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Sustainable Aluminum Recycling Method

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Abstract

Aluminium, renowned for its advantageous combination of low weight and high strength, has firmly established itself as a fundamental component of contemporary industrial sectors, leaving a lasting impact on diverse fields such as aerospace engineering and ordinary consumer goods. However, the widespread use of this adaptable metallic element results in the production of significant quantities of waste and discarded materials, hence requiring the implementation of efficient recycling strategies. This comprehensive review study examines the range of recycling procedures commonly used in the aluminium sector, discussing their historical importance and investigating novel approaches that have the potential to transform aluminium recycling. The utilisation of traditional procedures, shown by conventional recycling practises, provides significant knowledge regarding the progression of the area. Nevertheless, the advent of solid-state recycling and direct recycling methods presents a positive outlook for the future, since it brings about increased resource efficiency, lower energy requirements, and a smaller ecological impact. This article functions as a comprehensive manual outlining several recycling procedures, providing a detailed analysis of their unique attributes, benefits, and obstacles. This assessment seeks to shed light on the progress made in aluminium recycling, to highlight sustainable practises that can alter the sector, promote energy saving, and reduce waste output. These practises are in line with the current emphasis on environmental stewardship. This review study serves as a guiding tool in our examination of aluminium recycling methodologies, providing direction toward the establishment of a sustainable aluminium sector.

1. Introduction

Aluminum, a versatile and extensively used material, undergoes a complex life cycle with multiple phases including extraction, production, usage, and recycling. In the current era, marked by a growing emphasis on environmental sustainability and resource conservation, it's imperative to develop efficient and eco-conscious strategies for industrial processes. Traditional primary aluminum production, a widely used material, consumes significant energy, resulting in substantial carbon emissions. For instance, primary aluminum production can require up to 113 GJ per tonne, primarily due to energy-intensive electrolysis [1].

However, data from the International Aluminum Institute (IAI) indicates that recycling aluminum uses just 5% of the energy needed to produce an equivalent quality aluminum alloy from bauxite ore [2]. This considerable difference in energy usage underscores the environmental advantages of aluminum recycling. Additionally, the extraction process for primary aluminum has been linked to detrimental environmental effects, including carbon dioxide emissions, hazardous gases, solid waste production, and landscape disruption [3].

To address these environmental concerns, the aluminum industry should explore various technologies for optimizing recycling processes. There are three primary recycling methodologies for aluminum: conventional recycling (CR), semi-direct recycling (SDR), and direct recycling (DR).

Of these, solid-state recycling, particularly the direct recycling process, offers a promising alternative to traditional recycling methods. Direct recycling, also known as non-ferrous metallic scrap conversion, involves transforming non-ferrous metallic scrap like aluminum and its alloys into final products without the need for melting. Unlike conventional methods, which involve extensive melting and purification, solid-state recycling employs mechanical techniques such as milling, extrusion, or forging to work with the material in a solid state [4]–[6]

2. Recycling Technique

2.1 Conventional Recycling

Current aluminum recycling practices in most industries use a melting technique to produce a secondary ingot by controlling the composition of alloys to match the standardized grades. Refiners and remelters play integral roles in aluminum recycling, establishing links with collectors, dismantlers, metal merchants, and scrap processors who deal with the collection and treatment of scrap. Aluminum recycling uses aluminum scrap as raw material. After scrap is collected, it is sorted and cleaned before it is used in metal production. Scrap is fed into melting furnaces to liquefy the metal, which is subsequently purified, adjusted to the desired alloy, and produced in a form suitable for processing and fabrication. The types of furnaces used to melt scrap include rotary and electric furnaces. The general structure of secondary aluminum production from secondary raw materials is summarized in the process diagram presented in Fig 1.

