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Review article

## Recycled Metal Utilization on the Microstructure and Mechanical Properties of Casting Alloys

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### ABSTRACT

Recycled metals have become a strategic resource for the casting industry in the transition toward sustainable manufacturing and circular material flows. This review summarizes the present understanding of using 100% recycled alloys in foundry applications, covering microstructural evolution, mechanical properties and energy efficiency. The aim is to make an integrated assessment of the scientific findings and industrial practices that underpin the wider adoption of recycled feedstock in metal casting. This review summarizes what is known about the influence of impurities, oxide formation and melt treatment on the resultant microstructure. Various observations are reported that trace impurities of alloying elements may modify the dendritic morphology, eutectic phases, and porosity of recycled metals; often these can be minimized by proper refining and filtration. The mechanical performance results vary depending on the alloy type, recycling route and melting practices; nevertheless, a considerable number of research findings prove that tensile strength, hardness and fatigue resistance of castings manufactured from 100% recycled feedstock remain comparable to those produced from primary metals when proper process control is applied. This review also points out the importance of melt cleanliness, degassing procedures and alloy chemistry stabilization in achieving consistent quality. Overall, the collected research indicates that 100% recycled metals can be effectively integrated into the casting processes and are an essential part of sustainable foundry operations. In this context, the utilization of recycled metals brings considerable benefits in terms of energy consumption reduction, minimizing carbon emissions, and supporting circular economy principles. This review is expected to help future studies and industrial practices by summarizing challenges, key technological developments, and opportunities for full-scale implementation.

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### 1. INTRODUCTION

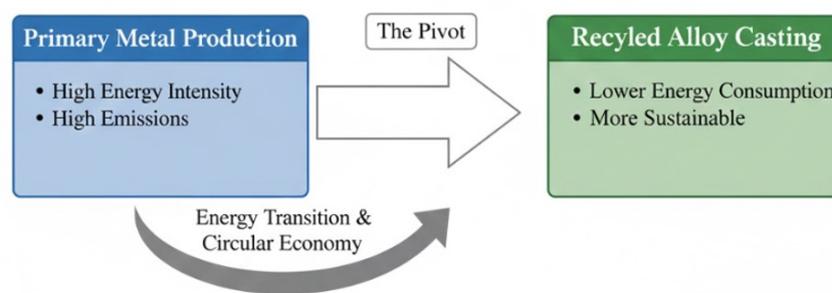
The transition towards the use of renewable energy worldwide and the current focus on future environmental requirements have influenced the selection of materials as well as the related processing techniques for engineers (Nwokediegwu et al., 2024). Metal casting is an established industrial technology in the energy, transportation, construction, and manufacturing industries (Lehmhus, 2022). However, traditional

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casting technology based on the use of primary metals is increasingly faced with criticism on several aspects: energy intensity, availability of raw materials, as well as environmental issues. Among the most notable approaches proposed to improve the environmental performance of casting shops is the use of metal recycling processes. On a general note, the idea of recycling rather than refining is advantageous to the extent that energy required for refining is significantly higher than re-recycling for the most relevant case of ‘non-ferrous’ aluminum materials (Mrówka-Nowotnik et al., 2024).

Despite these benefits, there also exist some technical difficulties in using recycled alloys in casting processes. The differences in chemical composition, trace elements, oxides and melt contamination cause varying solidification processes and microstructure, resulting in varying hardness values after some treatments due to differences in microstructural features (Callegari et al., 2023). Hence, the need for in-depth knowledge concerning the metallurgical aspect of recycled materials usage in order to provide guarantees of the performance capabilities of the casting material. This narrative review aims to summarize the use of recycled material alloys in casting from a scientific perspective, particularly focusing on the role of recycled material on microstructures and mechanical properties. Through the integration of recent discoveries and results, the paper will discuss how recycled materials could be utilized in casting technologies to meet certain performance standards. The review is based on an assessment of recent studies in academia as well as industry reports and results of experiments conducted for cast alloys using recycled metals (figure 1).



