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High-purity alloys for enhanced service performance: processing, mechanisms and prospects

X.Y. Xu^{1,2}, Weng-Jia Liu¹, Bing-Qiang Wei^{1*}, Min Deng¹, Jia-Ning Zhu^{3*} and Hui-Yuan Wang^{1,4*}

ABSTRACT With the rapid advancement of high-performance systems and the growing demands for material reliability in extreme environments, high-purity alloys have become indispensable in next-generation technologies. Trace impurities—even at parts-per-million levels—can drastically deteriorate mechanical properties, corrosion resistance, and long-term stability in critical applications such as aerospace, nuclear reactors, advanced microelectronics, and medical implants. High-purity alloys are therefore key to meeting the stringent performance and reliability demands of these technologies. This review provides a comprehensive overview of recent advances in the development of high-purity alloys, including purification approaches, processing strategies, and performance optimization. It summarizes how trace impurities affect microstructural evolution and material properties and discusses techniques for achieving ultralow impurity levels. The review also highlights impurity sensitivity across major alloy systems and summarizes current strategies to mitigate impurity-related degradation. Moreover, it outlines the role of advanced characterization techniques in detecting and quantifying impurities. Finally, this review emphasizes the essential role of high-purity alloys in the development of advanced structural and functional materials, and outlines the key challenges and future directions in this emerging field.

Keywords: high-purity alloys, trace impurities, alloy purification, impurity-induced degradation mechanism, impurity-property relationship

INTRODUCTION

High-purity (HP) metals and alloys are foundational materials in advanced industries, providing the critical properties needed for technologies in aerospace, electronics, healthcare, and energy. These materials are distinguished by their extremely low levels of impurities, often measured in parts per million (ppm) or higher purity grades such as 99.999% (5N) from base metals [1]. The control of impurities is not merely about achieving a high degree of purity; it also involves managing and mitigating the negative effects of trace elements to enhance performance and reliability [2–5].

The development of high-purity alloys was driven by the need to improve material properties such as mechanical strength, corrosion resistance, and electrical and thermal conductivity. For instance, high-purity aluminum has been employed in the electronics and aerospace sectors by enabling lighter and more conductive materials [6]. High-purity titanium alloys have expanded the possibilities in biomedical implants and extreme environment applications due to their strength-to-weight ratio and corrosion resistance [7]. Advances in nuclear energy and renewable technologies further underscore the importance of high-purity metals like vanadium alloys, where even minor impurities (e.g., C, N, O) can drastically impact functionality [4].

The production of high-purity alloys involves complicated refining techniques, such as vacuum melting, zone refining (ZR), and chemical vapor deposition, to achieve the desired purity levels [4]. However, in many cases, achieving absolute purity is impractical or unnecessary. Modern approaches focus on managing the effects of impurities through advanced alloy design, grain refinement [2,3], or surface treatments [8], allowing high-purity alloys to meet the growing demands of cutting-edge applications. This highlights the critical role of purity not just as a material attribute, but as a key design parameter in advanced materials engineering.

To date, the term high-purity metal lacks a precise and universally agreed-upon definition, as its meaning remains inherently qualitative and highly dependent on context [9]. The concept of “pure metal” can be traced back to 1951, when the International Union of Pure and Applied Chemistry (IUPAC) established the Commission on Pure Metals and Their Protection. This commission proposed two definitions: a theoretical definition of an ideally pure metal, and a practical definition of a “practically pure metal”. Their definition of an ideally pure metal is as follows: “an ideally pure metal consists of atoms of only one element having the isotopic abundance ratios as given in the International Commission of Atomic Weights. The atoms are in internal thermodynamic equilibrium with ions of the same element with vacancies, and with electrons, while the surface has a minimum specific surface-free energy.” The practically pure metal definition was more complex and included the following key criteria: (i) the metal consists essentially of one element. (ii) Metallic and non-metallic impurities should be determined and reported as percentages or parts per million. The pure metal

¹ School of Materials Science and Engineering, Hebei University of Technology, Tianjin 300130, China

² Department of Mechanical Engineering, The University of Hong Kong, Hong Kong 999077, China

³ Department of Materials Science and Engineering, Delft University of Technology, Delft 2628, The Netherlands

⁴ State Key Laboratory of Metastable Materials Science and Technology & School of Materials Science and Engineering, Yanshan University, Qinhuangdao 066004, China

* Corresponding author (email: bingqiangwei@hebut.edu.cn; J.zhu-2@tudelft.nl; wanghuiyuan@hebut.edu.cn)

content should also be determined. (iii) Two or more sensitive physical properties should be measured as a function of impurity with the lowest concentration possible. If the measured physical property is constant with purity change, it may be called pure with respect to this impurity [9]. These definitions apply to metals, and specifically to pure elemental metals. However, defining high purity for alloys is more challenging, particularly with the emergence of complex systems like high-entropy [10] and multi-principal element alloys [11]. These advanced materials require a re-evaluation of what constitutes high purity in the context of multi-component systems.

With the development of techniques for manufacturing high purity alloys, the definition of high-purity alloys has evolved over time. Based on the definition of the International Commission of Atomic Weights. The high purity alloys can be understood in two ways: a narrow and a broader sense. In a narrow sense, high-purity alloys are materials with extremely low levels of impurities, often in the parts per million range or with purities such as 99.999% (5N) or 99.9999% (6N) base metals [1]. These alloys are typically produced using advanced refining techniques like vacuum melting, zone refining and levitation melting to remove and avoid impurities.

In a broader sense, high-purity alloys also refer to materials where some impurities are present, but their negative effects are minimized through special designs or treatments [2–5]. For example, magnesium alloys can achieve grain refinement by utilizing the detrimental element of iron [2] or by applying protective surface coatings to prevent impurities from reacting [8]. This broader interpretation reflects the practical reality that absolute purity is often neither achievable nor necessary. Instead, managing impurities to preserve or even enhance performance has enabled high-purity alloys to meet the demanding requirements of modern engineering applications in a more cost-effective and flexible manner.

To avoid conceptual ambiguity, it is important to clearly distinguish high-purity alloys from cleanliness alloys. High-purity and cleanliness alloys share a similar goal of enhancing material performance through impurity control, but they differ significantly in focus and methodology. High-purity alloys prioritize the reduction of elemental impurities, such as Fe, Ni, and Cu, as well as interstitial elements like O, N, and C, often to parts-per-million levels or lower. This process improves critical properties, including corrosion resistance, mechanical strength, and conductivity [12–15]. In contrast, cleanliness alloys—such as cleanliness steel—focus on minimizing non-metallic oxide inclusions while carefully managing their morphology, composition, and size distribution to enhance fatigue strength and toughness [16]. Both materials utilize advanced refining techniques like vacuum processing, yet their evaluation methods differ: high-purity alloys are measured by chemical composition and trace-element levels, while cleanliness steel is assessed by inclusion size, morphology, and volume fraction [16,17]. Although the term “high purity” could conceptually include cleanliness steel due to its emphasis on impurity control, technically, the two remain distinct, addressing different types of impurities and performance challenges [1,16].

Despite decades of progress in alloy purification, the control of trace impurities in metallic systems remains one of the most persistent challenges in materials science. Trace impurities like oxygen [18], nitrogen [19], sulfur [20,21], phosphorus [22], or iron [23] can severely degrade material performance. Even at

ppm levels, these elements may trigger phase instability [24], segregation [21], intergranular embrittlement [25,26], or property degradation [21]. As the chemical complexity of alloys increases, especially with the rise of multi-principal element alloys [10] and advanced metastable systems [27], understanding and controlling impurity effects becomes increasingly critical, yet also more difficult.

Among challenges in advancing high-purity alloy systems, the fabrication route remains a central concern. Achieving and maintaining high purity during alloy processing requires not only high-grade raw materials, but also purification techniques that minimize contamination from crucibles [28,29], atmospheres [30], and handling environments [31]. Over the past decades, a wide range of fabrication methods have been developed—from vacuum-based melting [32] to electrochemical refining [33]—each offering distinct advantages and limitations in impurity control [4]. These methods vary in their scalability, efficiency, contamination risk, and suitability for scientific research. Therefore, a systematic comparison of current fabrication strategies is necessary to clarify their capabilities and boundaries. The corresponding techniques have been summarized in this review.

In this context, electromagnetic levitation (EML)-based melting has attracted growing attention as a contactless, contamination-free approach [34–36]. When used with high-purity feedstock, it offers a unique opportunity to fabricate and study alloys under truly inert conditions. This technique not only supports the production of ultra-clean alloys for advanced applications but also provides an ideal experimental platform to isolate and investigate fundamental structure–property relationships.

While the ideal route to high-purity alloys often starts with high-grade raw materials, the high cost and scarcity of ultra-pure metals remain practical constraints. With growing demands for sustainable manufacturing, there is increasing interest in producing high-performance alloys from low-grade or recycled materials, which are typically burdened with higher levels of residual elements [37,38]. In such cases, enhancing impurity tolerance through compositional design or microstructural engineering becomes a critical challenge—but current understanding of impurity–property correlations and mitigation strategies remains limited and fragmented.

Prior reviews have focused on specific aspects of high-purity alloys, such as purification techniques [39], individual alloy systems [40–42], or electronic applications [43–46]. However, a comprehensive summary connecting impurity control mechanisms to microstructural evolution and performance across diverse metallic systems is still lacking. In particular, the integration of recent experimental advances, including containerless processing and high-resolution characterization, with alloy design strategies has not been systematically discussed.

To address this gap, this review aims to provide an up-to-date and holistic overview of high-purity metallic alloys, with a special focus on their impurity sensitivity, processing strategies, performance implications, and emerging applications. Fig. 1 illustrates key industrial and scientific fields where high-purity alloys are essential. This article also highlights the specific value of containerless levitation melting for fabricating and studying high-purity alloys and outlines the key scientific and technical challenges that must be addressed to expand the use of high-purity alloy systems, both from clean and recycled sources.

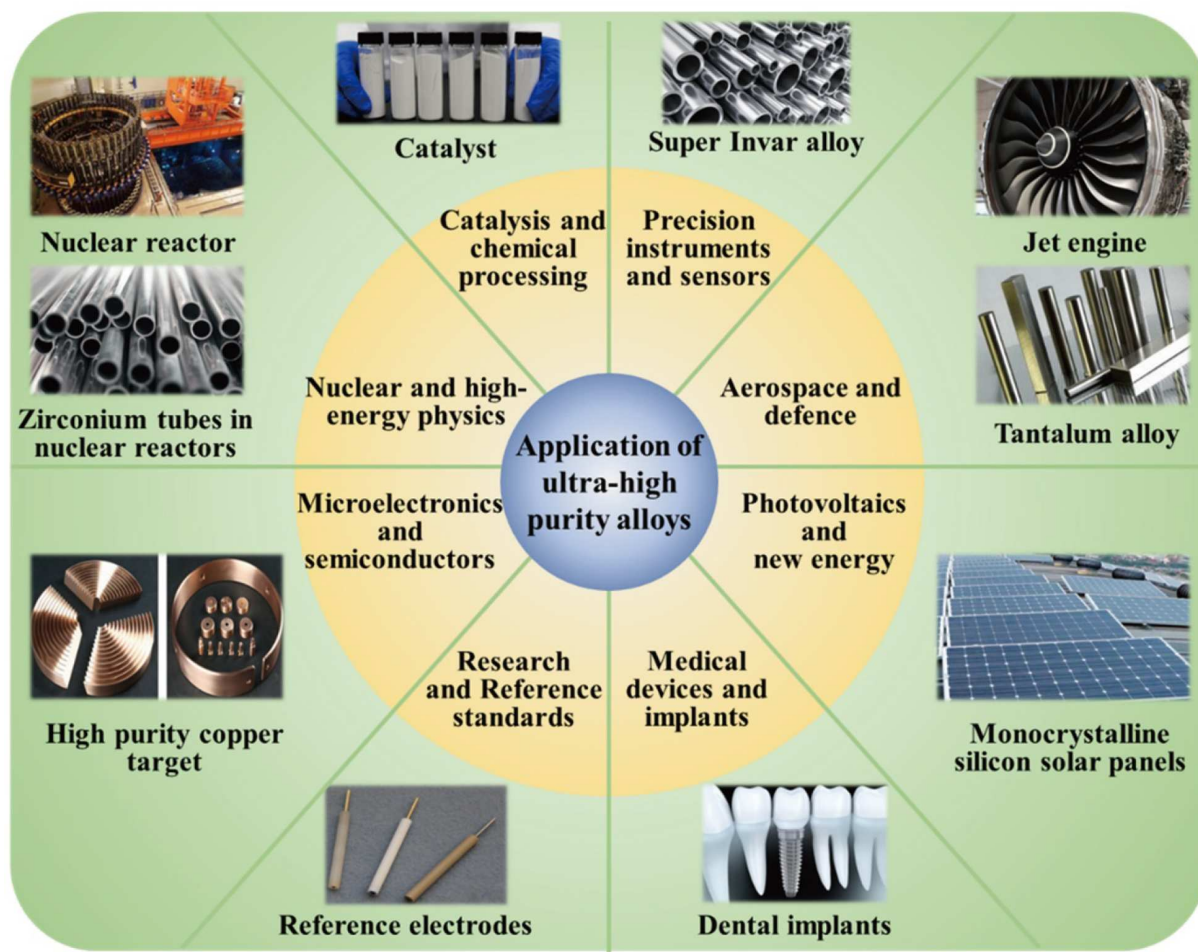


Figure 1 Application of high-purity alloys in various application fields.