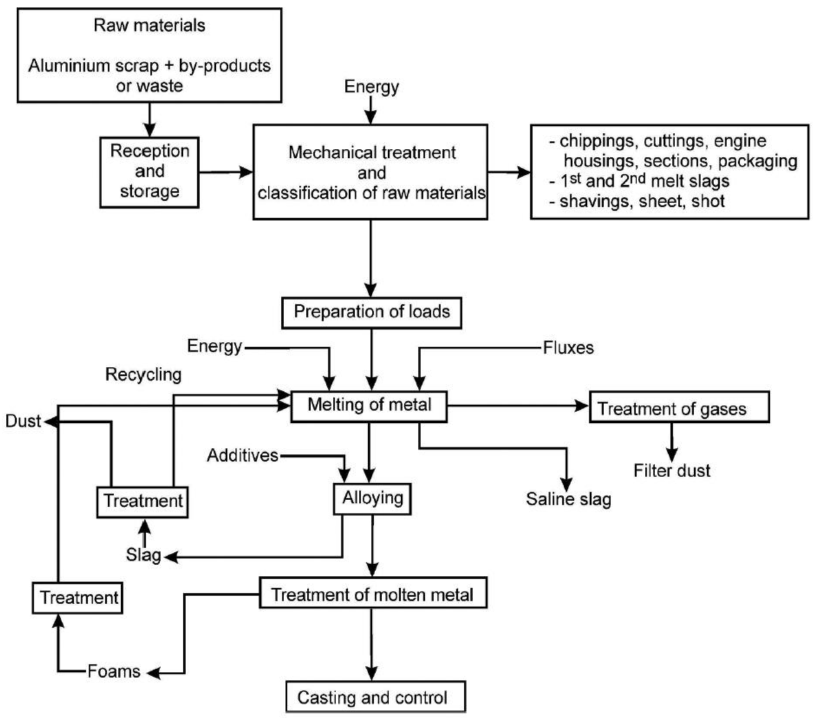

Fig. 1 *Process diagram of secondary aluminium production* [7]

Before the melting process, chips must be cleaned, dried, and compacted. Traditionally, remelters use a degreasing fluid to clean the finely machined chips, which was followed by a heating operation to dry the chips. This process often leads to the development of new oxide films. However, there were losses at every stage of the recycling process, such as losses caused by metal oxidation during melting, losses through mixing with the slag from the surface of the melt, and scraps resulting from casting and further processing of the aluminum ingots [8].

Generating waste and scrap materials is inherent in the aluminum production cycle. Recycling processes face unique challenges when dealing with chips resulting from machining semi-finished aluminum products, particularly elongated spiral-shaped chips. These chips have a small physical dimension, and low apparent density, and were often coated with oxides and oil emulsion. These characteristics make handling, transportation, and recycling through remelting impractical [9], [10].

During the remelting process, material losses increase due to oxidation, and aluminum and its alloys were especially susceptible to this phenomenon. This results in higher labor, energy, and environmental costs [11]. The conventional recycling process for aluminum faces various challenges, including significant material losses and increasing expenses related to labor, energy, and environmental protection measures. For instance, the conventional process can recover a maximum of 52% of the metal, with up to 38% of the material lost during remelting [12].

Due to these limitations, researchers have explored alternative methodologies to enhance the efficacy and sustainability of aluminum recycling. One such approach was the direct recycling of aluminum chips, which can reduce energy consumption and minimize material losses by eliminating extensive melting procedures. Implementing direct recycling has the potential to optimize resource utilization and waste reduction in the aluminum industry.

2.2 Semi Direct Recycling

Aluminium foundries are responsible for 1% of the world's total man-made greenhouse emissions, with 0.4% attributed to aluminium production and 0.6% to the electricity needed for this process [13]. In the context of environmental accountability and integrity, solid-state recycling emerges as a preferable process due to its efficiency in recycling, reduced energy consumption, and cost-effectiveness. This new approach to recycling consumes only 5% of the energy required for producing primary aluminum from ore, making secondary aluminum widely accepted globally.

Instead of using CR techniques that use very high temperatures to reach the melting point, recycling of wrought aluminum alloys by SDR is preferable. High energy consumption for conventional aluminum recycling and subsequent refinement has been considered in previous studies. The SDR method was defined as a partially direct recycling process that requires additional steps before the recycling process is completed. The three SDR techniques involve powder metallurgy, extrusion, and spark plasma sintering techniques under solid-state conditions and can result in significant energy savings. In both techniques, additional steps are required for the recycling process to be completed. The powder metallurgy technique utilizes ball mills before cold compaction to grind the aluminum chip scraps, whereas the hot extrusion techniques require ball mills, pre-heating, and cold compaction to produce cold billets, and spark plasma sintering needs cold compaction to produce billets.

2.2.1 Powder Metallurgy Technique

Powder metallurgy (PM) was the process of blending powdered materials, pressing them into a desired shape or form (compacting), and subsequently heating the compressed material in a controlled atmosphere to bond the material (sintering). The powder metallurgy process generally consists of four basic steps: powder manufacturing, powder blending, compacting, and sintering. Compacting is generally performed at room temperature, and the high-temperature process of sintering was usually conducted at atmospheric pressure. Fig 2 shows the general flow of PM processing [14]. Among many other manufacturing processes, powder metallurgy was also highly ranked because it can produce near-net shape products with properties that are comparable with those of conventionally produced products and require less or no secondary machining other than increased mass production rates [15]. Many components used in automobiles, aircraft, spacecraft, nuclear reactors, computers, and household appliances were also produced using powder metallurgy. Powder metallurgy appears to be a flexible and versatile manufacturing process because of its ability to process various types of materials to produce porous products with uniform porosity, electric and magnetic properties from a combination of different materials, refractory metals with high melting points, which were difficult to process using conventional methods, hard metals for cutting tools, frictional materials and dispersion strengthen materials, such as aluminium with the addition of alumina as the strengthening particles [16].