**Figure 1.** Conceptual framework of the transition from primary to recycled metal casting.

Figure 1 schematically illustrates the conceptual transition from primary-metal-based casting to recycled-metal-based casting and highlights the main metallurgical control steps required to maintain quality. The studies cover non-ferrous cast alloy systems used in foundry applications for which special emphasis is placed on studies for aluminum, magnesium, as well as copper cast alloys. Studies conducted for total or high recycled fraction, processes used for melt treatment, as well as techniques for quality control are taken into consideration for this review. In this context, instead of reviewing various cast alloy systems extensively, representative results are pointed out for casting properties as affected by recycled metal.

The scope of the review is threefold. First, it outlines the major recycled alloy systems currently used in casting processes and their recycling characteristics. Second, it examines how recycled feedstock affects microstructure development and mechanical properties in representative alloy systems. Third, the discussion points to the technological approaches that allow the inclusion of recycled metals such as through the melting treatment, alloy development and process control, to ensure the successful incorporation of recycled metals into the casting process without compromising the desired performance level. Through the above approaches, the review aims to provide a comprehensive perspective on the metallurgical challenges and opportunities associated with the increasing trend of recycled metals in the development of sustainable casting technologies.

## 2. LITERATURE SEARCH STRATEGY AND SCOPE OF THE REVIEW

This study aims to offer a narrative synthesis of the available literature regarding the role of recycled metals in casting alloys, focusing particularly on the effects of such metals on the microstructure and mechanical properties of the alloys in question. The study aims to offer an integrated overview of the findings of various scholarly and industrial studies conducted in recent times regarding this area of study and technology. The study has relied on the findings of the literature search conducted through prominent scientific databases such as Scopus, Google Scholar and Web of Science. The sources were selected based on the combination of the following keywords: "recycled metals," "secondary alloys," "casting alloys," "microstructure," "mechanical

properties," "recycling in foundry processes," and "recycling in casting alloys." The sources were mainly selected from the studies conducted between 2000 and 2025, focusing particularly on the more recent studies conducted in the past ten years. The sources were selected based on the following criteria: peer-reviewed articles, reviews and industrial studies focusing particularly on the effects of the presence of recycled metals in casting alloys on the microstructure and mechanical properties of the alloys in question. The study focuses particularly on aluminum, magnesium, and copper alloys because of the more prominent role these alloys play in the process of recycling metals in the casting industry. Publications unrelated to casting processes or those lacking sufficient metallurgical analysis were excluded.

This work does not follow a formal systematic review protocol. Instead, the objective is to provide a conceptual and integrative overview of representative studies in order to highlight key mechanisms, challenges, and technological developments related to recycled metal utilization in casting processes. Consequently, the review may not capture all available publications in the field and should be interpreted as a narrative synthesis rather than an exhaustive systematic analysis.

### 3. RECYCLED ALLOY SYSTEMS IN CASTING

At present, recycled metals are used as a casting alloy system for a broad variety of applications and non-ferrous alloys cover a more extensive application area (Gerold et al., 2024). Aluminum and copper-based alloys are more suited for recycling due to a high recycling ratio and relatively less degradation of inherent properties if proper control during melting is exercised (Vahedi Nemani et al., 2024). In ferrous casting, recycled cast iron and steel are also used substantially, but composition control is relatively more difficult.

#### 3.1. ALUMINUM-BASED CASTING ALLOYS

The largest portion of recyclables used in the casting industry are aluminum alloys (Nunes et al., 2023). Secondary aluminum processing consumes just a fraction of the energy required in the production of primary aluminum; thus, it forms the backbone of sustainable manufacturing techniques (Raabe, 2023). Al-Si, Al-Si-Mg and Al-Cu series are some of the widely used recyclable aluminum casting alloys (Nunes, 2023).

It has been found that aluminum alloys made from recycled material can have properties equivalent to primary material if certain conditions regarding melt cleanliness and chemistry are met. However, recycled aluminum may contain a high amount of iron, copper, and other residual elements (Yakubov et al., 2024). High iron content can lead to the formation of intermetallic which can decrease ductility and resistance to fatigue (Keerthipalli et al., 2023). The addition of grain refiners, modifiers, and filtration methods has been found to counter these effects.

#### 3.2. MAGNESIUM-BASED CASTING ALLOYS

Magnesium alloy is increasingly preferred for weight-sensitive applications because of its lower density and specific strength (Xie et al., 2024). Recycling magnesium alloy is possible, though it is more prone to oxidation and melt loss than an aluminum alloy (D'Errico et al., 2022). This series of casting alloys like AZ and AM is not very prone to deterioration of microstructure and strength due to recycled materials.