DETRIMENTAL ELEMENTS FOR VARIOUS ALLOYING SYSTEMS AND CORRESPONDING PROPERTIES

Impurities in alloying systems can significantly impact the performance of materials, even at trace levels. Each alloy system has specific tolerance thresholds for impurities, beyond which undesirable phases form, leading to degraded mechanical, corrosion, or thermal properties. This section discusses the detrimental effects of impurities in various alloy systems, along with their associated tolerance levels and forming phases.

Impurities in aluminum alloys

In non-heat-treatable aluminum alloys, iron (Fe) and silicon (Si) are among the most detrimental impurities due to their significant impact on mechanical properties and conductivity. The tolerance for Fe in high-purity aluminum is typically below 0.2 wt%, as higher concentrations lead to the formation of FeAl_3 , a brittle intermetallic phase that precipitates along grain boundaries and acts as a crack initiation site under stress [47,48]. The intermetallic phase reduces elongation and ductility by up to 30%, severely limiting the alloy's toughness [49]. Silicon, on the other hand, interacts with Fe to form complex intermetallic compounds such as Al_3FeSi or AlFeSi , which exhibit a needle-like morphology that further exacerbates crack propagation under mechanical loading [50]. Excess Si impurities, typically

above 0.1 wt%, also disrupt the formation of desirable phases in aluminum and reduce its thermal and electrical conductivity by approximately 10%–20% [1].

The combined presence of Fe and Si impurities amplifies these negative effects due to their tendency to form ternary Al-Fe-Si compounds, which are thermodynamically stable but mechanically brittle. Nová *et al.* [50] demonstrated that the Al_3FeSi phase significantly degrades the structural integrity of aluminum alloys, making them unsuitable for applications requiring high ductility and conductivity. Moreover, these intermetallic phases are often difficult to remove during processing, necessitating advanced refining techniques such as directional solidification or zone refining to reduce Fe and Si levels. Chen *et al.* [48] emphasize that controlling Fe and Si impurities is critical for maintaining the performance of aluminum alloys in high-performance applications, such as aerospace and electronics, where mechanical reliability and conductivity are paramount.

Impurities in magnesium alloys

Magnesium alloys are particularly sensitive to iron (Fe), nickel (Ni), and copper (Cu) impurities due to their detrimental effects on corrosion resistance. The corrosion of Mg and its alloys often results in cracking, deformation, and spallation. Macro-cracks have been observed in AZ31 after 1–3 months of exposure (Fig. 2a, b), while focused ion beam/scanning electron micro-

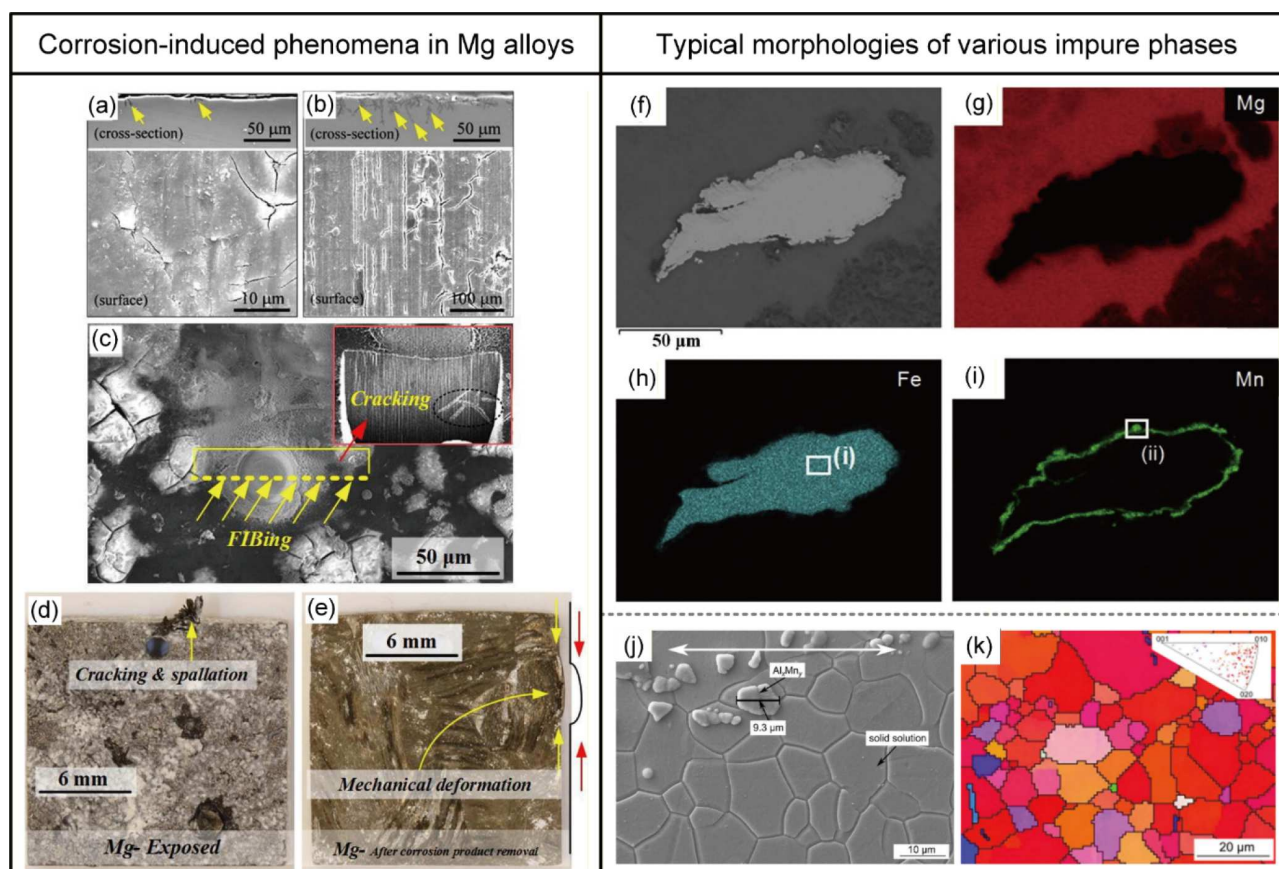


Figure 2 Corrosion-induced phenomena in Mg and Mg-Al alloys. (a, b) Plan-view and cross-sections of AZ31 after atmospheric exposure; (c) FIB/SEM analysis of AM50 after 168 h corrosion; (d, e) HP Mg surface before and after pickling after 672 h exposure; (f–i) backscattered electrons (BSE)-SEM of Mn-Fe particle and energy dispersive X-ray spectroscopy (EDS) maps of Mg, Fe, and Mn. Reprinted with permission from Ref. [51]. Copyright 2017, Elsevier. (j) SEM and (k) electron back scatter diffraction (EBSD) of wrought AZ31 with Mn impurity. Reprinted with permission from Ref. [58]. Copyright 2021, MDPI.

scopy (FIB/SEM) revealed micro-cracks in AM50 after 168 h (Fig. 2c) [51]. Pure Mg also exhibited cracking, surface spallation (Fig. 2d), and substrate deformation (Fig. 2e). According to Song and Atrens [52,53], Fe impurities must be maintained below 0.004 wt%, as higher concentrations lead to the formation of galvanically active phases that accelerate localized corrosion. This closely aligns with other studies, setting the Fe limit at 0.005 wt%. Fe-containing phases catalyze corrosion rates, particularly in humid and marine environments, often increasing corrosion rates by up to 100 times compared to purer alloys [51–53]. The typical Fe-containing phase is shown in Fig. 2f–i.

Nickel and copper impurities have similarly strict limits, with Ni restricted to 0.001 wt% due to its role in promoting severe pitting corrosion and Cu limited to 0.02–0.03 wt%. Both elements form cathodic intermetallic phases, such as Mg_2Ni and Mg_2Cu , which exacerbate electrochemical activity and compromise the alloy's structural integrity. Song and Atrens emphasize that Cu impurities, while less cathodic than Ni, still significantly accelerate corrosion in chloride-rich environments [54–57]. Moreover, the trace impurities of Al and Mn are also present in magnesium alloys, which affect their corrosion performance (Fig. 2j, k) [58].

Fattah-alhosseini *et al.* [59] investigated the influence of purity on the corrosion behavior of Mg. Their study shows that low-purity Mg exhibits significantly lower corrosion resistance compared to high-purity Mg due to the presence of metallic

impurities. These impurities act as micro-cathodes within the Mg matrix, establishing localized galvanic cells that accelerate the anodic dissolution of Mg [59]. In addition, variations in alloy composition can alter the electrochemical potentials of the constituent phases, further influencing corrosion kinetics. Overall, controlling impurity levels is critical for enhancing the corrosion resistance of Mg and its alloys, as even trace amounts of detrimental elements can dramatically impact localized corrosion processes.

These findings highlight the necessity of impurity control in magnesium alloys. Refining processes, such as melt filtration and selective intermetallic phase separation, are critical for reducing Fe, Ni, and Cu levels to within tolerance limits. Such strategies ensure magnesium alloys achieve the durability required for demanding applications, particularly in automotive and aerospace industries [56,57].

Impurities in magnesium alloys primarily originate from raw materials, recycling processes, equipment contact, alloying elements, and environmental exposure. Raw magnesium sources, such as magnesite and dolomite, often contain trace Fe, Ni, and Cu, which carry over during extraction and reduction processes, especially when ferrosilicon is used as a reducing agent [52,53]. Recycling introduces significant impurities, as scrap magnesium frequently contains residual Fe and Cu from coatings or contact with non-ferrous materials [55–57]. Equipment used during melting and casting, particularly uncoated steel crucibles, con-

tributes Fe and Ni through direct contact with molten magnesium [57]. Alloying elements like aluminum or rare earth metals can also introduce impurities if not of high purity themselves [54]. Additionally, environmental factors, such as dust and moisture during storage or handling, can further contaminate magnesium due to its high reactivity [60]. Advanced refining techniques, such as fluxing, vacuum refining, and the use of high-purity feedstock, are crucial for minimizing these impurities and maintaining alloy performance [52,53,57]. The corrosion rates of high-purity magnesium and its alloys processed by different routes are summarized in Table 1. The data indicate the strong dependence of degradation behavior on alloy composition and processing methods.

Impurities in titanium alloys

For titanium alloys, interstitial elements such as oxygen (O), nitrogen (N), and carbon (C) are the primary impurities of concern [64]. Oxygen content should be limited to below 0.15 wt% to avoid embrittlement, while nitrogen and carbon should not exceed 0.04 and 0.08 wt%, respectively, to prevent the formation of hard, brittle phases such as TiO₂, TiN, and TiC. Excess oxygen, for example, can reduce ductility by up to 40% and significantly impair fatigue resistance, posing challenges for titanium alloys used in critical aerospace and biomedical applications [3]. As reported by Chong *et al.* [65], interstitial oxygen can significantly increase the strength, but it can also severely deteriorate the ductility rendering titanium extremely brittle at 77 K when the oxygen content merely exceeds 0.3 wt%. Interstitial oxygen not only presents in pure Ti but also exists in the Ti alloys, such as TiNbZr-based alloys [66].

Impurities in zirconium alloys

In zirconium alloys, commonly used in nuclear reactors, the presence of iron (Fe), chromium (Cr), and silicon (Si) can have severe consequences [67,68]. Fe and Cr impurities, if present above 0.01 and 0.02 wt%, respectively, can reduce corrosion resistance in high-temperature and high-radiation environments. Silicon levels must be kept below 0.03 wt% to prevent the formation of silicide phases, which degrade toughness and mechanical stability. Studies have shown that excess Fe can decrease corrosion resistance by up to 50%, emphasizing the importance of impurity control in nuclear-grade zirconium alloys [4]. As investigated by Nikulina and Malgin [69], impurities can dramatically affect the corrosion resistance, fracture toughness and nucleation energy of cracking for nuclear applications.

Impurities in copper alloys

Copper alloys are highly susceptible to impurities such as oxygen (O) and lead (Pb). Oxygen levels above 0.01 wt% promote the formation of copper oxides, which reduce electrical conductivity and create microcracks that weaken the material under stress. Lead, while sometimes added for machinability, must be kept below 0.005 wt% for precision applications, as it forms weak inclusions that lower mechanical strength. Excess oxygen impurities, for example, can reduce electrical conductivity by up to 20%, limiting the performance of copper alloys in electronic and thermal applications [5]. Oxygen and lead significantly impact the properties of high-conductivity copper. Oxygen reduces electrical conductivity by forming oxides that scatter electrons, with a 0.01% increase lowering conductivity by about

Table 1 Corrosion rates of high-purity Mg and its alloys

Alloying system	Processes	Corrosion rate (weight loss, mm/a)	References
HP Mg	Casting	0.88	[8]
WZ21	Extrusion	0.48	[8]
AZ91	Casting	6.70	[8]
AZ31 (with 4N HP Mg)	Casting	0.81	[61]
Mg-8Y	Casting	2.17	[62]
Mg-Sc-REE-Zr system	Casting	4.4	[63]

0.12% IACS. It also interacts with lead, reducing its harmful effects by promoting oxide formation. Lead, a major impurity, decreases conductivity by 0.10%–0.12% IACS for every 5 ppm, though higher oxygen levels mitigate this. Lead also raises hardness and the half-softening temperature by 1.44°F (0.8°C) per ppm. Both impurities enter copper during smelting and refining, with careful management needed to preserve copper's performance [70].

