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REVIEW

Recent advances in the remelting process for recycling aluminium alloy chips: a critical review

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Abstract
This critical review examines advances in preprocessing and remelting processes for aluminium alloy chip recycling, emphasizing pre-treatment and remelting techniques that improve both resource recovery and material quality. Pre-treatment strategies, particularly cleaning methods and compaction are critically evaluated. Various cleaning methods, including centrifugation, ultrasonic solvent washing, extraction, and distillation are compared based on their ability to remove residual cutting fluids. Cold compaction, which augments chip density to approximately 2.5 g/cm^3, significantly curtails oxidation losses and enhances metal recovery. During remelting, NaCl-KCl-based fluxes with limited fluoride additions (e.g., 3–7 wt% Na_3AlF_6) disrupt oxide networks but require careful dosage control to minimize furnace corrosion and environmental hazards. Moreover, mechanical stirring combined with suitable melting temperatures reduces porosity while enhancing melt purity. Future research should prioritize the development of low-energy cleaning methods, flux composition optimization, and scalable production techniques to further advance sustainable aluminium recycling.

Keywords Aluminium alloy · Metallic chips · Remelting recycling process · Material recovery

Introduction

Aluminium alloys, recognized for their high mechanical properties—including strength and corrosion resistance [1–3], are extensively used in various industrial sectors, such as aerospace [4], aircraft [5], automotive [6], and marine engineering [7]. The machining process involves substantial material removal in the form of chips to achieve the desired final shape and size. Notably, in sectors such as mold making and aeronautics, chip removal can constitute up to 80% of the original workpiece mass [8]. The compelling economic and environmental advantages of aluminium recycling have drawn increasing attention. In particular, primary aluminium production requires approximately 45 kWh per kg and produces 12 kg CO_2 per kg, while secondary production through aluminium scrap remelting requires only 2.8 kWh per kg and emits 0.6 kg CO_2 per kg [9]. This pronounced disparity in resource utilization is mirrored in market pricing, as secondary aluminium enjoys a cost advantage of $441–$661 per ton relative to primary aluminium in North America, sometimes more [10]. Collectively, these factors underscore the potential of aluminium recycling to dramatically enhance the metal's sustainability profile while delivering significant economic benefits. Over the past forty years, the recycling and recovery of aluminium alloys have significantly increased, driven by their cost-effectiveness, environmental sustainability, and reliability in the production of aluminium parts [11]. Additionally, aluminium is considered one of the critical raw materials in Europe, underscoring its importance in the region's industrial landscape [12]. This increased focus on sustainability is evidenced by the emergence of a market trend for "green aluminium," with the establishment of a new trading platform for low-carbon aluminium at the London Metal Exchange in 2020. Currently, about one-third of aluminium production is sourced

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from scrap aluminium. The International Aluminium Institute projects this number to surpass 50% by 2050, as shown in Fig. 1. Consequently, research on scrap aluminium recycling has emerged as a prominent area of focus.

Researchers have proposed various methods for recycling aluminium chips, categorizing them into two main approaches: remelting methods and alternative methods [15]. In remelt recycling, the chips are typically heated and melted before being re-prepared through casting or other techniques [16]. However, this method presents certain challenges including a relatively higher metal loss and lower recovery rate due to the increased chemical reactivity and larger specific surface area of the metal chips [17, 18]. The recovery rate was calculated using Eq. (1) [19]. Moreover, the combustion of the oil emulsion adhering to the scrap chips can lead to the generation of toxic gases [20]. Consequently, the remelting casting method for recycling usually requires the processing of the chips [21], like cleaning, which leads to greater energy consumption and higher costs. Therefore, many scholars have changed their research direction to develop many new technologies.

$$R = \frac{m_1}{m_0} \times 100\% \quad (1)$$

Where R is the recovery rate of aluminium chips; m_0 is the total mass used of aluminium chips; m_1 is the mass of recycled aluminium.

In recent years, technologies that have been reported so far are: hot extrusion [22], Equal Channel Angular Pressing (ECAP) [23], Cyclic Extrusion Compression (CEC) [24], Friction Stir Extrusion (FSE) [25], High Pressure Torsion (HPT) [26], Ploughing Extrusion Cutting (PEC) [27], Screw Extrusion (SE) [28] Spark Plasma Sintering (SPS) [29], and Solid-State Electrolysis (SSE) [30]. These new recycling methods can be divided into two methods [20]: solid-state recycling techniques based on Severe Plastic Deformation (SPD) and solid-state recycling techniques based on Powder Metallurgy (PM). SPD methods including hot extrusion, ECAP, CEC, FSE, HPT, SE, and PEC, rely on extreme plastic deformation to bond aluminium chips into dense bulk materials. While these methods improve mechanical properties, they often require high processing loads, leading to excessive tool wear and high energy consumption [20]. These methods effectively achieve high-density structures but face issues like porosity, oxidation, and the need for additional processing steps, increasing costs [31]. Moreover, contamination from cutting fluid and oxide layers can hinder the bonding of aluminium particles, affecting mechanical strength [32]. PM methods such as SPS involve the compaction of aluminium chips into powder-like forms before consolidation. This process will also result in high energy consumption compared with other solid-state recycling methods, therefore, it is necessary to improve this problem by shortening the sintering cycle, mass production or improving energy efficiency [33].

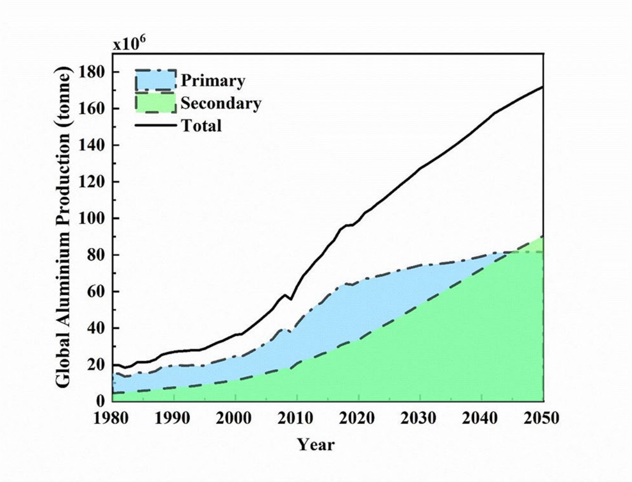


Fig. 1 Global aluminium production from primary and secondary sources [13, 14]

Given the inherent limitations of solid-state recycling processes, the remelting method has become the method of choice in industry owing to its simplicity [34]. Typically, the process involves remelting chip material followed by casting to produce new components. However, manufacturing generates chips often contaminated with cutting fluids or other substances; recycling these untreated chips can markedly reduce the metal recovery rate. Thus, the pretreatment of chips is essential. Here, we focus on two critical aspects: the pretreatment of chips and the optimization of the remelting-casting process.