It has been proven in the literature that the important consideration in casting recycled magnesium alloys regards the purification of the melted metal in the context of iron, nickel and copper content which strongly affects the casting's corrosion resistance (Murugesan et al., 2023). After the completion of the process, the tensile strength of the recycled magnesium alloys can still be ideal.

#### 3.3. COPPER-BASED AND FERROUS ALLOYS

Copper alloys, bronzes and brasses are established in recycling-based casting processes. They have a certain tolerance level to recycled materials, which have a relatively broad range of compositions. Nevertheless, brass can be expected to lose zinc and brasses can readily incorporate lead or other trace elements; hence, they have to be strictly checked. In ferrous casting processes, recycled steel scrap and cast iron returns constitute the primary raw materials. The extensive use of recycled feedstock provides significant energy savings and reduces greenhouse gas emissions compared to primary metal production. However, repeated recycling cycles may

lead to the accumulation of tramp elements such as Sn, Sb, and Cr, which can influence graphite morphology and phase transformations in cast irons and steels (Raabe, 2023).

As mentioned in the table 1, the different alloy systems which are recycled in casting processes have varying sensitivity to impurities, though with proper treatment of the melts, the feedstock can be utilized in the ferrous as well as the non-ferrous systems.

**Table 1.** Recycled alloy systems in casting based on information synthesized from recent literature (Nunes et al., 2023; Murugesan et al., 2023; Raabe, 2023; Li, 2024).

Alloy System	Recycling Suitability	Main Challenges in Recycled Casting	Common Control / Mitigation Strategies
Aluminum-based alloys (Al-Si, Al-Si-Mg, Al-Cu)	Highly suitable due to high recycling rates and low property degradation	Accumulation of Fe and residual elements; formation of brittle intermetallic phases; melt contamination	Melt filtration and degassing; grain refinement and modification; alloy chemistry control (e.g. Mn additions)
Magnesium-based alloys (AZ, AM series)	Moderately to highly suitable, but sensitive to melt handling	Oxidation, melt loss, and impurity elements (Fe, Ni, Cu) affecting corrosion resistance	Protective atmospheres; flux or fluxless refining; strict impurity control and melt purification
Copper-based alloys (bronzes, brasses)	Highly suitable with broad compositional tolerance	Zinc loss in brasses; incorporation of lead and tramp elements from scrap	Composition adjustment; controlled melting practice; scrap sorting and quality monitoring
Ferrous alloys (cast iron, steel)	Widely used in recycling-based casting	Accumulation of tramp elements (Sn, Sb, Cr); graphite morphology modification	Scrap dilution strategies; chemical composition control; melt treatment and inoculation

As indicated by the brief overview presented in Table 1, the tolerance of different alloy systems to the recycled material varies. In the case of aluminum alloys, the maximum compatibility with the process of recycling is observed. This is because the mechanical properties of aluminum alloys tend to remain stable if proper purification of the melt is carried out. In the case of magnesium alloys, the process of oxidation must be tightly controlled, as must the content of impurities like iron, nickel and copper. In the case of copper and brass alloys, the tolerance of the material composition is relatively wide; however, the problem of zinc volatilization is encountered.

#### 4. EFFECT OF RECYCLED CONTENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES

The current research trend has been concentrating progressively on the influence of recycling feedstock incorporation on the microstructure and properties of cast alloys, especially on aluminum base alloys that form a large group of sustainable recycling research. Some of the key research pieces were carried out by Yang et al. (2014) which tested microstructure and properties of a ductile aluminum, magnesium, and silicon alloy. They reported that while increasing levels of iron impurities were associated with a reduction in ductility and yield strength, the ultimate tensile strength remained relatively high at moderate iron contents and acceptable mechanical performance (yield strength >140 MPa, UTS >280 MPa) was maintained even after multiple remelting cycles. Focusing specifically on AlSi<sub>10</sub>MnMg alloy, recent research has shown that introducing 50–75% circulating scrap into the alloy significantly increases iron concentration, leading to more pronounced pre-eutectic iron-rich intermetallic phases as observed by optical microscopy. These inclusions influence solidification behavior and consequently, the mechanical response by promoting embrittlement if not controlled (Piatkowski et al., 2025). Other work has explored microstructural optimization via process design. A study on AA6111 alloys processed by melt conditioning twin-roll casting demonstrated that controlled melt treatment can refine and homogenize Fe-rich intermetallic compared to conventional twin-roll casting which contributes to a more uniform microstructure and mitigates the embrittling effects of Fe (Al-Helal et al., 2020)