Argon plasma-arc zone melting (APZM) has been demonstrated as an effective method for purifying 4N-grade copper, achieving significant reductions in total impurity concentration (Fig. 3a1) [71]. By coupling segregation and evaporation effects, impurities with low equilibrium distribution coefficients (e.g., Sn, As, Sb, Zr) are effectively driven to the rod tail, while volatile elements such as S, P, and Mg are additionally removed via evaporation due to their high partial pressure ratios (Fig. 3a2–a5).

Further insights into impurity effects on electrical conductivity were provided by first-principles simulations of Cu alloys doped with Ni, Al, and Si [72]. It was found that increasing impurity concentration consistently reduces electronic transmission, with silicon exerting the strongest detrimental effect, followed by aluminum and then nickel. Notably, nickel impurities introduce additional valence states near the Fermi level, which contribute to scattering but maintain relatively high conductivity compared to Al and Si (Fig. 3b) [72]. Moreover, impurity clustering—such as in b-Ni₃Si precipitates—was shown to mitigate conductivity loss, highlighting the importance of impurity distribution in optimizing alloy performance.

Beyond conductivity, impurity segregation also affects the mechanical integrity of Cu. First-principles studies show that 3sp elements (Mg, Al, Si, P, S) at grain boundaries alter the work of separation and dislocation emission [73]. Sulfur strongly reduces the work of separation and promotes intergranular embrittlement, while phosphorus lowers dislocation emission more effectively, enhancing ductility (Fig. 3c1, c2) [73]. These effects are mainly chemical in origin and correlate with electronegativity. Moreover, S tends to cluster at boundaries, amplifying its embrittling effect, whereas P remains more uniformly distributed (Fig. 3c3).

Impurities such as bismuth and arsenic can significantly affect the mechanical and physical properties of copper, even at trace levels [74,75]. Bismuth, with a solubility of less than 0.002%, severely impairs hot-rolling at concentrations below 0.01% and causes fracturing during cold-rolling above 0.05%. In contrast, arsenic enhances copper's ductility and can improve casting

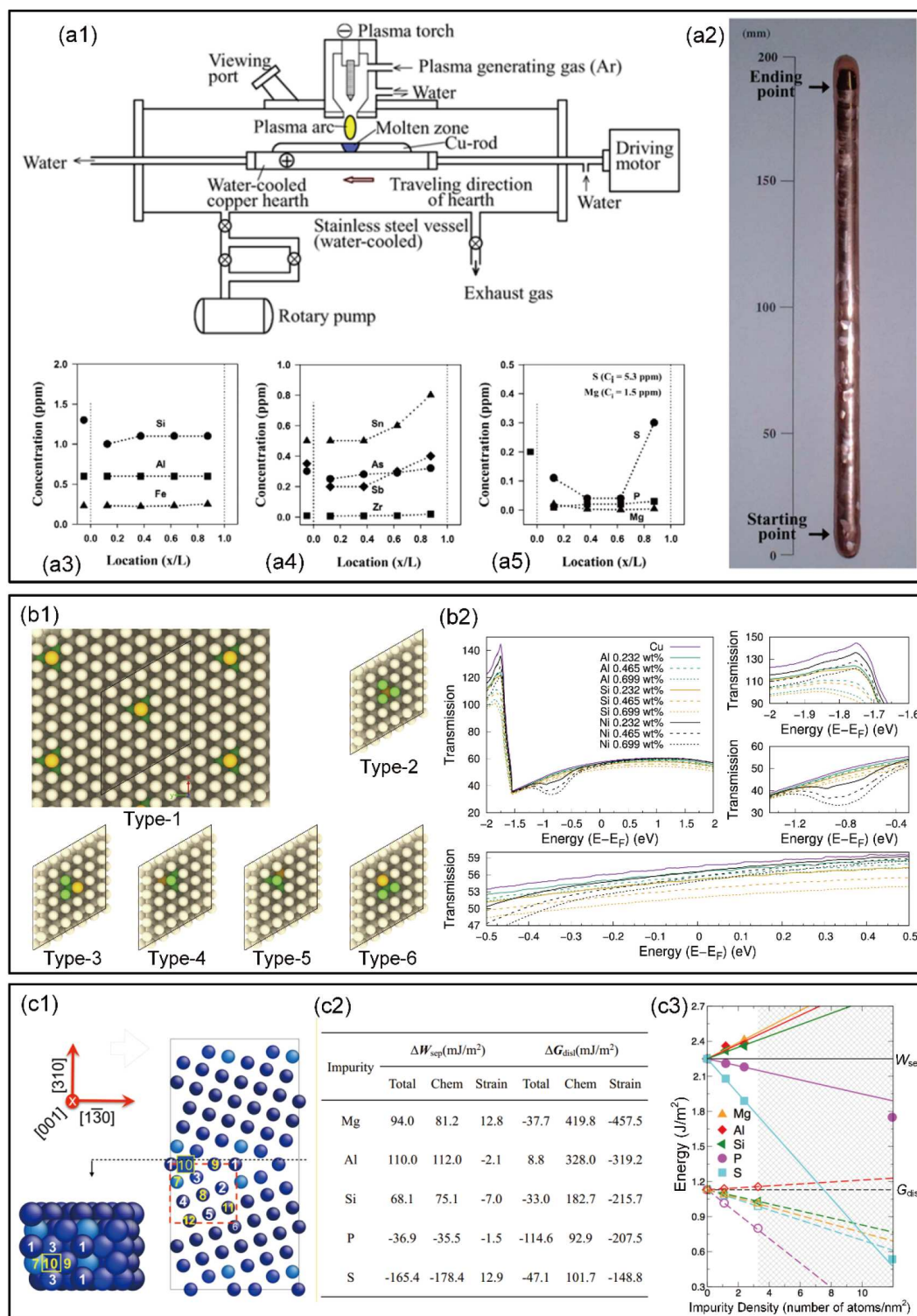


Figure 3 (a1) Argon plasma-arc zone melting setup; (a2) Cu rod after 10 refining passes; (a3–a5) impurity concentration profiles along the 4N Cu rod, plotted as a function of x/L (x : distance from head, L : total length). Reprinted with permission from Ref. [71]. Copyright 2009, Springer Nature. (b1) β -Ni₃Si alloy configurations in fcc Cu, viewed along [111] (Si: yellow, Ni: green); (b2) electronic transmission spectra of Cu alloys with varying Al, Si, or Ni impurity concentrations. Reprinted with permission from Ref. [72]. Copyright 2019, Elsevier. (c1) Atomic structure of the $\Sigma 5(310)[001]$ symmetric tilt grain boundary; (c2) segregation-induced changes in separation work (W_{sep}) and dislocation nucleation energy (G_{disl}) (chemical vs. strain effects); (c3) W_{sep} and G_{disl} vs. impurity segregation density. Reprinted with permission from Ref. [73]. Copyright 2017, American Physical Society.

properties, especially when combined with oxygen. Arsenic reduces the harmful effects of oxygen during cold-working, provided its concentration is sufficiently higher than that of

oxygen. These impurities primarily originate from copper ores, where arsenic is found in minerals like enargite and tennantite, while bismuth occurs in bismuthinite or as native bismuth. They

are introduced during smelting and refining, and can accumulate further through copper recycling. Managing their levels is essential for maintaining the desirable properties of copper in industrial applications [76].

Impurities in steels

For cleanliness steel, the main concern is about its inclusion, including alumina, magnesium oxide, calcium sulphide, manganese sulphide, and silica [77,78]. Achieving high cleanliness in steel involves minimizing non-metallic inclusions, refining their morphology, and controlling their size and distribution. Since this review mainly focuses on high purity alloys, the fabrication of cleanliness steel will not be discussed here.

With the growing emphasis on sustainable manufacturing, the demand for scrap-based steel production has been steadily increasing, bringing renewed attention to the effects of residual impurities on steel performance. The study by Duan *et al.* [79] systematically investigates the influence of typical residual impurities, including Cu, Ni, Cr, and Sn, introduced through increased scrap usage on the microstructure and mechanical properties of low-carbon steel. The base steel represents a

reference low-carbon steel composition corresponding to a conventional structural strip steel, while QA steel simulates a scrap-containing scenario with elevated impurity levels characteristic of a specific low-grade scrap type. A further increase in impurity content is considered in the 2QA steel, in which the impurity levels in QA are doubled to represent a higher recycled-content condition. The bainite fraction decreased and the pearlite fraction increased, attributed to the suppression of the bainite start temperature (Bs) and transformation kinetics by these alloying elements (Fig. 4a–c). Concurrently, the presence of these impurities led to a notable refinement in the effective grain size, primarily due to solute drag during cooling, without significantly altering the prior austenite grain size (Fig. 4d, e). Cu-rich precipitates were observed within grains, at grain boundaries, and at ferrite/cementite interfaces, contributing to precipitation strengthening (Fig. 4g). These microstructural changes resulted in enhanced yield strength but reduced ductility (Fig. 4f). Despite slight variations, the overall crystallographic texture remained weak and similar across all impurity levels, characterized by incomplete α - and γ -fibres (Fig. 4e). This work highlights the complex interplay between impurity content

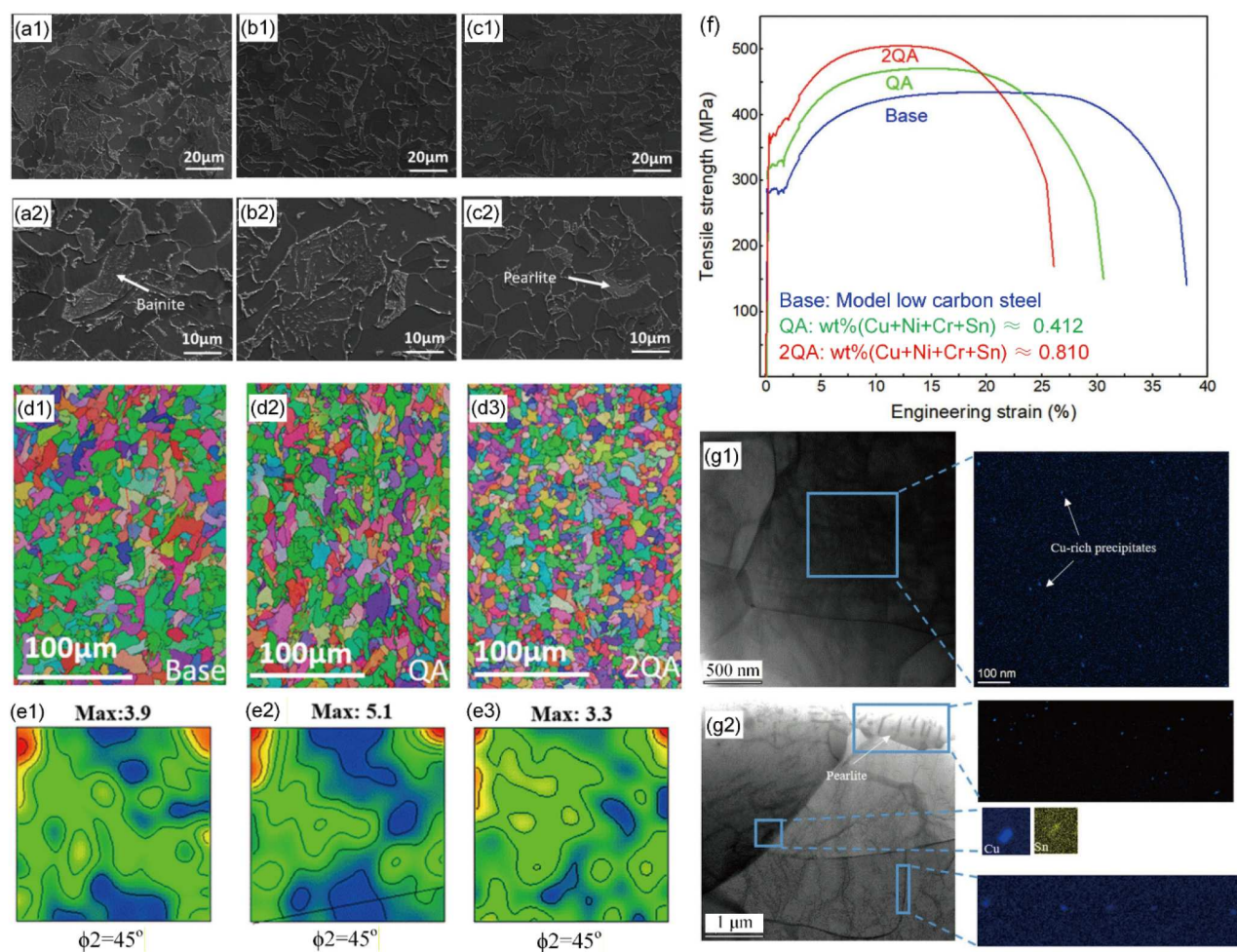


Figure 4 SEM images of experimental steels: (a1, a2) Base, (b1, b2) QA, and (c1, c2) 2QA, showing impurity effects on microstructures and phases. EBSD orientation and orientation distribution function maps: (d1, e1) Base, (d2, e2) QA, and (d3, e3) 2QA steel showing impurity effects on grain sizes and textures in low-carbon steels. (f) Engineering stress–strain curves of low-carbon steels with varying impurity contents. Transmission electron microscopy (TEM) images of 2QA steel with EDS Cu maps: (g1) Cu-rich precipitates in ferrite grains; (g2) Cu-rich precipitates at ferrite/cementite interfaces and grain boundaries, with Sn enrichment in one Cu-rich precipitate. Reprinted with permission from Ref. [79]. Copyright 2022, Taylor & Francis.

and microstructural evolution, essential for optimizing mechanical performance in steels produced from recycled materials.