Pre-treatment of chips

Cleaning methods

Thorough cleaning to remove residual cutting fluid is crucial in the process of recycling aluminium chips. Cutting fluids (e.g., oils, oil-water emulsions and so on) contain additives that may contaminate recycled aluminium. Ineffective cleaning poses environmental risks, complicates processing, and consumes resources. Moreover, conducting direct remelting recovery without any intermediate processing can result in the formation of flames or toxic gases, posing significant health risks to operating personnel [20, 35]. Current cleaning methods from literature research mainly include centrifugation, washing with solvents, extraction, ultrasonic cleaning, thermal methods, distillation and so on [17].

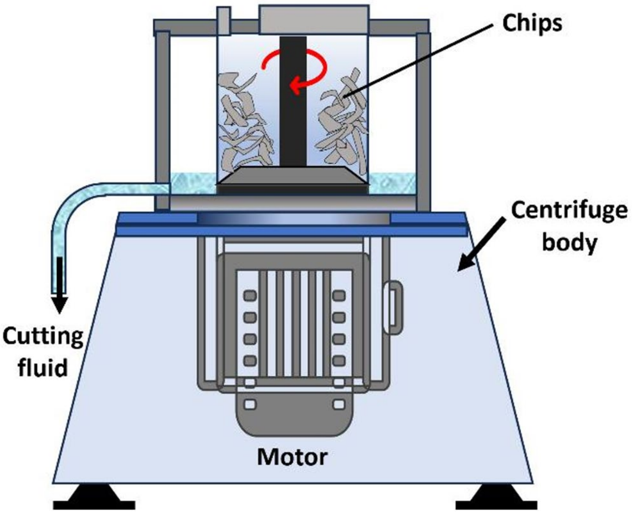


Fig. 2 Centrifugal separation system for chips cleaning. (Adapted from Ref [38, 39])

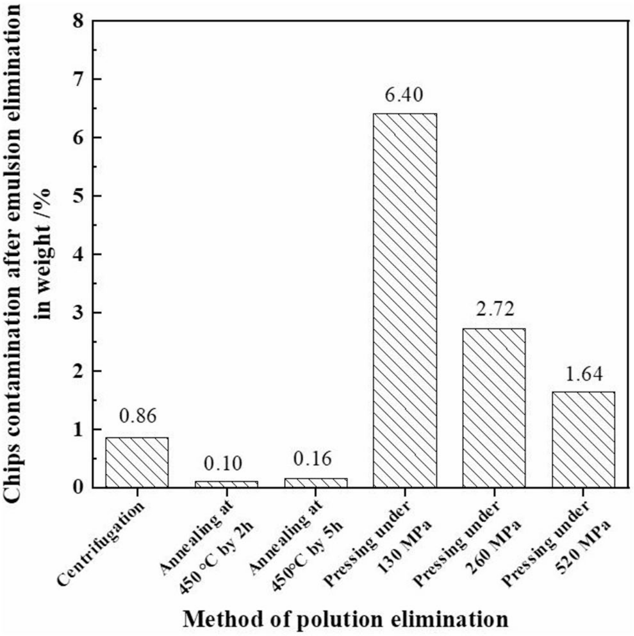


Fig. 3 Results of different emulsion elimination methods data from [37]

Centrifugation

Centrifugal separation leverages centrifugal force to remove cutting fluids from chips (Fig. 2). This method is widely adopted in industry due to its scalability. It has undergone continuous enhancement and optimization processes. Many scholars have adopted the centrifugal method to clean cutting fluid that is adhered to the chips. Wang et al. [36] combined cyclone separation with heating to purify chips, achieved high-quality recycled aluminium alloy with a 25.95% metal loss. Mateusz et al. [37] compared centrifugation, thermal, and pressing methods (Fig. 3), finding centrifugation eco-friendly and effective (< 1% contaminants), with reusable cutting fluids. Centrifugation is predominantly adopted in high-volume, low-cost sectors like automotive parts manufacturing (e.g., Mateusz et al. [37]'s study on casting Al-Si alloy). Its scalability and compatibility with cutting fluid reuse align with industries prioritizing rapid processing of bulk chips over ultra-high purity.

Ultrasonication and washing with solvents

Solvents such as water, alkaline solutions (e.g., NaOH), and organics (e.g., acetone) are used to dissolve cutting fluids. Cooper et al. [40] and Xiong [41] demonstrated that acetone reduces metal loss during remelting. Hyodo et al. [42] cleaned AA7050 chips with an alkaline solution, carefully dried them using a propane flame, and utilized them as raw materials for recycling processes. Perez-Rangel et al. [34] purified the chips by a solution of caustic soda (NaOH) in water, recycled them with the casting method, and obtained a solid aluminium bar that meets the hardness standard.

In some cases, ultrasonic cleaning is employed in conjunction with solvent cleaning to enhance effectiveness. Khamis et al. [43] and Pandey et al. [44] immersed chips in acetone with ultrasonication, achieving efficient degreasing. Kore et al. [45] crushed 6082 aluminium chips into particles smaller than 5 mm and then sieved them. The particles were cleaned with soap and acetone in an ultrasonic bath, demonstrating the effectiveness of the cleaning method in achieving good organization during solid-state recovery.

It is worth noting that titanium chip cleaning methods, similar to aluminium, provide valuable references. Bao et al. [46] and Malec et al. [47] compared the removal rates of cutting fluid attached to titanium chips in ultrasonic cleaning with different cleaning agents (Na_2CO_3, acetone-CH_3COCH_3, cyclohexane-C_6H_{12} and so on.), the measurement results, present in Fig. 4 (b), show that the cleaning effect of Na_2CO_3 and acetone is better, with a carbon removal rate of nearly 80%, while the cleaning effect of cyclohexane is relatively poor. In the study by Denkena et al. [48], the chips undergo a sequential cleaning procedure comprising immersion in water and liquid soap, followed by thorough rinsing until foam-free. Subsequently, the chips undergo a meticulous cleaning process utilizing acetone in an ultrasonic bath, with a duration of 15 min. Finally, the specimens are subjected to air drying. For the industrial application, the high cleanliness achieved by ultrasonic-solvent methods (e.g., < 1% contaminants) makes them suitable for high-performance alloy recycling, such as aerospace-grade AA7050 [42], where residual impurities critically affect mechanical properties.