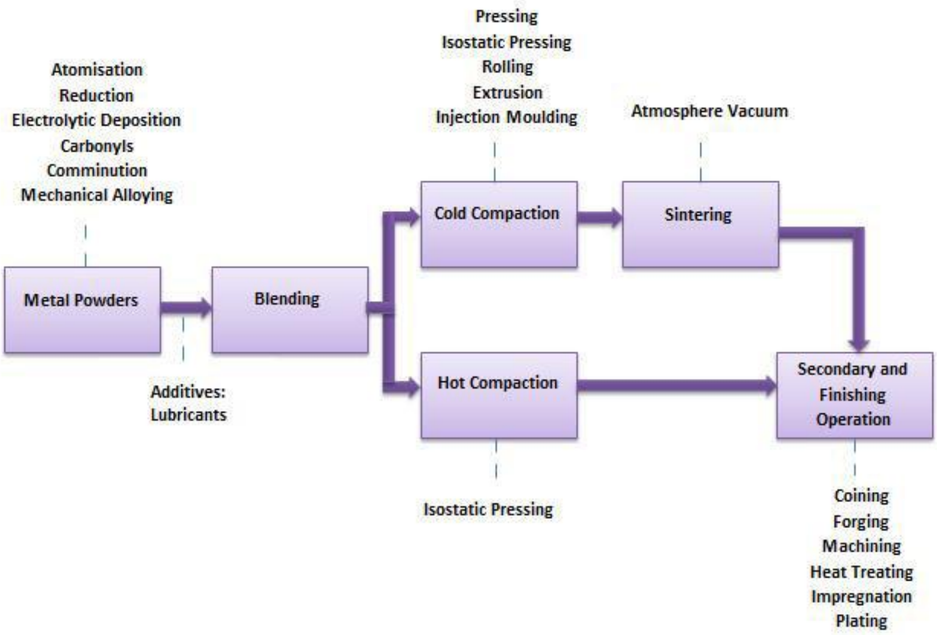

Fig. 2 *General flow sheet of powder metallurgy processing* [14]

Powder metallurgy was a good technique for aluminium recycling. In comparison to the melting method, powder metallurgy offers important advantages, including low processing temperatures compared to the melting process in conventional methods.

2.2.2 Extrusion Technique

Hot extrusion was an innovative process chain that combines optimized primary material usage and a reduction in process steps. This technique was a combination of hot profile extrusion with subsequent turning or machining and hot extrusion of the produced machining chips for semi-finished parts. This concept was introduced and patented by Stern in 1945 [17]. This method is possible due to the joining of the aluminum under high pressure, high strain, and a temperature just below the melting point. The strain results in cracking of the oxide layer, and the high pressure and temperature lead to joining caused by contact with the pure aluminum surface. This process chain requires a small amount of energy compared to conventional process chains and uses only 5-6 GJ.ton-1, which is only 5-6% of that needed for the conventional process chain. During the complete semi-direct conversion of aluminum chips into compact metal by extrusion, a portion of the chip from which impurities cannot be removed was wasted, amounting to approximately 2%; the extrusion waste can be as high as 3%. Thus, 95% of the aluminum chips were recovered [18]. These alternative recycling processes both include material transformation from chips to powder via ball milling. In this work, a new technique was employed that consists of directly recycling the material from the chips via cold or hot forging, which was followed by hot extrusion. As a result, the ball milling step is avoided, resulting in a more economical recycling process. This new technique can also be employed to recycle chips derived from aluminum matrix composites, which are even more difficult to obtain using other techniques.

Gronostajski's work emphasizes the preparation of aluminum chips for product manufacturing, including chip segregation, cleaning, and comminution to produce a granulated product [10]. In the case of direct conversion of aluminum and aluminum-alloy chips into compact metal through extrusion, up to 95% of the metal can be recovered. Fogagnolo's research explores the extrusion of pre-compacted AA6061 reinforced with Al_2O_3 fibers, aimed at eliminating the need for chip transformation into powder. This approach compared Aluminum AA6061 matrix composites and reinforced Al_2O_3, recycled through cold pressing and hot extrusion, with the conventional casting process alloy (primary material). The results indicate that the recycled material exhibits higher ultimate tensile strength (UTS) and hardness compared to the former composite [19].

2.2.3 Spark Plasma Technique

Spark plasma sintering (SPS) is a new approach to SDR. It consists of cold pressing as a pre-process and SPS as the main process for consolidating and recycling aluminum chips. SPS's main characteristic is that a pulsed DC current directly passes through the graphite die, compacting the chip, as shown in Fig 3. The dynamic scrap compaction, combined with electric current-based joule heating, achieves a partial fracture of the stable surface oxides, desorption of entrapped gases, and activates the metallic surfaces. This results in efficient solid-state chip welding, eliminating residual porosity [20]. Unlike conventional hot pressing, SPS generates internal heat, leading to a very high heating rate and generally fast sintering processes.