The presence of these detrimental elements and their associated phases highlights the critical importance of impurity control in high-performance alloy systems. Advanced refining techniques and precise impurity management strategies are essential to maintain the desirable properties of these materials and expand their applications in demanding environments.

As shown in Fig. 5, the tolerance for impurities varies significantly across alloy systems, governed primarily by solubility limits and the detrimental phases formed. In zirconium and titanium alloys, interstitial elements (O, N, C) and specific transition metals (Fe, Cr) must be strictly controlled to prevent embrittlement and maintain corrosion resistance in radiation or bio-implant environments [64,70,80,81]. Copper and aluminum alloys are highly sensitive to impurities like oxygen, iron, and silicon, which disrupt electrical conductivity and form brittle intermetallic phases (e.g., β -Al₃FeSi) that serve as crack initiation sites [82–86]. Magnesium alloys exhibit the lowest tolerance levels, particularly for nickel, iron, and copper, as these elements act as active cathodic sites that drive catastrophic galvanic corrosion [87]. Control strategies across these systems range from vacuum arc remelting (VAR) and electrolytic refining to the use of specific alloying additions to modify or precipitate harmful impurities, which are summarized in Table 2. More specific strategies for controlling impurities are reviewed in the section “Strategies to mitigate impurity effects in metallic alloys”.

This indicates that when designing or selecting alloy compositions, careful consideration must be given to the specific impurity tolerance levels of each system. Variations in tolerance can significantly affect mechanical properties, corrosion resistance, and phase stability. Therefore, optimizing alloy performance requires tailoring processing conditions and refining raw materials to align with the impurity limits of the target alloy system.

Table 3 presents the mechanical properties of representative high-purity metals and alloys processed by different techniques. The data include tensile yield strength (TYS), ultimate tensile strength (UTS), and elongation to failure (EL), highlighting the broad range of strength–ductility combinations achievable by purity control and tailored processing routes. For instance, high-purity Mg shows tunable properties depending on extrusion

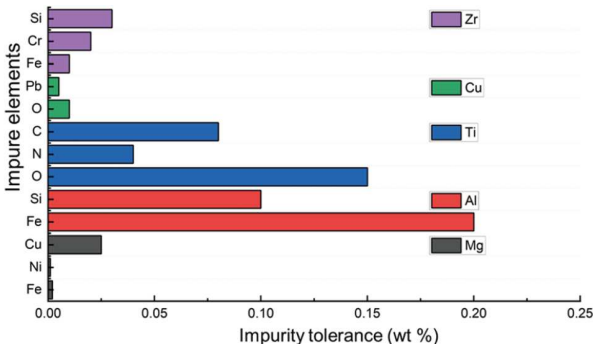


Figure 5 Tolerance for impurities in various alloying systems.

temperature and subsequent thermomechanical treatments, while high-purity Ti exhibits significantly enhanced ductility compared with commercially pure Ti owing to the reduced oxygen content. Advanced alloys such as Ti–Nb–Ta–Zr and V–Cr–Ti systems demonstrate the effect of both composition and impurity levels on strength retention and plasticity. Together, the summarized results emphasize how alloy purity and processing strategy critically influence mechanical performance across different metallic systems.

TECHNIQUES AND STRATEGIES FOR ACHIEVING HIGH-PURITY ALLOYS

Techniques for manufacturing high purity alloys

Achieving high-purity alloys is critical for applications requiring exceptional mechanical properties, corrosion resistance, and performance in extreme environments. Various advanced techniques are employed to refine alloys, remove impurities, and ensure homogeneity. This section elaborates on three primary methods: the triple melt process (vacuum induction melting–electroslag remelting–VAR (VIM–ESR–VAR)), electrolysis refining and electromagnetic levitation melting.

VIM-ESR-VAR triplex melting process

The VIM-ESR-VAR is a versatile and critical approach for producing high-purity, homogeneous alloys (illustrated in Fig. 6a), including nickel-based superalloys, high-cleanliness steels, and other advanced materials. The process begins with VIM, where recycled materials, master alloys, and pure metals

Table 2 Impurity tolerance, mechanisms, and control

Alloy system	Key impurities	Typical tolerance (wt%)	Influence mechanism	Control strategy	References
Zr	Cr, Fe, Si	Cr ≤ 0.02 Fe ≤ 0.01 Si ≤ 0.03	Corrosion & toughness: reduces radiation corrosion resistance; forms brittle phases	Purification: Kroll process; VAR	[70,80]
Cu	O, Pb	O ≤ 0.01 Pb ≤ 0.005	Conductivity & strength: embrittlement; conductivity loss; hot shortness	Refining: electrolytic refining; deoxidizers; VIM	[82]
Ti	O, N, C	O ≤ 0.15 N ≤ 0.04 C ≤ 0.08	Embrittlement: lattice distortion; precipitation of hard ceramic phases	Process control: extra low interstitial grades; vacuum processing; clean powder	[64,81]
Al	Fe, Si	Fe ≤ 0.20 Si ≤ 0.10	Ductility: formation of brittle, needle-like phases	Alloying: Mn addition (modifies phase); high-purity smelting	[83–86]
Mg	Ni, Fe, Cu	Ni ≤ 0.002 Fe ≤ 0.005 Cu ≤ 0.025	Corrosion: impurities act as cathodes, driving severe galvanic corrosion	Precipitation & Dilution: Mn addition settles Fe; required for Ni/Cu	[87]

Table 3 Summary of mechanical properties of high-purity metals and alloys

Alloying system	Processes	TYS (MPa)	UTS (MPa)	EL (%)	References
HP Mg	Extrusion at 150°C	129	183	17.7	[88]
Mg-8Y	Casting	156	257	14	[62]
Mg-Sc-REE-Zr system	Casting	240	320	25	[63]
	Casting	66	180	24	[89]
HP Mg (4N)	Extrusion at 200°C	128	200	12	[89]
	Extrusion + forging + annealing	103	212	6.5	[89]
HP Al (5N)	Equal-channel angular pressing with 2 passes	–	92	28	[90]
Al-11Si	Casting	–	191	13.4	[91]
CP Ti (O: 0.14)	Casting + rolling	340	504	30.8	[92]
HP Ti (O: 0.02)	Casting + rolling	142	255	72.8	[92]
Ti-6Al-4V	Cold-isostatic pressing + vacuum sintering	740	830	6	[93]
Ti-35Nb-2Ta-3Zr	Arc melting + rolling	–	896	9	[94]
Ti-44Al-48Nb8	electromagnetic levitation processing	382	297	1.7	[95]
V-4Cr-4Ti	Forging in the temperature range of 1000–1200°C	297	389	33.2	[96]
V-10Cr-5Ti	O: 20 ppm	–	352	–	[97,98]
	O: 100 ppm	–	422	–	
	O: 450 ppm	–	543	–	

are melted under vacuum to achieve precise chemical compositions while minimizing oxygen, nitrogen, and hydrogen levels. This step enables the incorporation of reactive alloying elements, such as aluminum or titanium, without forming non-metallic inclusions, making it suitable for a broad range of alloys. The ESR process follows, where the VIM-produced electrode is melted through a reactive slag and solidified in a cooled copper crucible. ESR facilitates chemical refinement by removing impurities like sulphur and phosphorus through slag-metal reactions, while controlled solidification ensures a uniform microstructure. The final VAR step melts the electrode under vacuum via an electric arc, further reducing volatile impurities, such as oxygen, hydrogen, and high-vapor-pressure elements like lead or tin, while ensuring exceptional homogeneity through controlled melting and solidification. Unlike ESR, VAR does not employ slag, making it more focused on minimizing residual gas content. Post-melting, homogenization heat treatment is typically performed to eliminate residual segregations, achieving a consistent microstructure across the material. This integrated triplex process is pivotal for producing high-performance materials required in critical applications, including aerospace, energy, and medical devices, where purity and uniformity are paramount [99,100]. For single-crystal alloys such as DD98M, VIM-ESR-VAR can lower oxygen and nitrogen to ~5 ppm each, leading to reduced dendrite arm spacing, lower eutectic fraction, and diminished micro-segregation. These improvements arise from enhanced solidification control rather than inclusion-nucleated grain refinement [101].

This triplex route effectively combines compositional accuracy, low inclusion content, and refined solidification structure,

supporting the stringent performance requirements of turbine disks, blades, and other safety-critical components. However, its multi-step nature leads to higher production costs and longer processing cycles, which may limit its use for lower-value alloys.

Electrolysis refining

Electrolysis is a foundational technique for refining metals to high purity, leveraging electrochemical principles to separate impurities from the base metal. In electrolysis, an alloy or impure metal is used as the anode, while a pure metal serves as the cathode. When an electric current is applied, metal ions migrate from the anode to the cathode, leaving behind non-metallic impurities or forming sludge at the bottom of the electrolyte bath [102,103]. The process has been illustrated in Fig. 6b1, and the example of refining scrap Al is shown in Fig. 6b2, b3. This process is particularly effective for refining copper, nickel, scrap aluminum and other conductive metals, ensuring minimal contamination from oxides, sulfides, or gaseous inclusions. The resulting metal exhibits enhanced ductility, electrical conductivity, and corrosion resistance, making electrolysis a cornerstone for producing high-purity alloys for electronics, aerospace, and medical industries.

Zone refining

ZR is a purification technique that removes impurities based on their equilibrium distribution coefficients between the solid and liquid phases. By moving a narrow molten zone along a solid bar, impurities with $k_0 < 1$ (e.g., P, Al) are rejected into the melt and whereas those with $k_0 > 1$ (e.g., B, Si) migrate into the solidifying front (Fig. 6c). For instance, high-purity Ge (13 N)