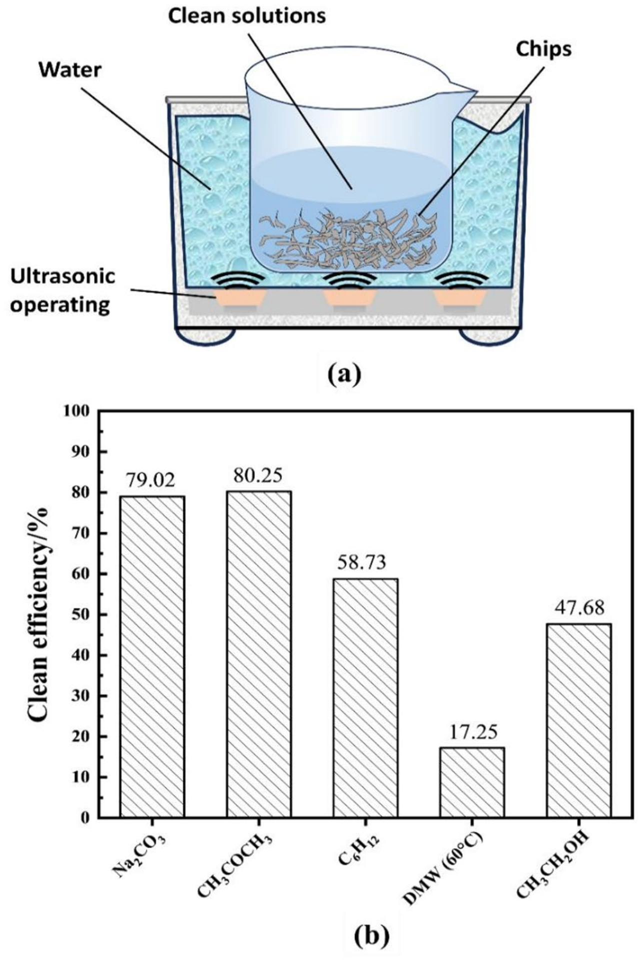


Fig. 4 Cleaning methods and results: (**a**) Ultrasonic cleaning machine, (**b**)The influence of different cleaning agent type on the clean efficiency (DMW-Demineralized Water) (data from [46, 47])

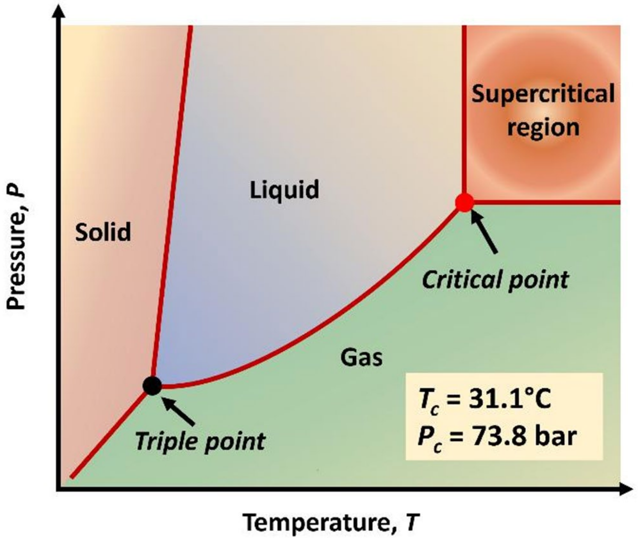


Fig. 5 Supercritical CO_2 P-T diagram [50]

Extraction

Research on extracting cutting fluid from chip surfaces dates to 1999, when scholars explored various separation methods using organic solvents and extractants to simultaneously achieve chip cleaning and cutting fluid recovery. A notable contribution came from Leffrang et al. [49], who proposed the separation of metal grinding sludge into oil and metal by using supercritical carbon dioxide (CO_2) extraction. Operating above its critical temperature (304.25 K or 31.1 °C) and pressure (73.8 bar), CO_2 behaves as a supercritical fluid—expanding to fill its container like a gas while maintaining a density akin to that of a liquid [50], as shown in Fig. 5. This method is particularly advantageous, as supercritical CO_2 exhibits solvent properties comparable to those of conventional organic solvents like benzene and carbon tetrachloride in dissolving grinding oils, yet it offers considerable environmental benefits over these traditional options. Fu et al. [51] discovered that the removal effect of cutting fluid using supercritical CO_2 extraction and washing with water-based surfactants is comparable. Moreover, Großwendt et al. [52] employed the supercritical CO_2 extraction process to clean tool steel swarf and separate cutting fluid. They subsequently utilized a densification process for metal recovery, resulting in less than 1 vol% residual contaminants in the recovered samples. Overall, supercritical CO_2 extraction can be adopted in specialized applications requiring ultra-low contamination, though its reliance on high-pressure systems limits broad industrial adoption.

Thermal methods

Thermal methods can also be employed to remove cutting fluids from machined aluminium chips. Heat application evaporates and decomposes organic cutting fluids, effectively cleaning chips without extra solvents [53]. Palimąka [21] and Gronostajski [54] report that the thermal method is also a good method to clean the chips; Cui et al. [55] conducted a study comparing the efficacy of thermal and acetone methods in degreasing aluminium chips, followed by their recycling using the CEC method. The findings revealed that utilizing the thermal method for degreasing aluminium chips, as opposed to the acetone method, led to a heightened oxidation of the aluminium chips and an increase in the thickness of the oxide film. In industry, thermal cleaning can be applied to low-grade scrap recycling (e.g., construction materials), where Cui et al. [55]'s observed oxidation losses are economically tolerable compared to upfront cost savings.

Distillation

During the distillation process, the method can be employed to remove cutting fluid from the surface of chips. Distillation removes cutting fluids from chips, enabling their recovery and reuse. Wang et al. [17] utilized the distillation method to eliminate cutting fluid from 7075 aluminium chips. They investigated the removal mechanism of this approach and, through integration with simulation techniques, identified the ideal operating temperature and processing duration for attaining the highest removal efficiency. Following the optimization process, the oil and water removal rates were remarkably enhanced, achieving a remarkable 99.7% efficiency. Distillation's high removal efficiency (99.7%) supports its use in high-value aluminium grades, where cutting fluid recovery offsets the process's energy intensity. Closed-loop fluid systems further enhance distillation's viability in resource-conscious industries like sustainable manufacturing.

Considerations such as safety of cleaning methods, equipment costs, and time consumption are crucial in actual production processes. While thermal methods offer a simple approach, they are often time-consuming and energy-intensive, potentially exacerbating oxidation of the aluminium chips, which can negatively impact metal recovery rates [55]. Alternatively, extraction and distillation techniques allow for the simultaneous cleaning of metal chips and recovery of cutting fluid lubricating oil. However, these methods introduce complexities that may hinder overall production efficiency. In contrast, combined approaches utilizing ultrasonic cleaning and washing techniques have demonstrated high effectiveness in removing cutting fluid residues from aluminium chip surfaces [56] and are widely adopted in current production due to their simplicity, cost-effectiveness, and practicality. Nevertheless, the responsible disposal of spent solvents from these processes remains a significant concern requiring diligent management. Table 1 summarizes cleaning methods, and their associated parameters as employed in selected studies focused on aluminium alloy recycling. It is worth noting that these studies provide strong evidence for the effects of different cleaning techniques on chip recycling, almost none have evaluated the related energy consumption and environmental impact.