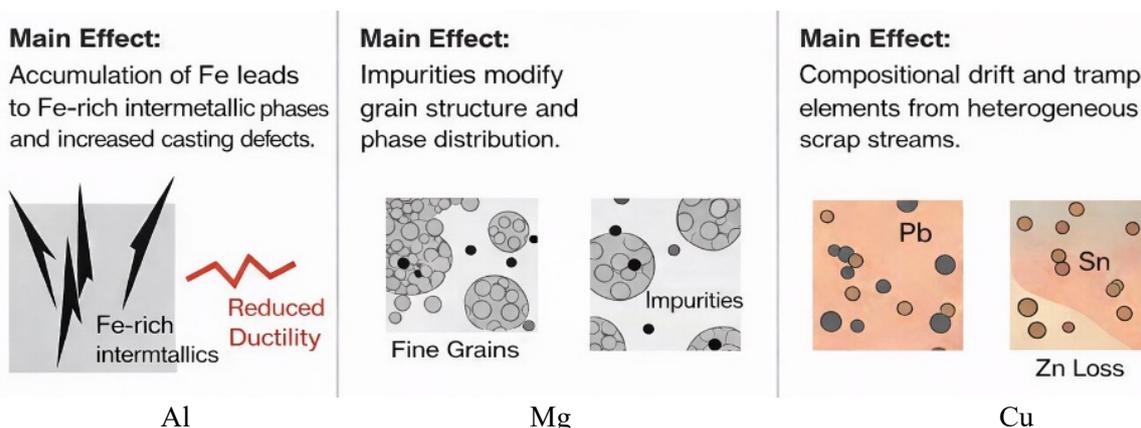
Beyond conventional casting routes, advanced manufacturing techniques have also been investigated. In research on direct strip casting of recycled Al-Fe alloys, rapid solidification was found to produce elongated grains and significantly smaller, more uniformly distributed Fe-rich intermetallic phases compared to sand-cast equivalents. This morphological refinement enhances tolerance to higher iron levels and suggests

improved mechanical stability in high-recycled alloys (Jiang et al., 2024). In addition, new alloys have been proposed to overcome the current recycling issues. Cinkilic et al. (2022) also introduce the production of a recycled Al-Si-Mg alloy with a relatively high iron content of around 0.44 wt%, which hinders the formation of the hard  $\beta$ -Al<sub>3</sub>FeSi phase by Fe/Mn ratio modification. The microstructure includes a modified  $\alpha$ -Al<sub>15</sub>(Fe, Mn)<sub>3</sub>Si<sub>2</sub> and a dispersed  $\pi$ -Al<sub>8</sub>FeMg<sub>3</sub>Si<sub>2</sub> phase, which are responsible for the mechanical properties and have a ductility of around 7-9% after heat treatment, which is near the value of the primary alloy. In semi-solid processing, a very recent comparative study of primary and recycled AlSi<sub>7</sub>Mg alloys produced by rheocasting highlighted the effect of iron on mechanical performance. Higher iron content in the recycled alloys led to more defects and intermetallic nucleation, reducing elongation and strength relative to primary material, particularly in as-cast and T6 conditions (Arcaleni et al., 2025).

Magnesium-based systems have also shown sensitivity to recycled content. In a study on AZ91 alloy with circulating scrap additions, researchers reported that moderate recycled inputs increased yield and ultimate tensile strength, although excessive scrap reduced hardness and elongation, emphasizing the need to balance recycled content with property requirements in Mg alloys as well (Dudek et al., 2021). Fluxless recycling techniques for die-cast AZ91 alloy have also produced secondary alloys with tensile properties comparable to primary AZ91, especially when Ar gas bubbling and manganese additions are used during melt processing. These treatments reduced oxide inclusions and improved corrosion resistance, indicating that appropriate melt handling can mitigate common recycled Mg alloy issues such as Fe contamination and inclusions (Jung et al., 2005). Additionally, although most solid-state recycling studies pre-date 2020, they demonstrate that solid-state recycled AZ91D processed by extrusion and annealing can achieve fine grain structures that enhance strength and ductility relative to conventional die-cast material, suggesting alternative routes beyond remelting for sustainable Mg alloy reuse (Lin et al., 2007).