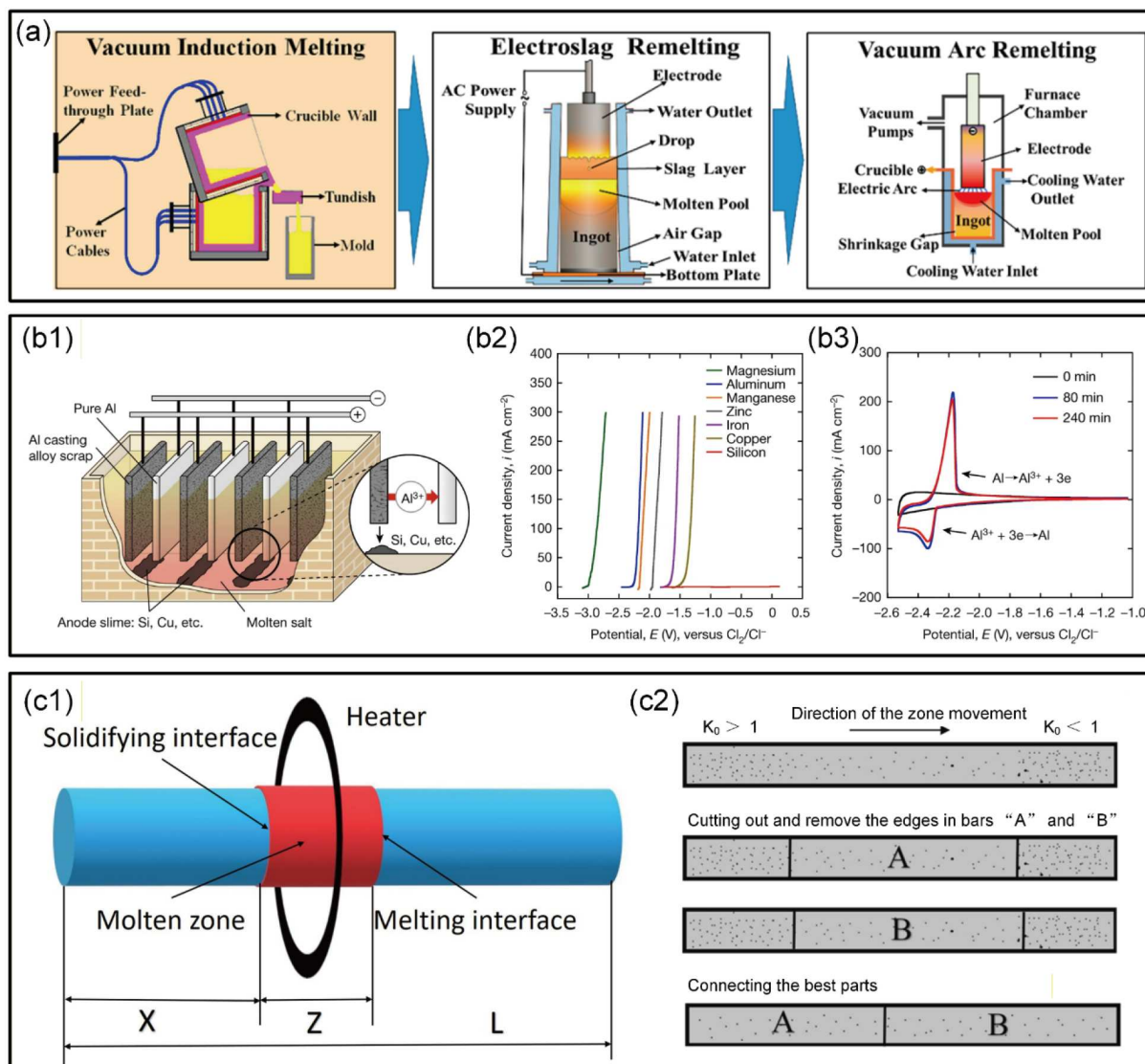


Figure 6 Schematic of the triple melt process: (a) vacuum induction melting, electroslag remelting, and vacuum arc remelting. Reprinted with permission from Ref. [105]. Copyright 2019, MDPI. (b1) Electrolysis refining, where aluminum dissolves from scrap and deposits on the cathode, with alloying elements forming anode slime; (b2) anode polarization curves of aluminum and common alloying elements in molten LiCl–KCl; (b3) cyclic voltammetry before and after dissolving an aluminum casting alloy in molten LiCl–KCl. Reprinted with permission from Ref. [103]. Copyright 2022, Springer Nature. (c1) Schematic of the zone refining process; (c2) schematic of the cropping and connecting process from zone refining. Reprinted with permission from Ref. [104]. Copyright 2025, Elsevier.

was produced from 4 N feedstock by optimizing ZR parameters—such as container material, atmosphere, zone length, and zone travel speed (4–5 mm/min)—and employing a two-stage process with graphite and quartz-smoke-coated quartz containers under hydrogen [104]. While the method achieved extremely low carrier concentrations ($4\text{--}9 \times 10^{10} \text{ cm}^{-3}$), its limitations include sensitivity to container–melt interactions at low zone velocities, which can cause impurity back-diffusion, and the high processing time and cost required for large-scale industrial application.

Electromagnetic levitation melting

EML is an innovative technique that allows alloys to be processed without contact with a container, eliminating contamination risks. In this process, metal samples are suspended in a high-frequency electromagnetic field, where they are melted

and refined under controlled atmospheres, such as high-purity argon (Fig. 7a). This containerless melting method prevents interaction with crucible materials, reducing the likelihood of oxide formation and ensuring the purity of the melt [106]. This technique is widely used for producing high purity alloys.

For example, electromagnetic levitation melting has been used for fabricating high-entropy alloys (HEAs). Fig. 7b shows the $\text{CoCrNi}_2(\text{Al}_{0.2}\text{Nb}_{0.2})$ HEA alloys with homogeneous element distribution in FCC phase and nanoscale L_{12} phases. Due to such unique microstructure and high purity, such HEA alloys show superior wear performance [107].

In addition to fabricating HEAs, electromagnetic levitation is instrumental in refining Fe–Si alloys and Ti–Al systems. As illustrated in Fig. 7c, d, containerless solidification, coupled with electromagnetic stirring, promotes grain refinement in Fe–Si

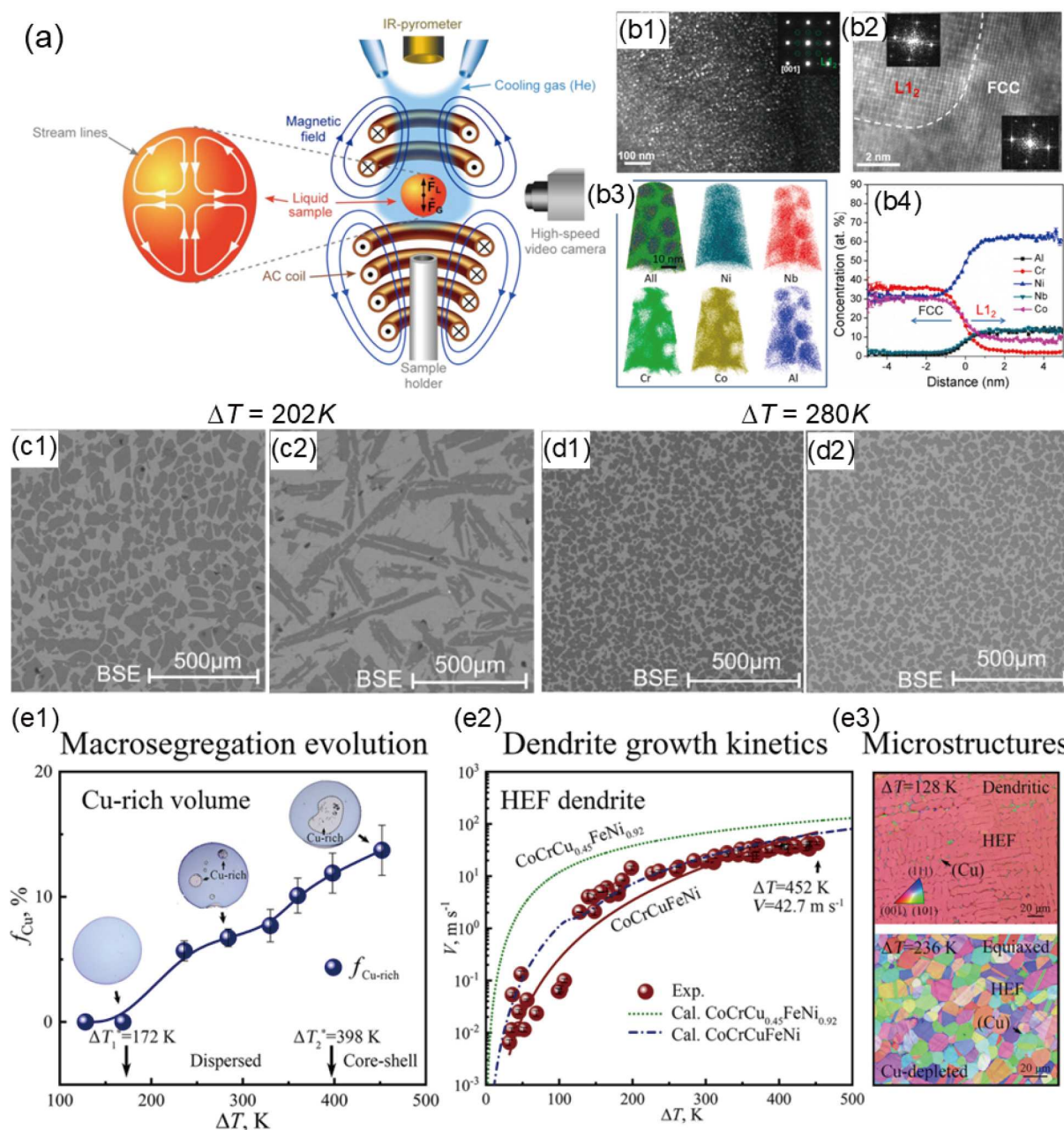


Figure 7 (a) Schematic view of an electromagnetic levitation facility and levitated liquid sample with stream lines of fluid flow as indicated inside the melt. Reprinted with permission from Ref. [106]. Copyright 2016, IOP Publishing. Electromagnetic levitation melting fabricated $\text{CoCrNi}_2(\text{Al}_{0.2}\text{Nb}_{0.2})$ alloys: (b1) dark-field TEM image and (b2) high-resolution TEM image; (b3) APT analysis and (b4) a proximity histogram across the interface between the matrix and the nanoprecipitate. Reprinted with permission from Ref. [107]. Copyright 2023, Elsevier. Fe-Si alloys obtained (c) after container solidification and (d) after containerless solidification at the undercooling of 280 K under vacuum electromagnetic levitation melting technique. Reprinted with permission from Ref. [108]. Copyright 2023, Elsevier. (e) Rapid solidification kinetics of undercooled liquid CoCrCuFeNi HEAs. Reprinted with permission from Ref. [34]. Copyright 2024, Elsevier.

alloys, enhancing mechanical performance [108]. Furthermore, by appropriately adjusting the processing parameters, oxygen can be effectively removed from the Ti-Al system, resulting in alloys with superior purity and reduced oxide inclusions [109]. Moreover, the ability of electromagnetic levitation to flexibly control melt undercooling and cooling rate—through coupling of contactless levitation with inert gas cooling—makes it especially suitable for studying metastable phenomena such as liquid phase separation and undercooling-dependent grain refinement.

Recent studies on CoCrCuFeNi high-entropy alloys [34] have demonstrated that EML can induce tunable phase segregation, orientation selection, and structural transitions, thereby providing critical insight into the interplay between chemical inhomogeneity, crystallographic evolution, and functional performance (Fig. 7e).

High-purity alloys need the integration of sophisticated techniques such as electrolysis, triple melt processes, and electromagnetic levitation. These methods not only ensure the

removal of impurities but also enable precise control over microstructure and chemical composition, paving the way for the development of next-generation materials essential for cutting-edge applications.

Strategies to mitigate impurity effects in metallic alloys

The detrimental impact of impurities on the mechanical and functional performance of metallic alloys is a major obstacle to their structural stability and service reliability. Various strategies have been developed to mitigate such effects, targeting either the direct removal, redistribution, or performance compensation of impurity elements. This section outlines six key approaches currently employed or explored in high-purity alloy research and engineering.

It is important to emphasize that the advanced processing techniques discussed previously are not only used for direct purification but also serve as essential enablers for the impurity-mitigation strategies outlined in this section. A strong synergy exists between processing and impurity management. For example, rapid and non-equilibrium solidification inherent to EML and laser-based additive manufacturing significantly enhances impurity trapping by suppressing equilibrium segregation pathways and forcing impurities to remain in the matrix rather than segregating to grain boundaries. This same principle underpins strategies such as massive interstitial solid solution (MISS) formation, where the extremely high cooling rates ($>10^6$ K/s) achievable in laser-based methods are precisely what allow large concentrations of interstitials to be incorporated without forming brittle compounds. Thus, the processing route is often the fundamental tool that enables the execution of impurity-tolerance and impurity-trapping strategies, highlighting the crucial interplay between technique selection and alloy design.

Directly reducing the content of impurity levels

The most straightforward approach to mitigate impurity effects is to minimize their concentration during alloy processing. This can be achieved through advanced refining techniques such as vacuum arc remelting, electron beam melting, zone refining, and electrochemical purification. These methods are particularly effective for removing oxygen, sulfur, phosphorus, and other harmful elements, especially when combined with high-purity raw materials and controlled atmospheres. Since these purification techniques have already been detailed in the section “Techniques for manufacturing high purity alloys”, they are not repeated here. While the technical details of purification techniques are covered in the section “Techniques for manufacturing high purity alloys”, the present section highlights their role in pushing material properties beyond conventional limits.

What should be emphasized, however, is that for certain metals and alloys, reducing impurity levels beyond a critical threshold can lead to substantial property breakthroughs. A recent study on titanium revealed that lowering the oxygen content from 0.14 wt% (commercial purity) to 0.02 wt% nearly doubled the mode-I fracture toughness—from ~ 130 to ~ 255 MPa m^{1/2} [92]. This exceptional toughness was attributed to the activation of deformation twinning and abundant $\langle c + a \rangle$ dislocation activity, which are otherwise suppressed by interstitial oxygen. Such findings clearly illustrate that precise control over trace impurities can unlock intrinsic deformation mechanisms and performance limits that remain inaccessible in

conventional-purity grades.

Core-shell precipitate formation

Cu induced embrittlement is challenging for scrap iron alloys. One effective method involves the nucleation of the MnNiSi phase on pre-existing copper-rich precipitates, forming core-shell structures that eliminate Cu embrittlement in Fe alloys. This approach leverages heterogeneous nucleation to modify the microstructure, reducing the risk of brittleness while enhancing strength and ductility. As illustrated in Fig. 8a–c, the Cu-MnNiSi precipitate morphology demonstrates the concentration profile along the precipitate, showcasing the effective encapsulation of copper by MnNiSi phases [110–112].

Recent studies on Mo alloys dispersed with irregular-shaped La₂O₃ nanoparticles highlight a promising core-shell design strategy for simultaneously enhancing plasticity and mitigating impurity-induced embrittlement (Fig. 8d–g) [113]. In this system, the La₂O₃ particle serves as a crystalline core, while severe plastic deformation promotes the formation of an amorphous, oxygen-vacancy-rich shell at the particle–matrix interface. This disordered shell not only provides multiple dislocation sources to activate diverse slip systems, thereby improving low-temperature ductility, but also scavenges residual oxygen and other reactive impurities, immobilizing them away from grain boundaries. Such engineered interfaces offer a pathway to alleviate the adverse effects of incomplete alloy purification, enabling the design of impurity-tolerant refractory metals without the prohibitive costs associated with achieving ultra-high bulk purity.