From the preceding discussion, it is evident that although numerous cleaning methods are currently available, achieving an optimal balance among cleaning efficiency, energy

Table 1 Clean methods employed in the chips recycling process

Ref	Cleaning Type	Operation parameters	Main outcome
[57]	Centrifugation	Centrifuged for 10 min at 400 rpm	
[55]	Thermal method	Thermally treated in a muffle furnace at 460 °C for 30 min	Thermal degreasing of aluminium scrap increases the thickness of the oxide film layer
	Washing with solvents	Cleaned with acetone	
[42]	Washing with solvents	Washed with alkaline cleaner	
[35]	Centrifugation	Centrifuged for 10 min at 400 rpm.	
[43]	Ultrasonic solvent cleaning	Cleaned by ultrasonic bath using acetone solution	
[37]	Centrifugation	Centrifuged with rotation speed of 2800 rev./min	centrifugation was found to be both eco-friendly and successful in keeping contaminants below 1%
	Thermal method	1.Heating: 450 °C for 2 h or 5 h 2.Annealing: 450 °C for 2 h	
	Pressing method	Pressed under the pressure of 130 MPa, 260 MPa and 520 MPa	
[45]	Washing with solvents, ultrasonication	Cleaned via soap solution → ultrasonic acetone bath	
[58]	Washing with solvents, ultrasonication	Cleaned via acetone then cleaned by ultrasonic bath for 30 min	
[44]	Ultrasonic solvent cleaning	Chips were cleaned by acetone in an ultrasonic bath for 30 min	
[48]	Washing with solvents, ultrasonic solvent cleaning	Chips are first washed with water and liquid soap, then cleaned in an ultrasonic acetone bath for 15 min	
[56]	Ultrasonic solvent cleaning	Best condition: Ultrasonic cleaning for 30 min with a 2:5 scrap-to-agent ratio, 60 °C temperature, and 28 kHz frequency	
[46]	Ultrasonic solvent cleaning	The chips were immersed in sodium carbonate (Na_2CO_3) /acetone/cyclohexane (C_6H_{12}), ultrasonically cleaned at 40 kHz, rinsed with deionized water to neutrality, and oven-dried at 105 °C for 2 h	
[52]	Extraction	Residual oil was removed via supercritical CO_2 extraction (scCO_2)	
[17]	Distillation	The chips underwent centrifugation, followed by distillation to remove and collect residual oil/water, with heating at 370 °C for 70 min under a 3 cm loading thickness	The removal rate of water and oil is up to 99.7% with best conditions.
[59]	Thermal method	Heated at temperatures around 250 °C for approximately 2–3 h	

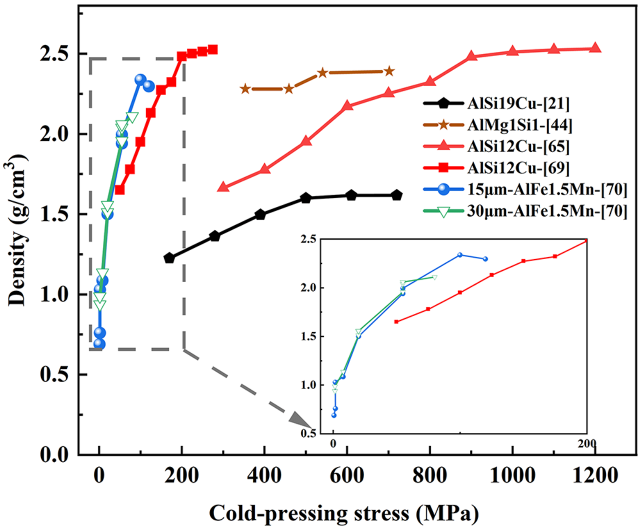


Fig. 6 Compressibility curve of different Al alloy (The data used to rebuild the diagrams were obtained from [21, 44, 65, 69, 70])

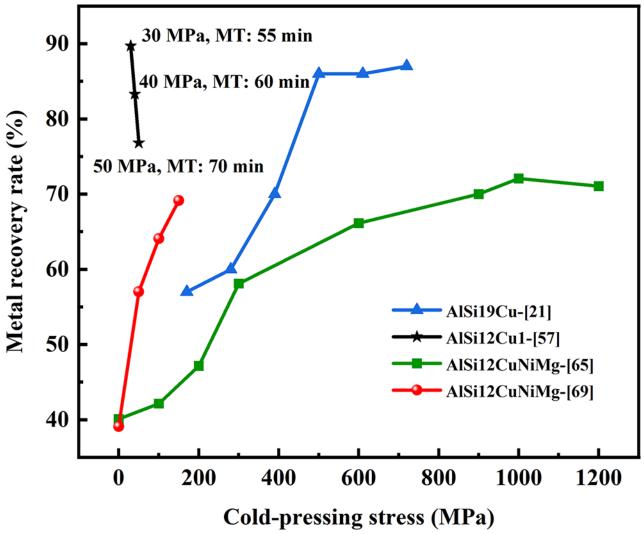


Fig. 7 The impact of different processes on the recovery of Aluminium scrap (MT: Melting time) (The data used to rebuild the diagrams were obtained from [21, 57, 65, 69])

consumption, and environmental impact remains a challenge. Addressing these issues at their source may present a more effective solution. In this context, a novel approach is gaining traction within the manufacturing sector - cryogenic machining. This innovative technique eliminates the need for conventional oil-based emulsions as cutting fluid, instead employing environmentally benign alternatives such as liquid nitrogen [60] or liquid carbon dioxide [61] as cutting fluids.

In machining applications, cryogenic assistance enabled a better heat absorption in the contact zone, significantly reducing tool wear and thereby extending tool life [62]. This method also enhances surface finish quality [63]. From a chip recycling perspective, chips generated using cryogenic-assisted methods are free from contaminant residues [64], eliminating the need for cleaning during recycling. Furthermore, the reduced processing temperatures help mitigate chip oxidation, which may be helpful to improve metal recovery rates.

Chips compaction

Compaction is a critical preprocessing step in aluminium chip recycling, directly enhancing both logistical efficiency and metallurgical outcomes. By reducing chip volume and increasing density, compacted materials are easier to handle, charge into furnaces, and exhibit lower oxidative losses during remelting [65, 66]. These combined effects significantly improves overall metal recovery rates [67].

Studies consistently highlight the influence of compaction pressure on recycling efficiency. For example, Bhaskar et al. [68] demonstrated that compacting aluminium scrap, regardless of the furnace type, reduces melt losses and enhances metal recovery. Research consistently demonstrates that varying compaction pressures result in chips with different densities, significantly influencing recycling efficiency. Despite variations in target materials across studies, the compression-density curve consistently follows a similar pattern. As illustrated in Fig. 6, increasing compaction pressure raises chip density. However, once the density approaches approximately 2.5 g/cm³, further increases in pressure yield minimal density gains.

The correlation between compaction pressure and recovery efficiency has been systematically investigated. Moloodi et al. and P. Palimąka [21, 65, 69] examined cold pressing effects on aluminium alloy chips through controlled experiments, including pure scrap recycling and flux-assisted treatments. Despite minor variations in material composition, the experimental results demonstrate that cold pressing within optimal pressure ranges significantly enhances metal recovery rates. This trend is illustrated in Fig. 7, which shows that pressing with or without flux results in measurable improvements. The established near-linear relationship suggests higher pressures generally correlate with improved yields.