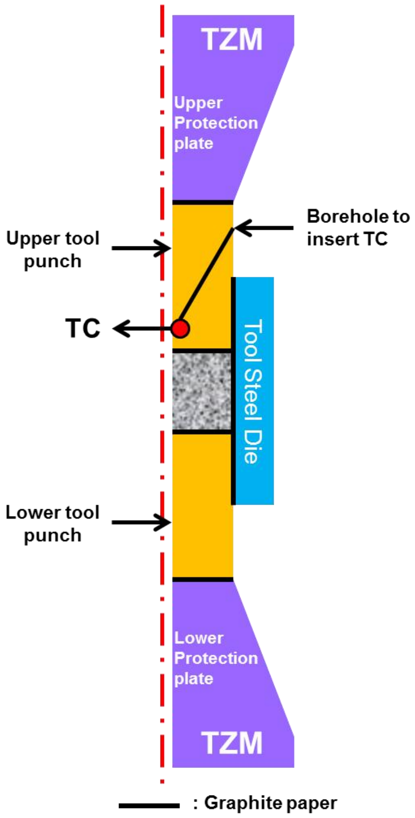

Fig. 3 *Spark plasma sintering schematic*

SPS technology allows for flexible production of near-net-shape parts or multiple parts in one cycle. Industrial-scale SPS systems are already available. Additionally, a field-activated/assisted sintering (FAST) system, capable of efficiently producing near-net-shaped products with a cycle time below 1 minute, is under development [21]. These latest developments in the field can aid in the direction of industrial implementation, scaling up, and the valorization of the proposed approach.

In Samuel's study, aluminum scrap was ball milled and mixed with green density particles before sintering. The research showed that recycled aluminum triggered higher productivity and caused relatively lower air pollution while saving more metal compared to conventional methods [12].

The strength of composites without reinforcement differs only marginally from that of corresponding solid materials. However, the strength can be improved significantly by introducing the reinforcement phase during the recycling process, especially at higher temperatures. This approach has a substantial effect on the quantity and distribution of the matrix when the reinforcement phase is introduced into comminuted aluminum and aluminum alloy chips. This enhancement in strength is a crucial aspect of solid-state recycling techniques.

2.3 Direct Recycling

Direct recycling (DR) was an innovative process chain that combines optimized primary material usage and a reduction in the number of process steps. This process chain requires less energy compared to conventional process chains for the re-melting step of scraps to produce new billets. These alternative recycling processes were slightly different from the former technique in that the material was not transformed from chips into powder. This new technique consists of direct material recycling from chips (waste from industrial machining processes) through cold or hot forging (also known as cold or hot pressing). The recycling of aluminum and its alloys by this direct conversion method was relatively simple, consumes small amounts of energy, and does not harm the environment.

Three different types of DR aluminum techniques are currently available. However, the techniques are often classified according to the temperature at which the recycling is performed because metal deformation can be conducted in either the hot or cold mode. Cold forging is performed at room temperature. The hot-forging and compressive torsion techniques are the plastic deformation of a metal at a temperature and strain rate such that recrystallization occurs simultaneously with deformation.

Besides conventional recycling techniques, there's an alternative for recycling metal chips involving the direct conversion of chips into compact metal. This innovative recycling technique eliminates the melting process, which has adverse effects on the environment. Several processes have been proposed for recycling aluminum chips using hot extrusion. This direct recycling method reduces energy consumption by up to 95%, making it a more environmentally friendly and efficient option compared to conventional recycling processes [22].

2.3.1 Compression Torsion Process

The Compressive Torsion Process (CTP) involves the simultaneous application of compressive and shear loadings on cylindrical objects. During this procedure, a cylindrical specimen is placed within a container, after which the upper and lower dies undergo vertical movement to exert compressive stress. Simultaneously, the dies circle in opposing directions to apply a torsional load, as depicted in Fig 4. The Cyclic Torsion Process (CTP) differs from the high-pressure torsion method in that it operates at significantly lower pressures, often in the range of several hundred megapascals. This allows for the application of severe deformation to a cylindrical specimen, as opposed to solely thin discs, as is the case with high-pressure torsion. The aforementioned procedure offers a significant benefit as it enables the achievement of extreme plastic deformation while maintaining the original shape of the specimen [23]. The Cylindrical Tube Process (CTP) involves subjecting cylindrical metals to significant shear strain through rotational loading while simultaneously applying compressive force, all while maintaining the cylindrical shape of the metal. The application of shear loading under hydrostatic compressive conditions allows for the utilisation of the Consolidation by Torsion Process (CTP) in many materials, including bulk metals as well as non-continuous metals such as powder or chips. The enhancement of mechanical characteristics in bulk metals can be achieved by the process of microstructure refinement, as demonstrated by Tahara [24]. In contrast, while considering the utilisation of powder and chips, it has been observed that they possess the ability to be efficiently and compactly consolidated at low temperatures [25].