Massive interstitial solid solution alloys

Liu *et al.* [66] introduced the concept of MISS alloys, utilizing a highly distorted substitutional host lattice to incorporate substantial amounts of interstitials without forming ceramic phases. For instance, in a TiNbZr–O–C–N system, oxygen reaches up to 12 at% without oxide formation, resulting in ultrahigh compressive yield strength (4.2 GPa) and exceptional deformability (65% strain) [66]. This breakthrough allows alloys to maintain superior mechanical properties under high containing of impurities of oxygen, carbon and nitrogen.

Impurity getters

Introducing reactive elements that act as impurity getters represents an effective strategy to control detrimental interstitials in alloys. For instance, titanium (Ti) readily reacts with nitrogen (N) and oxygen (O) to form stable precipitates, thereby preventing the formation of interstitial solid solutions that can otherwise compromise alloy performance. By sequestering these interstitial elements, Ti additions mitigate their adverse effects on microstructural stability, phase formation, and mechanical properties. This approach has been demonstrated in a variety of alloy systems, including high-entropy alloys and V–Cr–Mn alloys, where Ti-containing precipitates play a critical role in enhancing overall alloy stability and strengthening performance [114].

In magnesium alloys, iron (Fe) is a detrimental impurity that is challenging to eliminate. Alloying with yttrium (Y) facilitates Fe removal by promoting the precipitation of Fe-containing particles, which settle at the bottom of the crucible during melting. This process enhances the ductility, formability, and corrosion resistance of Mg alloys. As shown in Fig. 9, Y-con-

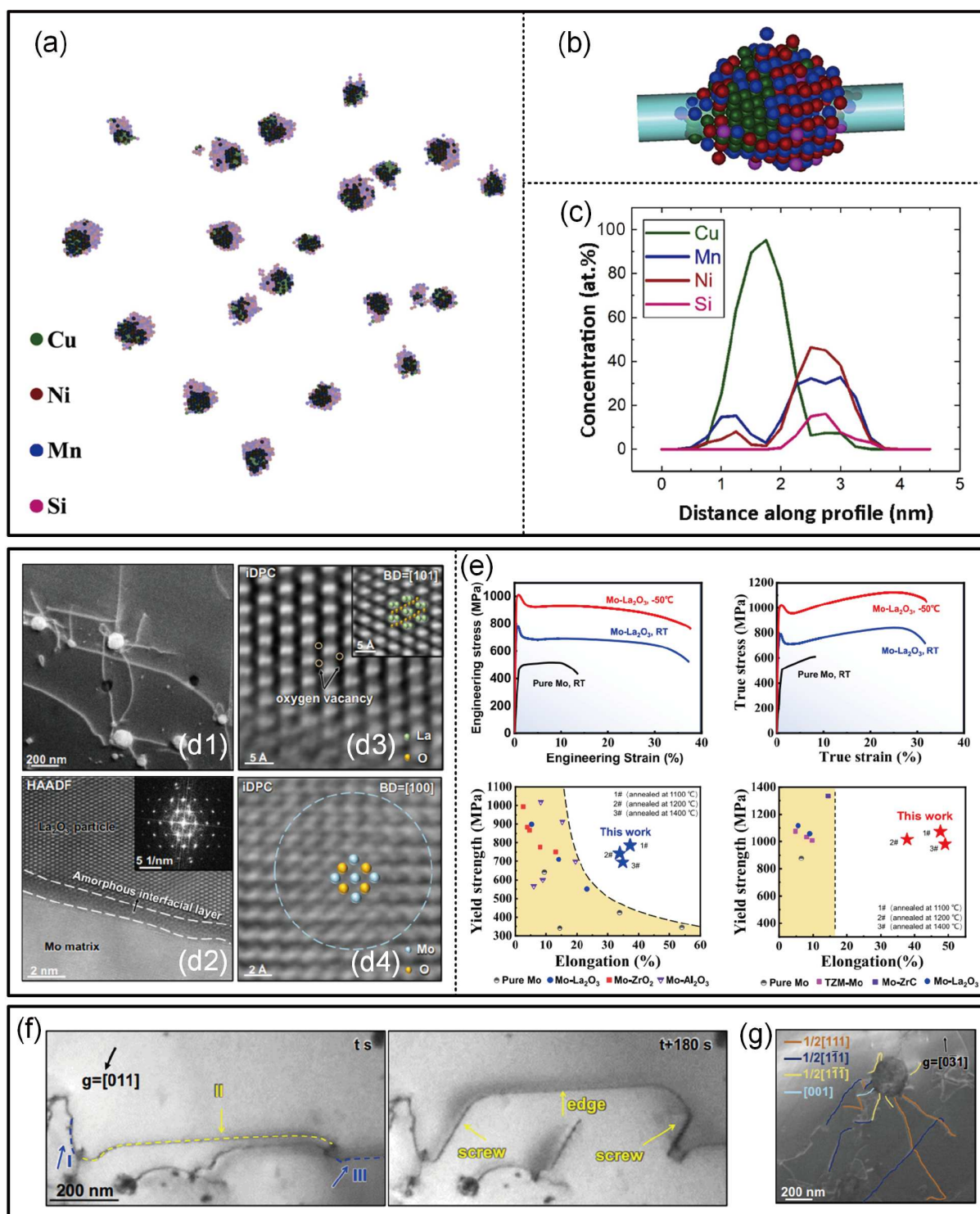


Figure 8 (a) Core-shell structure with increased Cu-Fe interfacial energy; (b) magnified Cu-MnNiSi precipitate; (c) 1-D concentration profile along the z-axis within the selected analysis region. Reprinted with permission from Ref. [110]. Copyright 2018, Elsevier. (d1) High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image of La₂O₃ nanoparticles and dislocations at the interface; (d2) amorphous interfacial layer, and the fast Fourier transform (FFT) image in the upper right corner displayed an amorphous ring accordingly; (d3) integrated differential phase contrast (iDPC)-STEM image showing oxygen vacancies in La₂O₃, and the inset highlights a magnified view of a typical oxygen vacancy configuration; (d4) oxygen clusters near the Mo matrix interface; (e) strain-stress curves for pure Mo and Mo-La₂O₃ alloys at room temperature and -50°C; (f) *in-situ* TEM tensile test on Mo-La₂O₃ alloy showing dislocation behavior; (g) dislocation structures in deformed Mo-La₂O₃ alloy. Reprinted with permission from Ref. [113]. Copyright 2024, Springer Nature.

taining Mg alloys exhibit significantly reduced corrosion rates after immersion tests, reflecting the beneficial impact of Fe removal [115].

A recent study by Nutor *et al.* [37] proposed a nanoscale

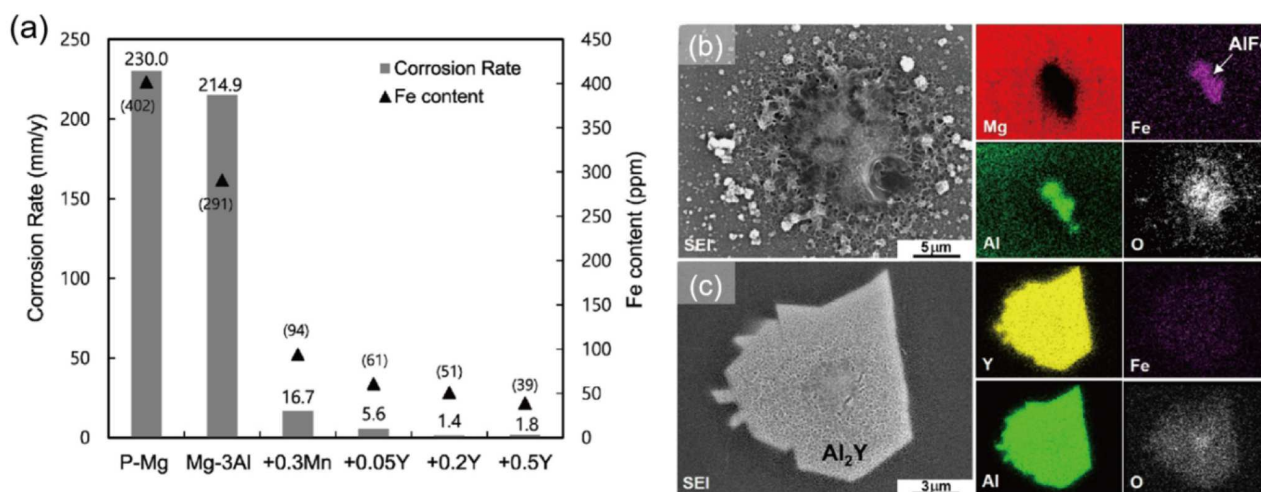


Figure 9 (a) Comparison of corrosion rates after a 72 h immersion test in a 3.5% NaCl solution and Fe contents of cast samples, and EDS mapping results showing changes in the surfaces of AlFe and Al_2Y particles in (b) Mg-3Al and (c) Mg-3Al-0.5Y alloy cast samples, respectively, after immersion for 5 s in a 3.5% NaCl solution. Reprinted with permission from Ref. [115]. Copyright 2019, Elsevier.

impurity management strategy for recycled copper recovered from scrap Cu foils, wherein impurity elements such as Fe, Co, Ni, and Mn—introduced during battery recycling—were effectively removed from solid solution via thermally induced precipitation. By employing a sequence of casting, rolling, and controlled annealing, these elements were driven to form FeCo-rich nanoprecipitates with controlled size and spatial distribution (Fig. 10a). Atom probe tomography revealed that when the interparticle spacing exceeds the electron mean free path (~ 40 nm), the resulting matrix behaves electronically similar to high-purity Cu, minimizing resistivity degradation (Fig. 10b, c). This self-purification mechanism not only restores electrical conductivity but also enhances mechanical strength via precipitation and grain boundary strengthening, providing a promising pathway for high-value reuse of recycled Cu (Fig. 10d).

Alloying to overcome impurity effects

Strategic alloying can counteract the negative effects of impurities. In Ti alloys, the addition of aluminum (Al) and oxygen (O) significantly boosts strength and ductility. For example, Ti-6Al-0.3O exhibits a six-fold increase in ductility compared to Ti-0.3O. Al and O solutes modify slip behavior, promoting a delocalized three-dimensional (3D) dislocation pattern that sustains strain-hardening. Fig. 11 illustrates the stress-strain response and the enhanced dislocation mechanisms in Ti-Al-O systems [116].

To address the persistent challenge of Fe impurity in recycled Al-Si alloys, Mohammed *et al.* [23] proposed a thermodynamics-guided alloy design framework that quantitatively defines impurity tolerance based on phase stability, nucleation driving force, and interfacial energy. Their findings reveal that the Fe tolerance of Al-Si alloys varies significantly with composition and solidification behavior (Fig. 12a, b). Under moderate Fe contamination, near-eutectic compositions promote the formation of benign Chinese-script α -AlFeSi phases, while under high Fe levels, off-eutectic alloys facilitate the nucleation of γ -phase and refinement of β -phase intermetallic (Fig. 12c, d1 and d2). The study further shows that Mn addition is not universally required; instead, compositional tuning alone—particularly Si

content—can enhance Fe impurity tolerance by stabilizing favorable Fe-rich phases (Fig. 12d3–d6). This work shifts the focus from impurity removal to impurity management, offering a sustainable pathway for designing secondary Al alloys with improved mechanical properties and higher scrap compatibility [23].

Trapping impurity via improved processes or techniques

One effective strategy to improve the impurity tolerance of structural alloys lies in the rational design of microstructural features that can immobilize harmful species. In steels susceptible to hydrogen embrittlement, incorporating stable hydrogen traps provides a dual function of mechanical reinforcement and impurity control. Recent studies have shown that nano-sized carbides such as TiC and VC not only contribute to precipitation strengthening but also act as efficient hydrogen sinks (Fig. 13a, b) [117]. Depending on their size and coherency with the matrix, these carbides offer multiple trapping sites—from interface dislocations to bulk carbon vacancies—with varying activation energies. Notably, even after high-temperature hydrogen charging, steels with these carbides retained their ductility, demonstrating that tailored precipitation can effectively suppress hydrogen-induced damage and enhance impurity tolerance without compromising performance.