Copper and its alloys are among the most recyclable engineering metals with recycling yielding energy and environmental benefits due to their high intrinsic recyclability. Globally, a significant and growing proportion of copper supply comes from scrap, with modern recycling practices offering improved sustainability in casting and remelting operations (Li et al., 2024). In casting applications, recycled brass alloys produced from waste feedstock have been investigated for gear components where recycled material microstructures, grain sizes, and mechanical properties were characterized after investment casting. One recent experimental study found that recycled brass could achieve yield strength up to ~180 MPa and ultimate tensile strength up to ~225 MPa with elongation values around ~7 %, results that were comparable to commercial CAC 302 brass in yield strength though somewhat lower in ultimate strength (Sugiyanto et al., 2024). Although comprehensive literature on casting performance of highly recycled copper alloys is less abundant than for aluminum or magnesium, existing reviews and industry analyses emphasise that the management of tramp elements (e.g., Pb, Sn, Fe) and refined sorting is critical for maintaining cast quality, especially when dealing with complex end-of-life scrap streams (Loibl and Espinoza, 2021).

These results suggest that recycled content is a factor that has consistently influenced microstructural development, often because of improved intermetallic phase and impurity-driven heterogeneity (figure 2). Some processing methods, such as melt conditioning or rapid solidification, combined with specific material compositions based on Fe/Mn ratios, may work to counter the disadvantages of the recycling process to the point where the properties of the recyclables may approach those of the original material, enhancing sustainability in the process.



**Figure 2.** Main effect on recycled casting alloys.

Figure 2 shows the major metallurgical effects associated with the recycling of the material in Al, Mg and Cu alloys, with specific reference to the accumulation of impurities, the generation of intermetallic compounds and the overall impact on the associated mechanical performance.

Table 2 summarizes representative recent case studies investigating the effects of recycled feedstock on the microstructure and mechanical properties of aluminum, magnesium and copper-based casting alloys. The selected studies focus on different alloy systems and processing routes, highlighting common challenges and mitigation strategies. Although the studies on the recycled magnesium alloys cited in the literature are based on earlier research work, the specific publications include conference proceedings from the mid-2000s, it was thought appropriate to include the studies as they provided the fundamental experimental work on the fluxless recycling and solid-state recycling of AZ91 magnesium alloys. These studies have established a number of important concepts related to the purification of the melts, oxide control and the mechanisms of grain refinement, which have a significant impact on the more contemporary work related to the recycling of magnesium casting alloys. As such, the inclusion of the earlier work provides a framework related to the overall evolution of the recycling routes in magnesium casting alloys.

