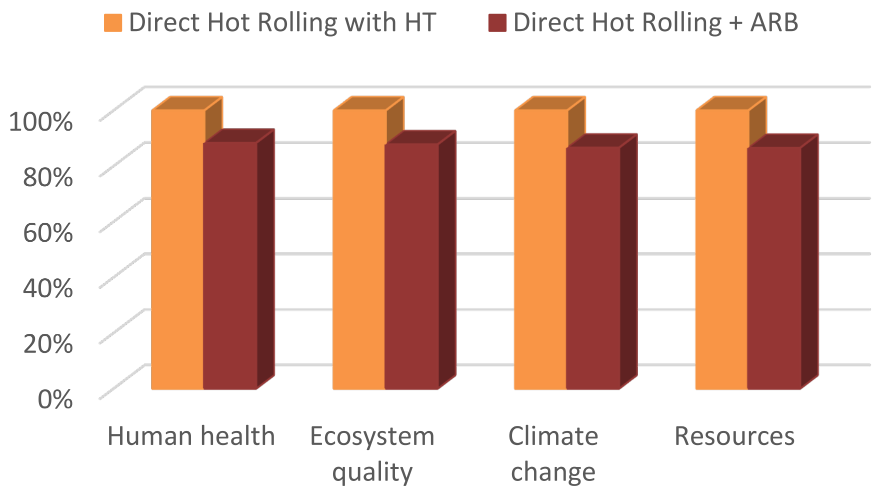

Figure 6 – Damage categories analysis for Direct Rolling and Direct Hot Rolling + ARB.

The single-score analysis reveals that Resources and Climate change are the most concerned categories about the overall damage for both Direct Rolling and Direct Hot Rolling + ARB processes (Figure 7). The reason is the background of energy production, and the high presence of carbon sources and subsequent pollution leads to higher impact in these categories. Green and eco-friendly energetic sources, like photovoltaic and wind turbine plants, are indicated for a better scenario of the national country mix, reducing the emissions and the pollution. In this case, the benefits introduced by Direct Hot Rolling process are enhanced and the overall impact, compared to secondary aluminum industry based on melting process, is drastically reduced.

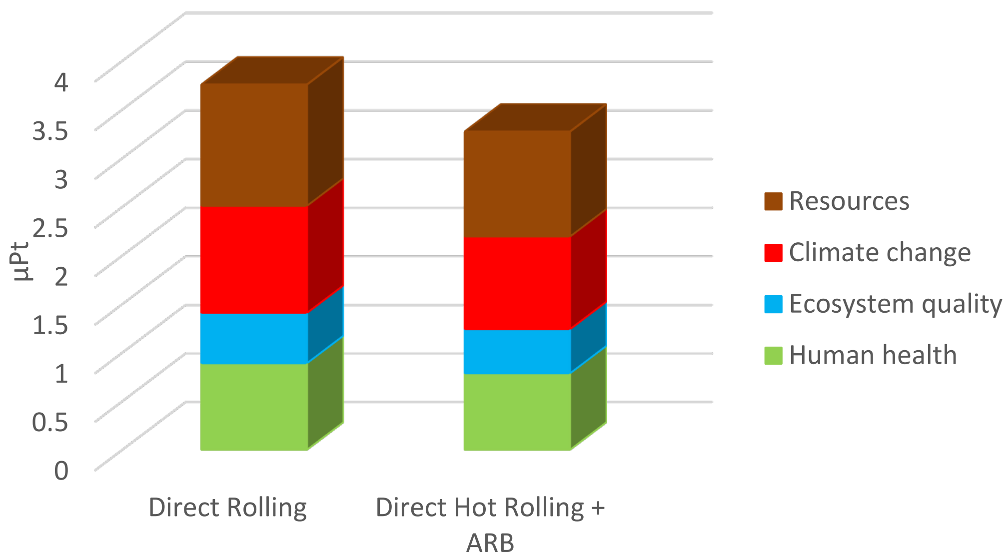

Figure 7 – Single score analysis for Direct Rolling and Direct Hot Rolling + ARB.

Conclusions

This study aimed to assess the environmental advantages of the innovative Direct Hot Rolling process in solid-state recycling and to compare its efficacy with the previously researched Direct Rolling + ARB method. The Life Cycle Assessment (LCA) performed here adopts a gate-to-gate approach. This LCA comparison between two distinct SSR rolling methods indicates that the Direct Hot Rolling + ARB technique might be more effective in reducing the environmental impact in the aluminum recycling industry. However, it's noteworthy that Accumulative Roll Bonding is seen as a lower productivity process for global industries due to challenges in automation and replicability. The findings indicate that both the Direct Hot Rolling and Direct Hot Rolling + ARB methods provide environmental advantages. However, the Direct Hot Rolling + ARB technique is slightly more beneficial in this regard. Despite this, it faces practical challenges for broad industrial use, making the simpler Direct Hot Rolling process a more viable option for potential industrial production.

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