Beyond microstructural engineering, advanced manufacturing techniques offer new possibilities for managing impurity effects during alloy processing. Laser additive manufacturing, with its inherently rapid solidification kinetics, enables the suppression of segregation and facilitates the incorporation of typically detrimental elements as interstitial solutes [118]. By carefully controlling the content and distribution of light elements such as carbon, nitrogen, and oxygen, recent work has demonstrated that these impurities can be stabilized as short-range ordered atomic clusters within an austenitic stainless steel matrix (Fig. 13c1–c3). These clusters not only provide substantial interstitial solid solution strengthening but also minimize boundary segregation, leading to a material that combines ultrahigh strength, high ductility, and enhanced corrosion resistance (Fig. 13c4, c5). This highlights the potential of laser

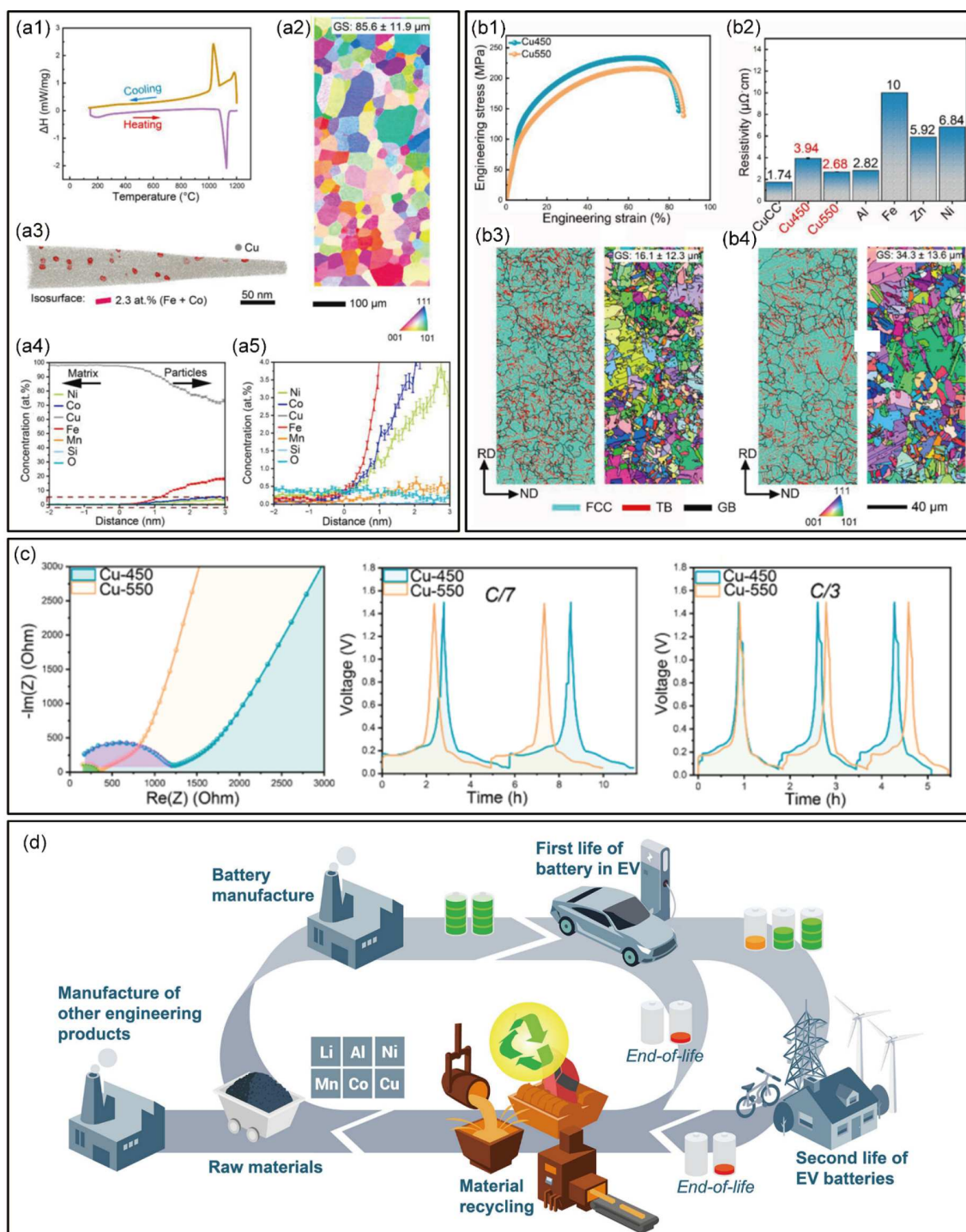


Figure 10 (a1) Differential scanning calorimetry (DSC) heating/cooling curves of the as-cast sample showing melting and solidification; (a2) EBSD inverse pole figure (IPF) map of the as-cast sample; (a3) 3D elemental distribution map in the as-cast recycled Cu; (a4) proximity histogram showing compositional differences between the matrix and nanoparticles; (a5) zoomed-in image of the selected region in (a4). Mechanical behavior and microstructure of Cu450 and Cu550 samples: (b1) tensile stress-strain curves; (b2) electrical resistivity of recycled Cu compared to commercial current collectors; (b3, b4) EBSD phase and IPF maps showing recrystallized grains with respect to the normal direction. (c) Electrochemical impedance spectroscopy (EIS) comparing impedance responses of Cu450 and Cu550 and galvanostatic charge-discharge profiles at different C-rates comparing electrochemical rate performance between Cu450 and Cu550. (d) Schematic of the circular economy of electric vehicle batteries, from material extraction to recycling. Reprinted with permission from Ref. [37]. Copyright 2025, Elsevier.

additive manufacturing as a powerful tool to convert impurity management from a constraint into a design opportunity.

These strategies collectively contribute to advancing the performance and reliability of alloys by addressing impurity-related

challenges at various stages of alloy design and processing. Therefore, when facing the challenges of removing specific elements or cost considerations, extra strategies should be considered.

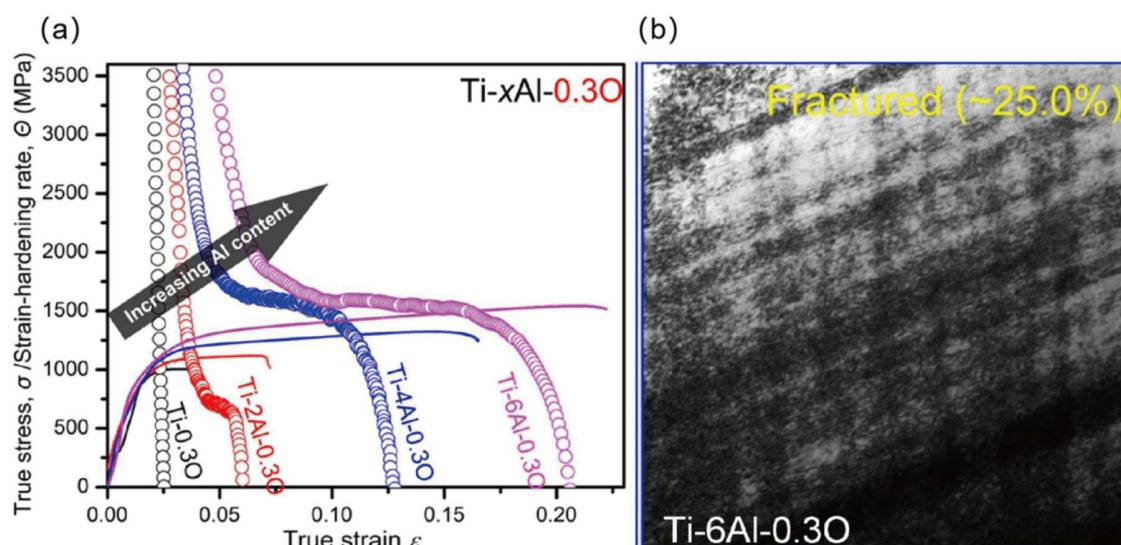


Figure 11 (a) True stress–strain curves (solid lines) and strain-hardening rate curves (symbols) of Ti-*x*Al-0.3 O alloy systems. (b) Representative deformation microstructure of the Ti-6Al-0.3O alloy, where a clear delocalization of deformation occurs, accompanied by frequent dislocation entanglements and possible cross-slip between planar slip bands. Reprinted with permission from Ref. [116]. Copyright 2021, Springer Nature.

CHARACTERIZATIONS OF IMPURITIES

Characterizing impurities is essential for understanding their distribution, concentration, and impact on alloy properties. A range of advanced techniques provides detailed insight into impurity behavior at different scales. This section discusses three primary methods: atom probe tomography (APT), secondary ion mass spectrometry (SIMS), and inductively coupled plasma (ICP) analysis.

3D atom probe tomography

APT enables the characterization of impurities at the atomic level, providing 3D compositional mapping with sub-nanometer resolution. This technique is highly effective for visualizing impurity segregation at grain boundaries (even for light elements) and interfaces. As shown in Fig. 14a–d, molybdenum impurities are detected along grain boundaries, highlighting the precise localization of impurity phases that may influence mechanical or corrosion properties [119].

Secondary ion mass spectrometry

SIMS offers both 2D and 3D imaging of impurity distributions by sputtering the sample surface with a focused ion beam and analyzing the ejected secondary ions. This technique is particularly useful for detecting light elements such as hydrogen. Fig. 14e–g illustrate the application of SIMS to visualize hydrogen trapping in a charged sample. The 2D images reveal hydrogen distributions alongside silicon (Si), chromium (Cr), and iron (Fe), while the 3D image reconstructs the impurity distribution within the sample volume. SIMS measurements are conducted with a raster size of 150 μm and a primary ion beam intensity of 200 nA, ensuring high spatial resolution and sensitivity to impurity concentrations [120].

Inductively coupled plasma analysis

ICP is a powerful tool for bulk elemental analysis, providing precise quantitative data on impurity concentrations. The ICP source generates high-temperature plasma (7000–10,000 K) by ionizing a flowing gas (typically argon). Excited atoms emit

characteristic wavelengths of light during de-excitation, allowing for elemental identification and quantification.

(1) ICP-OES (optical emission spectrometry). This method analyzes the emitted light from excited atoms to determine the elemental composition of the sample. It tests all elements simultaneously, making it efficient for multi-element analysis.

(2) ICP-AES (atomic emission spectrometry). Similar to ICP-OES, but it measures each element individually by analyzing the intensity of specific atomic emission lines. This method is ideal for ppm-range detection.

(3) ICP-MS (mass spectrometry). ICP-MS provides higher sensitivity, capable of detecting impurities at the parts-per-billion (ppb) level, making it suitable for ultra-trace analysis.

Fig. 14h presents a schematic of the ICP setup, demonstrating the ionization process and subsequent spectral analysis. ICP techniques are indispensable for quantifying impurities across a wide concentration range, supporting both research and industrial applications. These complementary techniques—APT, SIMS, and ICP—offer a comprehensive approach to impurity characterization, enabling researchers to identify impurity origins, refine alloy processing techniques, and enhance material performance.

APPLICATIONS

High-purity alloys play a pivotal role in shaping modern technology and industrial advancements, as reflected in the diverse applications shown in Fig. 15. In superconductors, high-purity alloys are essential for achieving near-zero electrical resistance, enabling magnetic levitation and efficient energy transmission. This application is critical for advancements in magnetic resonance imaging (MRI) and next-generation power grids.

For nuclear applications, high-purity alloys are indispensable due to their exceptional resistance to radiation and corrosion, ensuring the structural integrity of reactor components and fuel rods. These alloys contribute to the longevity and safety of nuclear power plants, addressing the demanding environments involving high temperatures and radiation exposure. In the electronics sector, high-purity alloys are vital for the fabrication