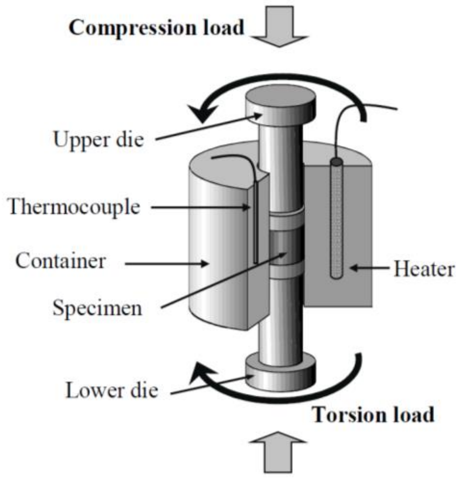

Fig. 4 *Compressive torsion process schematic*[23]

2.3.2 Screw Extrusion

Screw extrusion of aluminum is a new continuous solid-state process developed at the Norwegian University of Science and Technology (NTNU) together with Norsk Hydro [26]. Fig. 5 shows a schematic drawing of the screw extruder. A motor rotates a screw inside a container. Material in the form of granulation is fed through a feed hole at the rear part of the machine. The material enters the cavity between the screw and the container and is subsequently pushed forward by the rotating screw. Material is heated due to contact with the warm container walls and deformation work. The extrusion chamber positioned at the front end of the screw is filled up, and the granulate is consolidated due to a state of high pressure, elevated temperature, and the deformation the rotating screw introduces. Finally, the consolidated aluminum is continuously extruded through the die orifice, creating a profile.

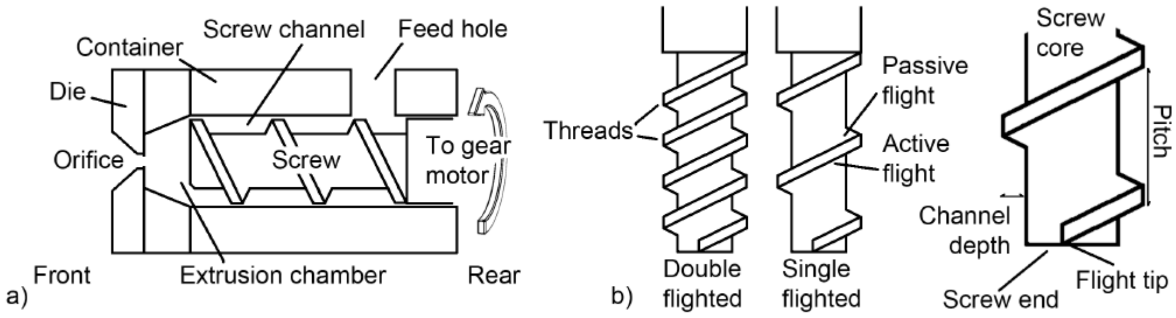

Fig. 5 *a) Schematic drawings of a screw extruder. b) Geometry of single and double flight screws* [27]

Fogagnolo's study focused on the direct recycling of aluminum alloy chips via cold and hot pressing, followed by hot extrusion. He found that the ultimate tensile strength (UTS) and hardness of the recycled materials were higher than those of the conventional casting process alloy [19]. Scott Whalen's study compares the tensile properties of ShAPE extruded Al 6063 tubing from unhomogenized billets with conventional extrusion of homogenized billets [28]. The results show that ShAPE extrusion can achieve similar, and in some cases superior, properties compared to conventional extrusion of homogenized billets. ShAPE, which stands for Shear Assisted Processing and Extrusion, represents a significant advancement in the field of aluminum recycling processes.

2.3.3 Hot Forging

This section presents a novel direct reduction (DR) approach employing hot forging, which effectively streamlines the process, minimises energy use, and offers significant operational cost advantages. The process of hot forging necessitates the occurrence of plastic deformation, thus necessitating the attainment of a high temperature in the workpiece that aligns with the recrystallization temperature of the metal. The described technique employs a singular process wherein the chip is subjected to direct pressure under certain temperature settings, as depicted in Fig. 6.