However, exceptions to this trend exist. Puga et al. [57] reported lower compaction pressures enhancing recovery rates when recycling AlSi12Cu1 alloy chips blended with 66.7% ingots, as shown in Fig. 7. It is important to note that differences in melting time across the experiments may also have contributed to the observed outcomes. Similarly, Vallejo-Olivares et al. [71] compared uniaxial compaction and Moderate Pressure Torsion (MPT) for aluminium sheet fragments. MPT-produced high-density samples generated 29 wt% dross (of charged mass) and achieved only 97% total metal recovery. This reduced yield was attributed to the compaction-induced restriction of pyrolytic decomposition of organic residues during melting. This study reveals the critical importance of removing organic residues from recycled materials. Accordingly, for aluminium alloy recycling, the optimal protocol involves eliminating organic contaminants—such as cutting fluids or other coatings—prior to compaction, thereby facilitating a higher metal recovery rate.

Collectively, these studies emphasize that compaction alone cannot maximize recovery. Effective preprocessing, particularly organic contaminant removal (e.g., cutting fluids)—is essential to mitigate dross formation. When combined with optimized pressure, such steps ensure energy-efficient recycling with minimal oxidative losses.

Remelting recycle process

Oxidation reduction using flux

The most crucial aspect of the aluminium chips recycling process is to enhance the recovery rate while preserving the performance of the recycled metal. The high oxygen affinity of aluminium inevitably leads to oxide formation during remelting [72], which degrades metal properties and increases energy consumption [57]. Fluxes counteract these effects by suppressing oxidation and enhancing melt purity, thereby improving both recovery rates and recycled metal quality [73, 74].

In conventional casting without fluxes, aluminium oxidation upon contact with water leads to the formation of white dross on the furnace surface [67]. Drosses usually contain around 60–80% aluminium, with the remaining portion being aluminium oxide. Improved fluxing and drossing techniques can reducing dross metal content to 30% [75]. According to Tenorio et al. [76], drosses present intricate structural compositions. The oxides in the dross form a continuous net structure that ensnares the aluminium within. This framework can be broken by the molten flux, which then assists in the coalescence of aluminium drops that sink into the aluminium molten, the mechanism of action of fluxes is depicted in Fig. 8. A widely employed flux is a blend of equimolar sodium chloride (NaCl) and potassium chloride (KCl), with the potential addition of fluoride to enhance the purification effect [77, 78].

Numerous studies indicate that optimal flux parameters depend on alloy composition and processing conditions. For instance, Cooper et al. [40] recovered AA6060 alloy using an equimolar NaCl–KCl flux (35% of the crucible mass) heated to 800 °C with the chips prior to casting, thereby enhancing material recovery. Similarly, Bhaskar et al. [68] employed a 3:1 NaCl–KCl mixture in Al-Si8Cu3Fe alloys at 750 °C to minimize metal loss, while Saleh et al. [16, 79] demonstrated that fluxes improve the melting of Al-Si7Mg swarf, and that melting temperature affects oxidation intensity.

The performance of flux is affected by the melting temperature, the flux-to-metal ratio, and the type of fluoride additives used. Commonly employed fluoride additives include KF, NaF, CaF_2, Na_3AlF_6, K_3AlF_6, $NaAlF_4$, $KAlF_4$, and their combinations [13]. Tenorio et al. [80] conducted a study that revealed the enhancing effect of an equimolar NaCl-KCl mixture when coupled with fluoride addition on the dissolution velocity. Research by Wan et al. [81] showed that reducing the interfacial tension between the molten aluminium and the salt flux promotes the flux's diffusion on the melt surface, facilitating the removal of solid inclusions. Additionally, lowering the interfacial tension between the salt flux and inclusions, while increasing tension between the aluminium melt and inclusions, also aids in the removal of solid inclusions by the flux. Figure 9 illustrates the impact of different fluoride additions in the flux on interfacial tension. Shi et al. [82] investigated the effects of fluoride type and content on interfacial tension using the sessile drop method [83] and observed its influence on impurity removal. Their results demonstrated a significant reduction in hydrogen content (by 40.4%) and impurity content in the alloy (by 90.2%) under optimal process conditions, resulting in improved mechanical properties. Figure 10 illustrates the impact of fluxes with varying types and fluoride contents on microstructure. Despite the differences in types and contents, all fluxes demonstrate a reduction in the shrinkage ratio. Furthermore, several studies have indicated that the use of Na_3AlF_6, NaF, and KF can significantly improve agglomeration efficiency [81, 82, 84].

This fluoride-driven interfacial optimization requires stringent concentration control in industrial settings to balance efficiency and sustainability. Ozer et al. [73] demonstrated that 5 wt% fluoride content in flux (added at 1 wt% of metal charge) as the optimal threshold for maximizing used Aluminium Beverage Cans recycling efficiency. While the addition of fluorides can improve the melt's cleaning efficiency, excessive fluoride levels may compromise the