**Table 2.** Effects of recycled feedstock on the microstructure and mechanical properties.

Study / Reference	Alloy System & Process	Microstructure & Mechanical Findings	Quantitative Results / Notes
Arcaleni et al., 2025	Rheocast AlSi <sub>7</sub> Mg alloys with varied recycled/Fe content	Increased iron content in recycled rheocast samples caused higher defect density and promoted Fe-rich intermetallic that acted as crack initiation sites.	Recycled (Fe = 0.19%): Rp <sub>0.2</sub> ~113 MPa, UTS ~208 MPa, elongation ~ 4.1 %; T6: Rp <sub>0.2</sub> ~240 MPa, Rm ~279 MPa, elongation ~1.40 %. Fe enrichment reduced ductility more than strength.
Cinkilic et al., 2022	Secondary Al–Si–Mg alloy with high Fe (~0.44 wt%)	Manganese addition modified β-Al <sub>3</sub> FeSi into less harmful α-Al <sub>15</sub> (Fe,Mn) <sub>3</sub> Si <sub>2</sub> & π-Al <sub>8</sub> FeMg <sub>3</sub> Si <sub>2</sub> phases, improving microstructure.	As-cast elongation ~7.4 %; after T6: ~9.1 %. Ductility is comparable to primary alloys at similar compositions.
Al- Helal, 2022	Recycled AA6111 alloy strips	High shear melt conditioning produced finer, more uniform Fe-rich intermetallic compared to conventional TRC, altering microstructure distribution.	Refined Fe-rich phases potentially mitigate mechanical property loss typical in recycled aluminum.
Dudek et al., 2021	AZ91 Magnesium alloy castings with recycled scrap	Addition of circulating scrap to AZ91 refined microstructure and changed mechanical characteristics.	75% scrap: UTS ~153 MPa vs 128 MPa for pure ingot; hardness ~80 HB at moderate scrap. Shows positive strength effect with scrap addition.
Jung et al., 2005	Secondary AZ91 via fluxless melt + treatments	Appropriate melt treatment (Ar bubbling, Mn addition) maintained tensile properties similar to primary alloy and improved corrosion resistance.	Recycled Mg with optimized melt treatments can match primary alloy tensile properties.
Sugiyanyo, 2024	Recycled brass via investment casting	Microstructure showed grain size ~74–85 μm; mechanical properties measured and compared with commercial brass (CAC 302).	Recycled brass: YS ~179.8 MPa, UTS ~225.2 MPa, elongation ~7.3 %. Derived material compared favorably to CAC 302 YS but UTS was lower.

It is important to note that the studies cited in Table 2 have differences related to the overall experimental procedures, the specific alloy compositions, and the overall routes employed, which may have a specific impact on the overall values related to the mechanical performance. For example, the studies may have focused on specific routes such as conventional casting processes, semi-solid metal processes, or rapid solidification techniques. These methodological differences affect microstructural development and may lead to variations

in tensile properties and ductility. Therefore, the results presented in the literature should be interpreted primarily in terms of general trends rather than direct quantitative comparisons across different studies.

As summarized in Table 3, recycled feedstock affects aluminum, magnesium and copper-based casting alloys through different dominant mechanisms; however, in all systems, appropriate alloy design and melt processing enable mechanical performance levels close to those of primary materials.

**Table 3.** Summary of the main effects of recycled feedstock on mechanical performance of casting alloys based on representative studies discussed in the literature (Arcaleni, 2025; Cinkilic et al., 2022; Dudek et al., 2021; Sugiyanto et al., 2024).

Alloy System	Main Effect of Recycled Feedstock	Overall Mechanical Response & Key Control Approach
Aluminum Alloys (e.g., Al–Si–Mg, AA6xxx)	Accumulation of Fe leads to Fe-rich intermetallic phases and increased casting defects, particularly in high recycled content alloys	Strength can be largely preserved, while ductility decreases unless alloy design (Mn addition), melt conditioning, or semi-solid processing is applied
Magnesium Alloys (e.g., AZ91)	Scrap additions introduce impurities that modify grain structure and phase distribution	Moderate recycled content may increase strength through grain refinement, but ductility and corrosion resistance strongly depend on melt cleanliness and impurity control
Copper / Brass Alloys (Cu–Zn)	Compositional drift and tramp elements arise from heterogeneous scrap streams	Mechanical properties remain close to commercial alloys if composition is controlled; yield strength is typically retained, while tensile strength may slightly decrease

The comparative overview presented in Tables 2 and 3 reveals several common trends across different alloy systems. In aluminum alloys, the main metallurgical problem associated with the recycled feedstock is the formation of Fe-rich intermetallic compounds that have been observed to reduce ductility more than strength. In magnesium alloys, the presence of recycled materials has been observed to refine the microstructure and strengthen the alloy; however, the presence of impurities has been noted to reduce ductility and corrosion resistance. In copper alloys, the main metallurgical problem associated with the presence of the recycled feedstock is the composition drift that results from heterogeneous scrap composition. Despite the metallurgical problems associated with the presence of the recycled feedstock in the various alloy systems discussed in the studies in Table 2, the studies suggest that the presence of the recycled materials in the alloy system can be effectively utilized in the casting process while maintaining the required mechanical properties close to the primary materials. This observation suggests that the metallurgical control strategies and the ability of the casting process to utilize the recycled materials depend more on the metallurgical control strategies than the ability of the process to eliminate the presence of the recycled materials in the alloy system.