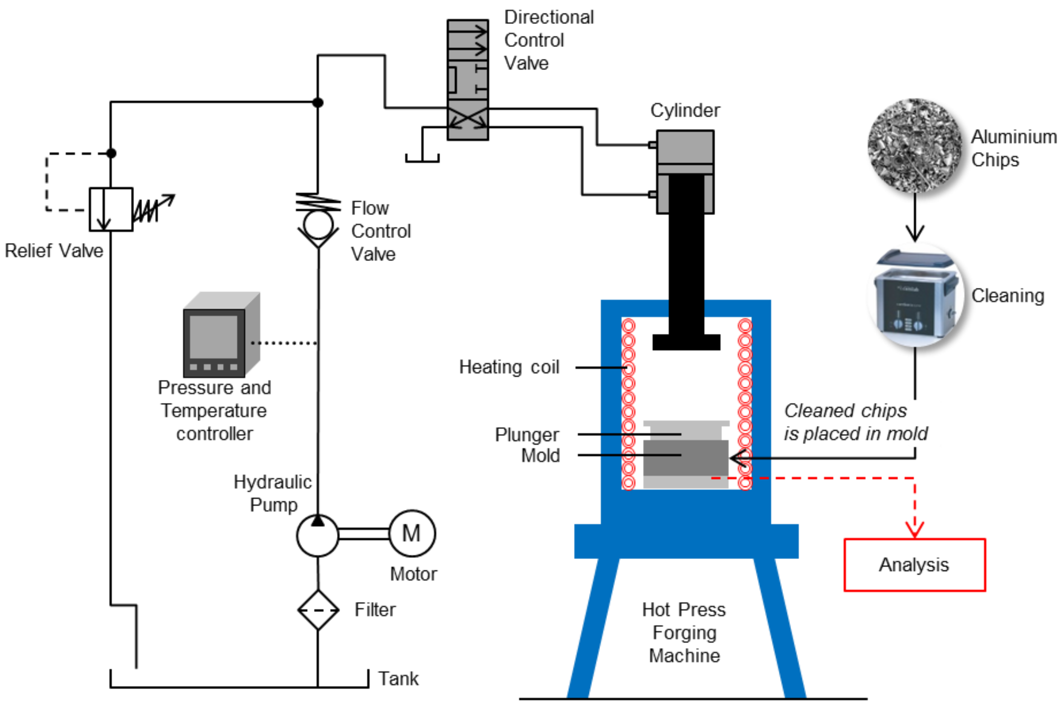

Fig. 6 *Hot forging schematic*

In general, the term "forging" typically refers to the process of hot forging, which involves conducting the forging operation at temperatures above the recrystallization temperature [29]. When an object is subjected to heating, it undergoes a transformation in which it becomes ductile. This ductility is attributed to the absence of strain-hardening during the deformation of the metal. The utilisation of less energy in metalworking facilitates the process by capitalising on the enhanced ductility of the metal and the diminished strength of the work material. Consequently, this approach effectively mitigates the issue of strain-hardening. According to Beddoes and Bibby, high-temperature metalworking conditions enable a greater degree of deformation and necessitate lower levels of forming energy [30]. In industrial contexts, two primary forms of hot forging are frequently employed: open-die forging and closed-die forging. The utilisation of closed dies is crucial in achieving accurate forging of components, hence ensuring the absence of burrs. Doege and Bohnsack made a significant finding in the field of closing devices, wherein they identified a novel mechanism that effectively reduces both the energy required for closure and the pressing load [31]. Hence, the utilisation of various strategies in recycling endeavours serves to enhance the overall efficacy of recycling operations.

2.3.4 Cold Forging

Cold forging (or cold pressing) is a process where a chip is inserted into a die and squeezed with a second closed die. The deformation happens at room temperature and changes the shape and size of the initial part until it has assumed the shape of the die as shown in Fig. 7. This process is usually highly automated, and parts can be made economically. Another benefit of cold forging is the lack of grain growth, and therefore perfectly aligned to the shape of the part metal grains with an exceptionally strong and resistant surface. The process is relatively simple, which leads to material savings, and is primarily focused on high-precision shapes, close tolerances, and better surface finishes without excessive finishing.