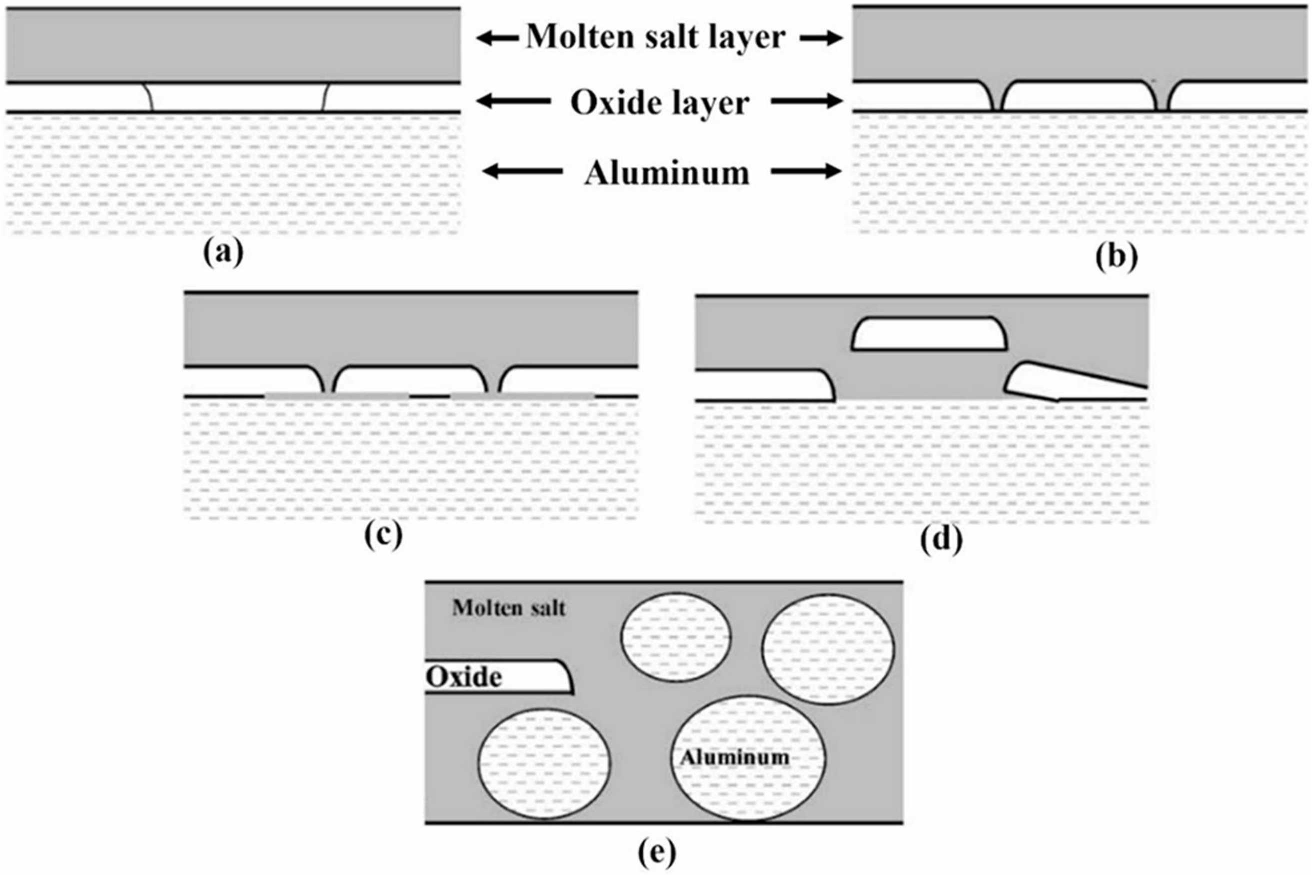


Fig. 8 Sketch of the oxide detachment caused by the molten salt: (**a**) Contact of molten salt and the oxide layer, (**b**) corrosion of oxide at the boundaries, (**c**) diffusion of Cl to the oxide/aluminium interface, (**d**) oxide detachment to the salt, and (**e**) aluminium drops [76]

furnace's refractoriness and pose potential environmental risks [13, 85], including hazardous gas emissions and increased greenhouse effect [86, 87]. Therefore, it is imperative to minimize fluoride addition to balance effective metal recovery with environmental considerations. In industrial processes, fluoride is typically added in concentrations ranging from 3 to 7% of the total flux weight. For scrap remelting, the amount of salt used for scrap treatment generally varies between 2% and 5% of the total scrap charge weight [88]. Table 2 summarizes the flux types employed in select studies on aluminium alloy recycling, along with their corresponding parameter selections.

Mechanical stirring and temperature control

Factors such as mechanical stirring and temperature control, in addition to regulating flux content and fluorides, play a significant role in the purification of aluminium melt and recycling efficiency. Mechanical stirring aids in metal agglomeration, a vital process in the operation of rotary furnaces [86]. As illustrated on Fig. 11, the melt pool was agitated by a mechanical rotating impeller, with flux concurrently introduced to ensure thorough and intimate contact with the aluminium melt. Research indicates that using mechanical stirring can reduce the formation of bifilms, with its effectiveness further enhanced when used in conjunction with flux. To achieve optimal reduction of bifilms, it is recommended to employ both stirring and flux simultaneously [93]. In Fig. 12, the results of research show that the combination of mechanical stirring and flux addition effectively reduces porosity, with a higher overall rate of decrease in pore density observed in the sample.

The melting temperature is another critical factor influencing the efficiency of flux agents, as it must be carefully balanced to optimize performance. The process of fluxing is inherently dependent on temperature, requiring a

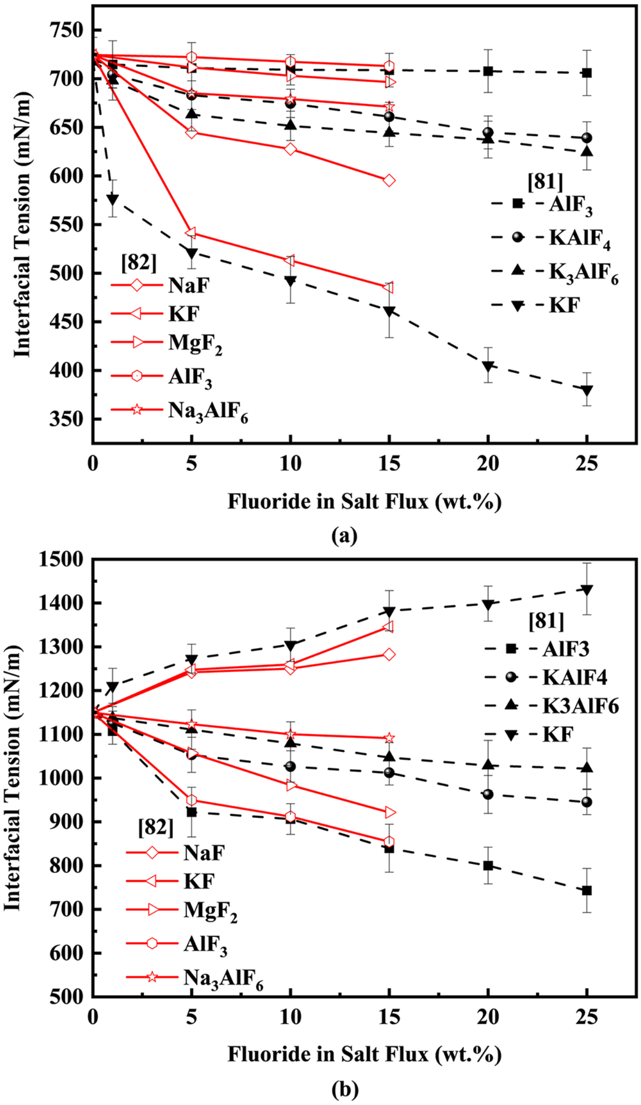


Fig. 9 Effect of some fluoride additions in the flux on the interfacial tension (**a**) between flux and aluminium melt and (**b**) between flux and aluminium oxide (The data used to rebuild the diagrams were obtained from [81, 82])

sufficiently high temperature to facilitate effective contact, reactivity, and physical separation [95]. However, excessively high temperatures can aggravate aluminium oxidation and introduce impurity ions due to reactions between the flux agent and the aluminium melt [81]. Therefore, determining the appropriate melting temperature is essential. Research by Máté et al. [90] investigated the melt cleaning efficiency of different fluxes, maintaining the furnace temperature between 730 °C and 750 °C. Their findings indicated that fluxes with lower melting points were more efficient in removing inclusions due to higher fluidity at the processing temperature. This conclusion aligns with previous research by Majidi et al. [78] and Baskar et al. [68], who investigated the recycling processes of various aluminium alloys —specifically, A380 and A319 by Majidi et al., and Al-Si8Cu3Fe (LM24) alloy by Baskar et al. Their studies suggested optimal melting temperatures of 740 °C and 750 °C, respectively.