Despite the studies discussed in the previous section offering useful information regarding the behavior of the casting alloys containing the recycled materials, the studies have been observed to have several limitations that should be taken into consideration before interpreting the results and the findings of the studies discussed in the previous section. The studies available in the literature have been observed to have several differences in the experimental conditions and the alloy systems investigated in the studies. The differences in the experimental conditions and the alloy systems have been noted to make comparisons of the results and findings of the studies difficult. The experimental studies have been observed to be conducted at the laboratory scale using small samples and specific processing conditions. Therefore, the results and findings of the studies should be regarded as indicative trends rather than the actual property values for the casting process. Despite the differences in the experimental studies and the findings of the studies in literature, the studies have been observed to suggest that the presence of the recycled materials in the alloy system can be effectively utilized in the casting process using the metallurgical control strategies discussed in the previous section.

Another advanced melt treatment technique that is considered to be a promising approach to improving recycled casting alloys is melt treatment. For example, modification treatment techniques, such as incorporating strontium (Sr) in Al-Si alloys are commonly used to improve the microstructural characteristics and mechanical properties of recycled casting alloys (Ganesh et al., 2022). In addition, ultrasonic melt treatment is also considered to be beneficial to improve melt cleanliness and grain refinement, as well as to minimize the formation of harmful intermetallic compounds in recycled casting alloys (Yang et al., 2025). Therefore, it is anticipated that these advanced melt treatment techniques will play a critical role in improving

the recycled content of future casting alloys. In conclusion, it is evident that, according to all the studies reviewed above, it is not possible to discuss the influence of recycled feedstock without considering other factors such as chemistry and processing route. It is also evident that, unlike ductility, strength is maintained in all cases. In addition, it is anticipated that recent studies in sustainable metallurgy also suggest that future progress in recycled casting alloys will be largely dependent on advanced recycling technologies, particularly impurity management and melt cleanliness. It is also evident that incorporating recent advances in sustainable metallurgy will play a critical role in improving the performance and reliability of recycled casting alloys.

## 5. CONCLUSION AND OUTLOOK

This short review examined the use of recycled metal feedstock in casting alloys from a microstructural and mechanical perspective with particular emphasis on aluminum, magnesium and copper-based systems. The reviewed literature clearly demonstrates that recycled metals can be successfully integrated into casting processes when appropriate alloy design and melt processing strategies are applied.

For aluminum alloys, the dominant challenge associated with high recycled content is the accumulation of iron and the formation of Fe-rich intermetallic phases which primarily affect ductility rather than strength. Various researchers have shown that semi-solid processing and alloying with Mn can be used for the modification of these phases and achieve levels of mechanical performance comparable to those of the base alloys. For the case of magnesium alloys, moderate amounts of recycled materials are likely for the realization of grain refinement and strengthening; nevertheless, control of purities and melt cleanliness are still very important for maintaining ductility and corrosion resistance. On the whole, copper and brass alloys show higher adaptability for scrap materials and can realize near-commercial levels of mechanical performance when composition drift and residual contents are properly controlled. On the aspect of sustainable development and the energy transition, casting using recycled metals presents substantial advantage in terms of lower energy requirements, lower greenhouse gas emission, and lower utilization of resource materials.

Several research directions appear particularly promising for advancing the use of recycled metals in casting technologies. One key area is the development of impurity-tolerant alloy design strategies that can accommodate higher levels of recycled feedstock without compromising mechanical reliability. In addition, advanced melt treatment technologies such as ultrasonic processing, high-shear melt conditioning and improved filtration systems may further enhance melt cleanliness and microstructural control in recycled alloys. Another important direction involves integrating sustainability assessment tools such as life-cycle analysis and energy efficiency modeling into alloy and process development. By linking metallurgical performance with environmental metrics, future research can better support the transition toward circular manufacturing systems in the foundry industry. These developments will be essential for enabling higher recycled content in structural casting alloys while maintaining the performance standards required in modern engineering applications.

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## AUTHOR CONTRIBUTIONS

**Doruk Gürkan:** Conceptualization, methodology, investigation, writing—original draft and writing—review & editing.

## COMPETING INTERESTS

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## DATA ACCESSIBILITY

The datasets generated during and/or analyzed during the current study are available from the author on reasonable request.

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