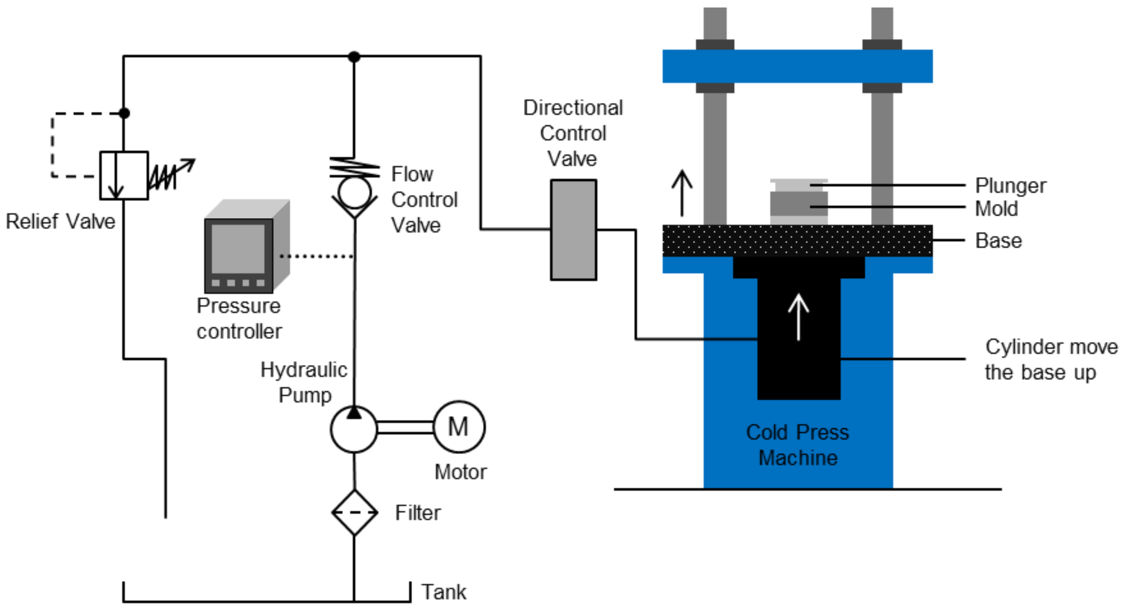

Fig. 7 *Cold forging schematic*

Investigations into the recycling of scrap aluminum through cold bonding were conducted by Allwood. The process involved loosening oxide layers on adjacent pieces of scrap aluminum, allowing the softer aluminum to be extruded through the cracks. Cold bonding processes resulted in considerably less material loss compared to conventional recycling and demanded only around 2% of the energy. This method primarily produced ingots and not final products, significantly reducing material waste [32].

3. Discussion

Direct recycling techniques also encompass 4 different methods, with hot forging being the most extensively studied, totaling 14 research studies conducted from 2013 to 2020. A recent study by Ahmad investigated the effect of temperature and holding time, specifically with the use of hot press forging [32]. The research found that hot forging can enhance the ultimate tensile strength of materials, like the characteristics of hot extrusion. These techniques hold the potential to optimize the properties of recycled materials, resulting in improved final products.

However, it's important to note that many of these techniques are not widely adopted among researchers due to limitations associated with the methods. These limitations include the availability of necessary supplies and the high costs of equipment and operation, which are common challenges faced by researchers conducting these experiments.

Fig 8 illustrates the historical progression of recycling techniques for aluminum. Research in this field began before 1995, focusing on conventional melting-based processes. This approach has seen continuous development, including upgrades to melting furnaces and the integration of secondary pre- or post-processing steps. For example, Puga highlighted the benefits of induction melting, achieving metal recovery rates of up to 90% while minimizing waste generation by avoiding traditional salts and fluxes. Velasco and Nino discussed the recycling of aluminum alloys in both rotary and reverberatory industrial furnaces, emphasizing their productivity, ease of operation, high melting rates, homogeneity, and energy efficiency[33], [34]. However, these early publications did not directly compare these conventional techniques with newer SDR or DR methods. This historical trend, as depicted in Fig 9, showcases the evolution of aluminum recycling research, starting with conventional melting techniques and gradually exploring modifications and innovations to enhance the recycling process.