Figure 13 presents the recycling casting temperatures for various aluminium alloy chips, highlighting the influence of flux composition. Research indicates that employing a NaCl–KCl flux facilitates operations at relatively lower temperatures. Conversely, the introduction of fluoride raises the casting temperature to a restricted thermal range of 710 °C to 800 °C. This increase in effective casting temperature can be attributed to fluoride-induced changes in the flux viscosity and the interfacial tension between the flux and molten aluminium, which subsequently affect the oxidation kinetics [96]. Among the different alloy systems, the Al–Si alloy, which has been extensively studied, exhibits a casting temperature averaging around 740 °C. However, there is a paucity of data on other alloys, emphasizing the necessity for further research to establish optimal thermal settings. Adjusting the casting temperature according to the specific aluminium alloy and flux type is crucial. Such precise thermal control is essential not only for maximizing metal recovery yield and enhancing alloy performance but also for reducing energy consumption and minimizing environmental impact.

Conclusion

The efficient recycling of aluminium alloy chips hinges on systematic optimization of preprocessing and remelting processes. Through a comprehensive analysis of current research, this study highlights the following critical insights:

1. For cleaning methodologies: Centrifugation cleaning and the integration of solvent cleaning with ultrasonication (e.g., acetone or alkaline solutions) effectively removes cutting fluid residues, mitigating oxidation and toxic gas emissions during remelting. While extraction and distillation show promise in niche applications, their scalability is constrained by operational complexity and cost.

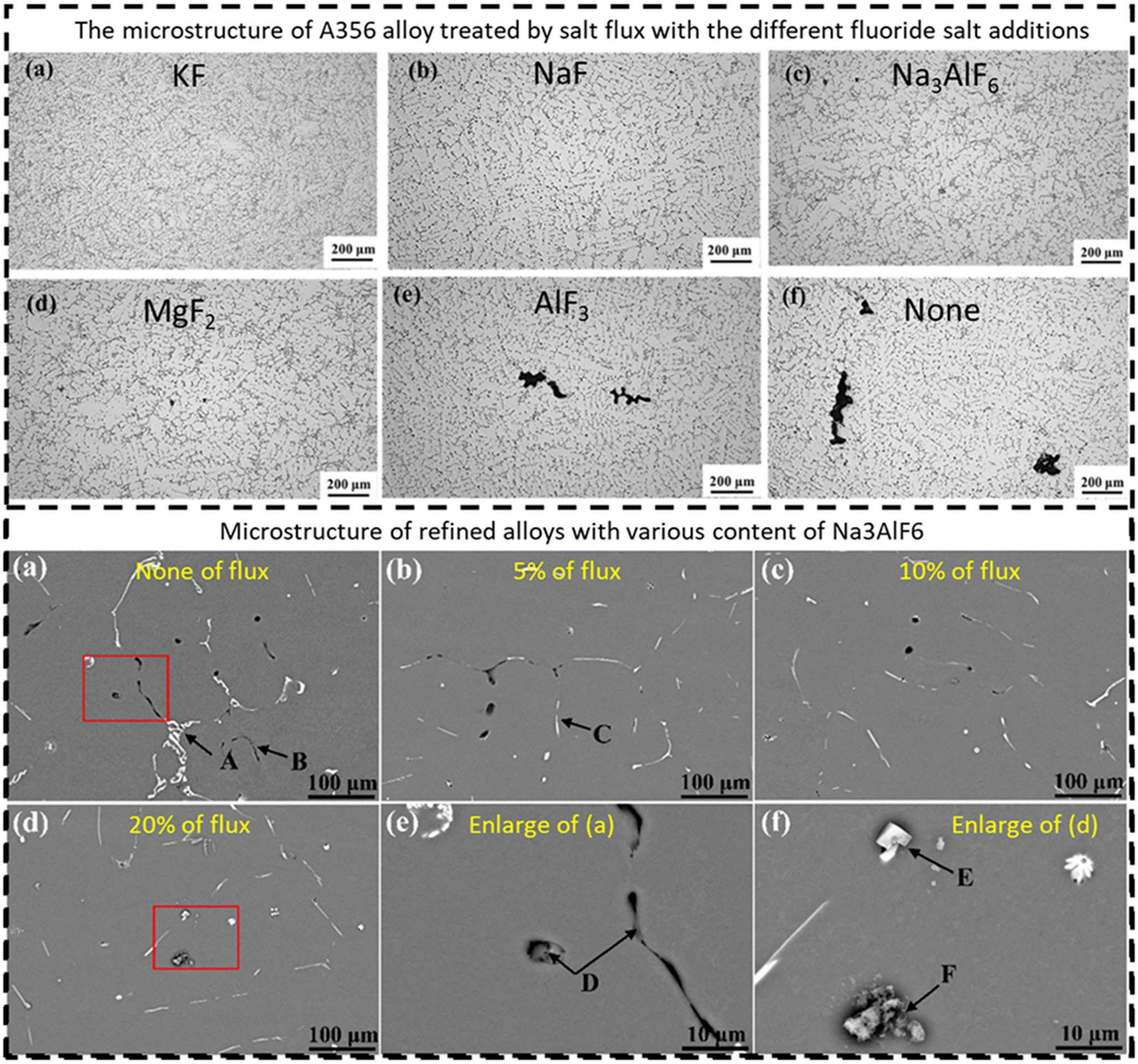


Fig. 10 The microstructure of Al alloy treated by flux with the different type and content fluoride salt additions(Image sources: References [82] and [59], rearranged.)

2. Compaction: Cold pressing enhances chip density (approaching up to 2.5 g/cm³), reducing surface oxidation and improving metal recovery rates. However, excessive compaction for uncleaned chips may impede organic residue burnout, necessitating synergistic optimization with cleaning protocols.
3. For flux engineering: NaCl-KCl-based fluxes disrupt oxide networks to promote aluminium coalescence. Fluoride additives (e.g., Na_3AlF_6 or KF) enhance flux reactivity but must be carefully controlled to mitigate environmental risks, including furnace corrosion and hazardous emissions.
4. Mechanical stirring combined with a suitable melting temperature can improve melt homogeneity, reducing porosity and inclusion formation.

Future research directions in aluminium recycling should prioritize three synergistic pathways to reconcile process efficiency with sustainability imperatives. First, the development of low-fluoride or fluoride-free flux formulations

Table 2 Fluxing agents employed during the casting process of recycled aluminium alloys

Ref	Material	Type of Flux	Operation parameters
[69]	AA 336 (AlSi12CuNiMg)	NaCl (40%), KCl (50%), KF (10%)	weight ratio of salt to scrap was kept constant of about 2.
[89]	AA319(AlSi5Cu3)	Flux contains NaCl (12wt.%) and KCl (13wt.%)	
[90]	AlSi7Mg	Flux contains NaCl, KCl, Na_2SO_4 and CaF_2	In each cycle, flux content: 0.2% wt% of the Al melt
[68]	AlSi8Cu3Fe	NaCl and KCl in the ratio of 3:1	Flux content:1 wt% of scrap
[91]	A356 (AlSi7Mg)	Best condition: $MgCl_2$ + KCl with Na_2SiF_6 addition	Flux content:1 wt% of melt weight
[79]	AlSi7Mg	NaCl and KCl of equimolar mixture	Flux content:10 wt% and 20wt.% of melt weight
[82]	AlSi7Mg	Best: NaCl and KCl contain 5 wt% KF	Flux content:0.5 wt% of Al weight
[16]	AlSi7Mg	NaCl (50wt.%) and KCl (50wt.%)	Flux content:10 wt% and 20wt.% of melt weight
[92]	AC3A (AlSi12)	Na_2SO_4 (44%), NaCl (34%), Na_2SiF_6 (9%), $NaNO_3$ (9%), KCl (2%)	Flux content:0.75wt.% of melt weight
[78]	A380(Al-Si9Cu3) +A319(AlSi5Cu3)	NaCl (45wt. %), KCl (45wt. %), Na_2SiF_6 (8wt. %), CaF_2 (2wt.%)	Flux content:0.3wt.% of melt weight
[73]	A3004(AlMn1Mg1), A5182(AlMg4.5Mn0.4)	Best condition: A mixture of NaCl, KCl, Na_3SiF_6, CaF_2, KBF_4, and $CaCO_3$ (fluoride in the flux: 5%)	Flux content: 1%
[19]	Aluminium foam	NaCl, KCl, and NaF with weight ratio of 3:3:1	Flux content: 35wt.% of total Al foam weight
[59]	6063(AlMg0.7Si) (40%), 6008(AlSi0.9Mg0.7) (60%)	Equimolar NaCl and KCl with 10%Na_3AlF_6 + 2% Fe powder addition	Flux content:0.25wt.% of melt weight

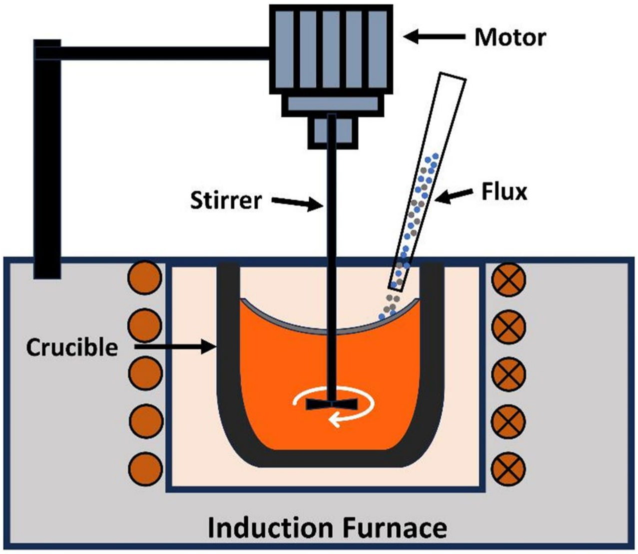
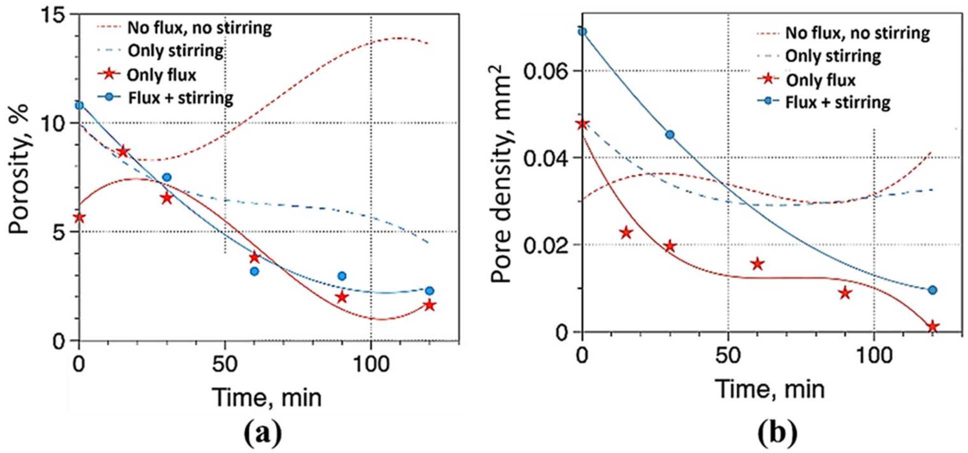


Fig. 11 Schematic image of mechanical stirring during casting. (Adapted from Ref [67, 94])

warrants intensified investigation to achieve effective oxidation suppression while minimizing environmental risks. The second pathway focuses on developing integrated processing systems that combine cleaning, compaction, and remelting operations. Within this context, emerging technologies such as cryogenic machining using liquid nitrogen or CO_2 cooling show promise for reducing contamination during preprocessing, though their process compatibility and economic viability require thorough industrial validation. The integration of these operations could significantly enhance energy efficiency and operational continuity through process intensification. Third, a comprehensive comparative analysis of the total costs and economic benefits associated with various treatment optimization strategies was conducted to identify the most promising technical solutions for diverse industrial applications. Finally, comprehensive life cycle assessments quantifying carbon footprints and resource utilization metrics across alternative recycling routes must be systematically conducted to inform industrial-scale implementation decisions.

Fig. 12 Change in (**a**) porosity and (**b**) pore density in the cast samples obtained from the fluxed-covered stagnant and stirred A356 melts (Reference [93], rearranged.)



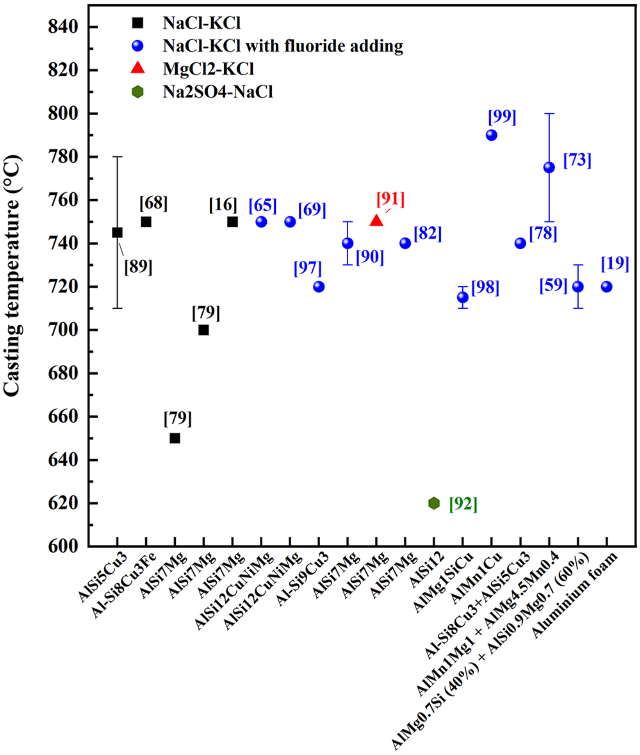


Fig. 13 Effect of different salt flux types on casting temperature of aluminium alloys' chips (The data used to rebuild the diagrams were obtained from [16, 19, 59, 65, 68, 69, 73, 78, 79, 82, 89–92, 97–99])

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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