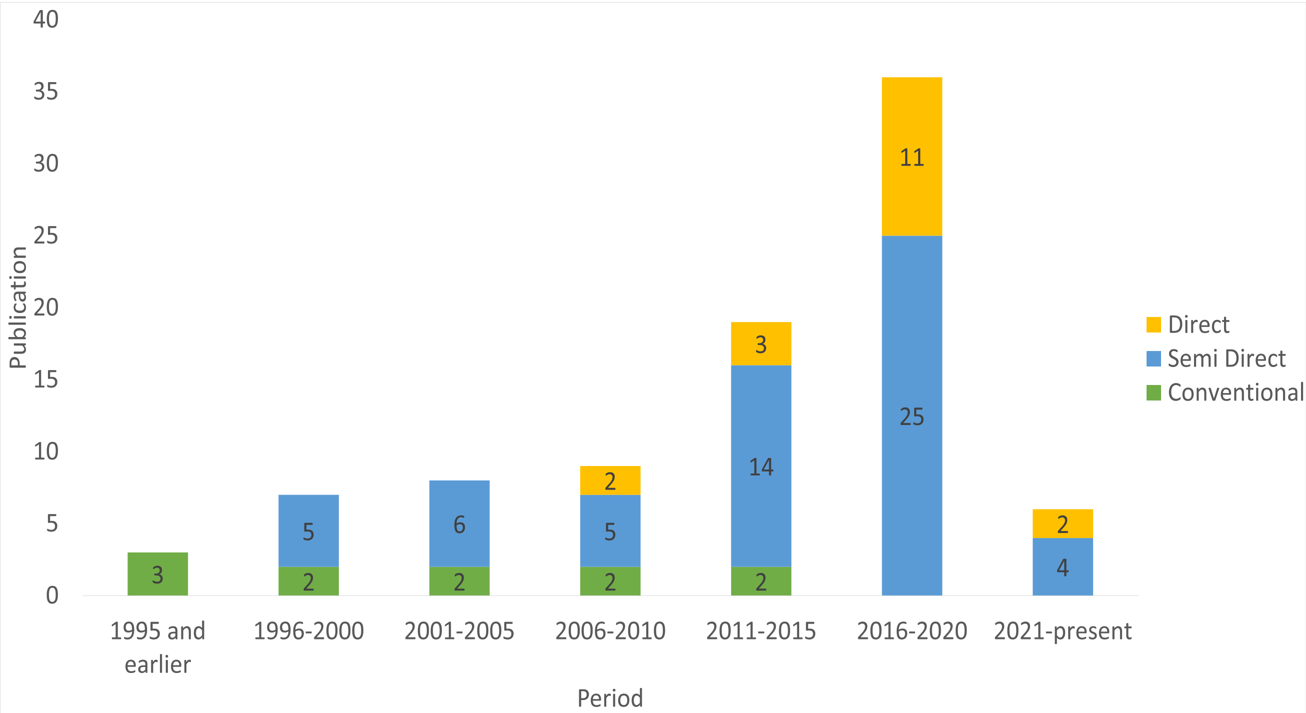

Fig. 8 *Chart diagram analysis based on table of literature review.*

In 1996, the era of semi-direct recycling commenced when researcher [35] described a method in which aluminum chips and their alloys could be directly converted into finished products. Since then, these techniques have undergone continual development through various modifications. These include adjusting the volume of machined chips, incorporating pre-processing steps, and experimenting with different die shapes to enhance the final product's characteristics.The most recent development in this journey began in 2011 with direct recycling techniques, pioneered by researcher Wideore [27]. In the years that followed, researchers have actively explored direct recycling methods, continually experimenting and conducting various modifications. These modifications encompass diverse factors such as temperature variations, holding times, and the addition of pre-processing steps and different materials.

The hot forging and extrusion route is an optimal process from a cost-benefit ratio perspective. Meanwhile, Gronostajski developed an SDR technique for granulated aluminium and its alloy chips by converting them into a finished product with reinforcing phases, including aluminium oxide, tungsten, carbon, ferrochromium, and aluminium bronze comminuted chips[9], [10], [36]. Other findings have shown that the relative densities of the composites after hot extrusion are nearly identical (more than 98%) to those of solid materials. Extrusion die geometry also plays an essential role in ensuring the bonding between chips. A proper die design leads to the extrusion route that guarantees sufficient billet densification and chip bonding. A recent study showed that Equal Channel Angular Pressing (ECAP), which was implemented by Cui is an alternative die geometry that introduces higher imposed strains and higher pressures on the recycled chip, resulting in no voids in the produced extrudates [37], [38]. Therefore, SDR can be described as the best technique because recycled aluminium exhibits similar mechanical and microstructural properties as conventional cast billet.

In this study, Scott Whalen employed the direct recycling technique to examine the viability of Shear Assisted Processing and Extrusion (ShAPE) as a means of accommodating elevated iron levels during the extrusion process of secondary aluminium scrap [28]. This method was introduce by Overman that combines high shear and extrusion [39].The significance of this matter is in the necessity to dilute iron impurities found in secondary aluminium scrap with primary aluminium during the process of conventional recycling. This is done to ensure that subsequent alloys produced adhere to the permissible limits of iron content. The objective of this work was to investigate an alternate approach that can withstand increased levels of Fe content without requiring the addition of primary aluminium for dilution purposes.

Meanwhile, DR is a newly developed alternative approach to the recycling of aluminium. This approach was first executed by Kuzman and Pepelnjak and Kuzman cold forging [40], [41]. Although compressed billets possess high relative density and compactness, the quality of the bond between the chips remains an issue. Lajis and Yusuf extended the work of Kuzman and Pepelnjak by utilizing hot forging for different-sized aluminium chips, demonstrating a remarkable potential in their strength properties and proving that this technique is an acceptable alternative recycling method[40]–[43]. Further research on DR is highly recommended to fill knowledge gaps and understand future trends in aluminium recycling.

4. Conclusion

This review provides appropriate alternatives for helping decision-makers use multi-criteria decision analysis for recycling aluminium techniques. In this paper, three recycling techniques, i.e., conventional recycling (CR), semi-direct recycling (SDR) and direct recycling (DR), were reviewed. Current aluminium recycling practices via melting techniques, in which the temperature exceeds the melting point, are CR methods. The SDR technique includes a pre-processing step before performing the main process of powder metallurgy and/or hot extrusion. DR only requires a single step to produce the final products. Currently, there are only two processes that have been recognized as DR techniques: cold and hot forging.

Publications on aluminium recycling originally introduced the melting technique in the early 1980s. The process evolved in 1996 with the invention of the solid-state recycling technique. Moreover, newly developed approaches were introduced in 2012. Parallel to this evolution, researchers have aimed to reduce the number of steps, which can diminish energy needs and reduce production costs. Waste reductions have led to relatively eco-friendly solutions, indicating increasing awareness of sustainable manufacturing among researchers. In the future, DR techniques still have much knowledge and contribution gaps that must be explored. We recommend that additional studies on DR techniques are needed to ensure knowledge continuity and environmental sustainability.

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