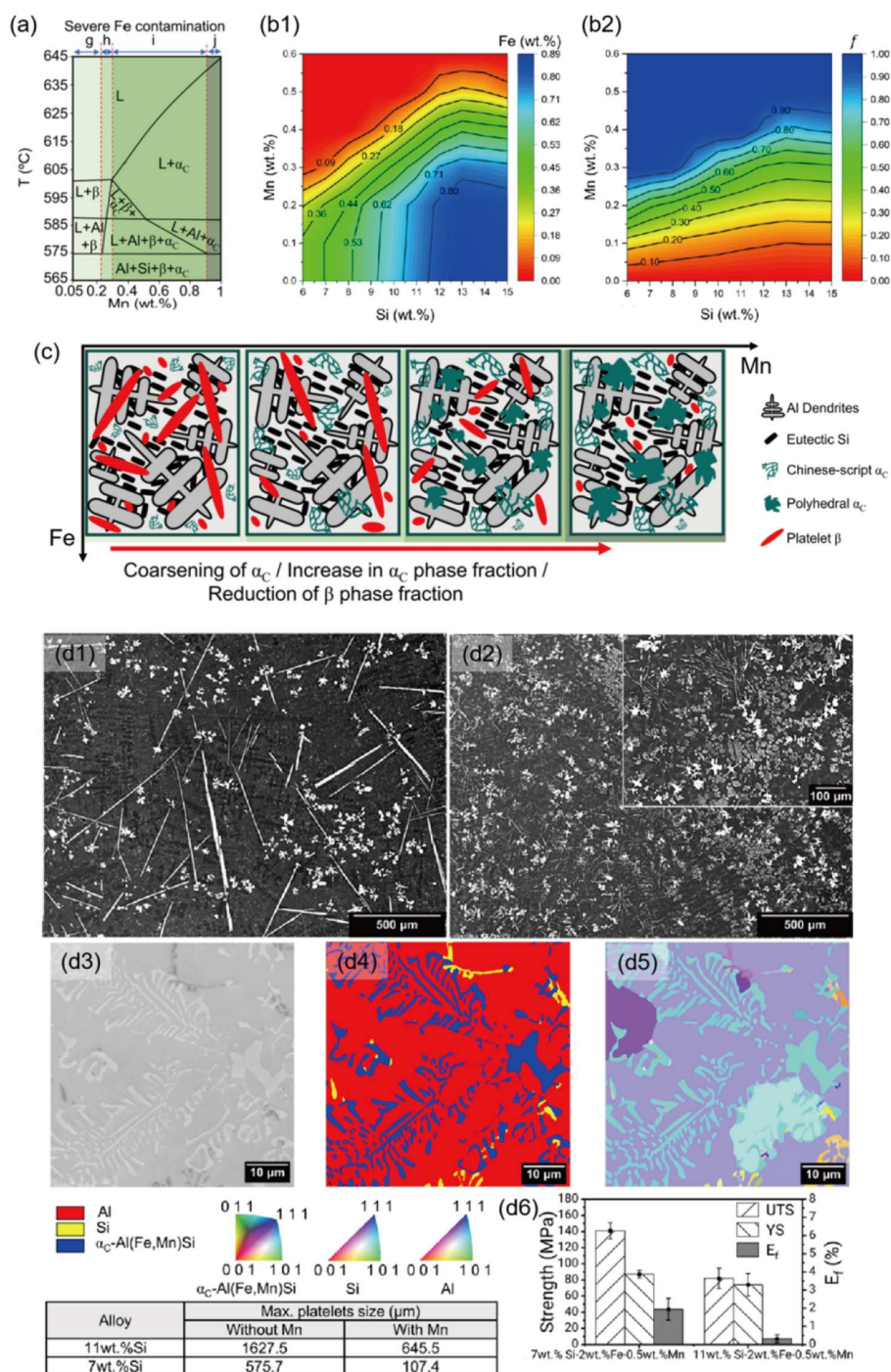


Figure 12 (a) Simplified isopleths of the Al-Si-Fe-Mn system at 11wt%Si-1.4wt%Fe-Xwt%Mn. (b) Thermodynamic modeling results for Fe and Mn tolerances: (b1) critical Fe content at each critical Mn content and Si amount; (b2) corrected fraction of the least harmful Chinese-script phase in Fe-IMC phases. (c) Effect of Fe and Mn contents on phase formation: increasing Fe promotes β - $\text{Al}_{4.5}\text{FeSi}$, while Mn reduces it by enhancing α_C - $\text{Al}_{15}(\text{Fe,Mn})_3\text{Si}_2$ formation; further Mn stabilizes the α_C phase at higher temperatures. (d) Microstructures of alloys after Mn addition: (d1) coarse platelet and polyhedral phases in Al-11wt%Si-2wt%Fe-0.5wt%Mn; (d2) coarse phases and branched Chinese-script phase in Al-7wt%Si-2wt%Fe-0.5wt%Mn; (d3) magnified view of polyhedral and Chinese-script phases; (d4) EBSD phase map; (d5) IPF map of crystallographic orientations of the phases; (d6) UTS, YS, and elongation at fracture (E_f) of the alloys after Mn addition. Reprinted with permission from Ref. [23]. Copyright 2025, Elsevier.

of microchips and circuit boards, where even the smallest impurities can significantly affect performance. Their use ensures better conductivity, precision, and miniaturization, supporting the development of faster and more reliable electronic devices. The aerospace industry relies on high-purity

alloys to produce lightweight, high-strength components capable of withstanding extreme temperatures and mechanical stresses encountered during flight. Similarly, in the marine industry, these alloys are crucial for building corrosion-resistant ship components, ensuring durability and reliability in harsh salt-

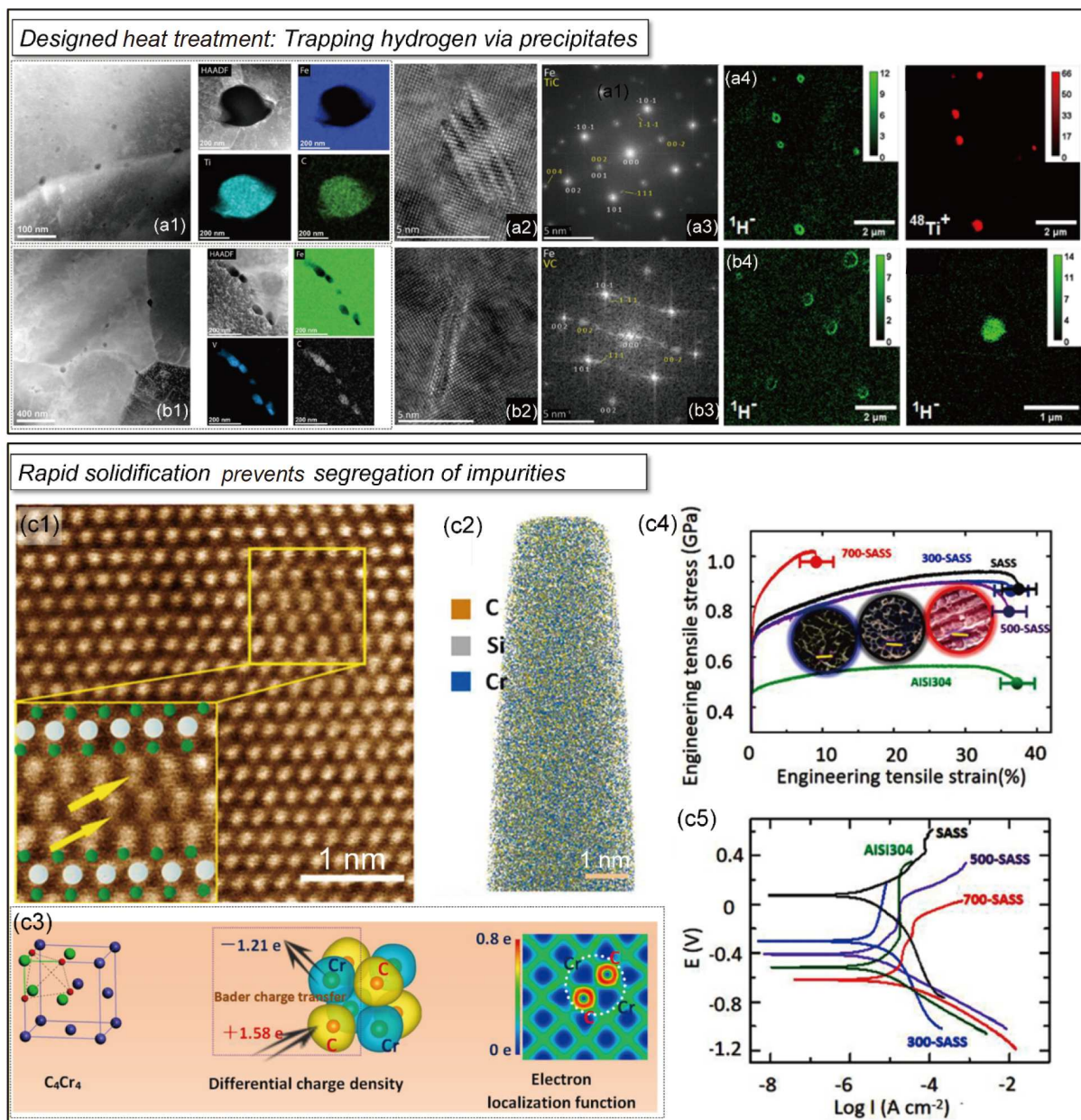


Figure 13 (a1, b1) HAADF and EDS images of TiC and VC in advanced high-strength steels; (a2, b2) high-resolution TEM images; (a3, b3) FFT images of TiC and VC; (a4, b4) SIMS images of hydrogen trapped in TiC- and VC-containing steels, with 1H^- and 48Ti^+ maps. Reprinted with permission from Ref. [117]. Copyright 2024, Springer Nature. Impurity-tolerant austenitic stainless steel prepared by laser additive manufacturing: (c1–c3) conceptual illustration of transforming impurities into interstitial atoms coordinated with Cr in steels; (c4) room-temperature tensile stress-strain curves for AISI304, SASS, and SASS samples annealed at different temperatures; (c5) polarization curves showing high corrosion resistance of manufactured AISI304 steel. Reprinted with permission from Ref. [118]. Copyright 2023, Elsevier.

water environments. Finally, in medical devices, high-purity alloys are essential for implants, surgical tools, and diagnostic equipment. Their biocompatibility and resistance to bodily fluids prevent adverse reactions and enhance the longevity of implants, improving patient outcomes. The versatility and superior properties of high-purity alloys make them foundational across industries that demand precision, reliability, and performance under extreme conditions.

CONCLUSIONS AND OUTLOOK

High-purity metals and alloys play an important role in advancing technology and meeting the high-performance needs

of industries such as aerospace, electronics, nuclear energy, and medical devices. Increasing the purity of metals improves their strength, resistance to corrosion, and ability to perform in harsh environments.

As discussed in this review, controlling impurities is essential for producing high-quality alloys. Even small amounts of unwanted elements can affect the structure and performance of materials. Techniques like vacuum melting, ESR, and electromagnetic levitation have made it possible to achieve very high levels of purity, improving the overall properties of alloys. However, in many cases, complete removal of impurities is not practical. Instead, researchers are developing methods to reduce

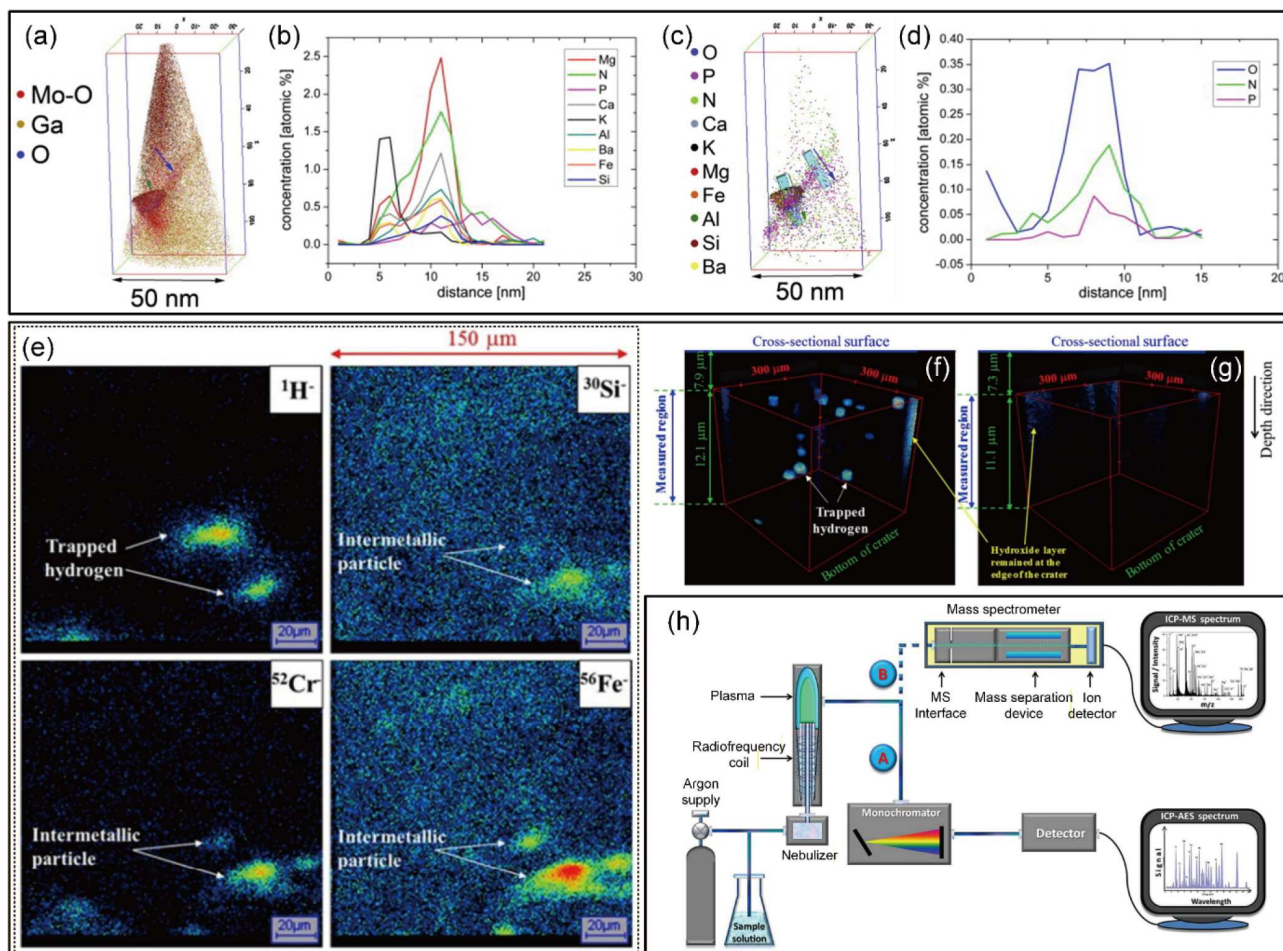


Figure 14 Characterizations of impurities. (a–d) Impurities along the grain boundary in molybdenum characterized by 3D-APT. Reprinted with permission from Ref. [119]. Copyright 2014, Elsevier. (e–g) 2D and 3D SIMS imaging of hydrogen trapped in the H-charged sample. Reprinted with permission from Ref. [120]. Copyright 2024, MDPI. (h) Schematic of ICP (reproduced by <http://www.viaduct-diadrasis.net/methods/6>).

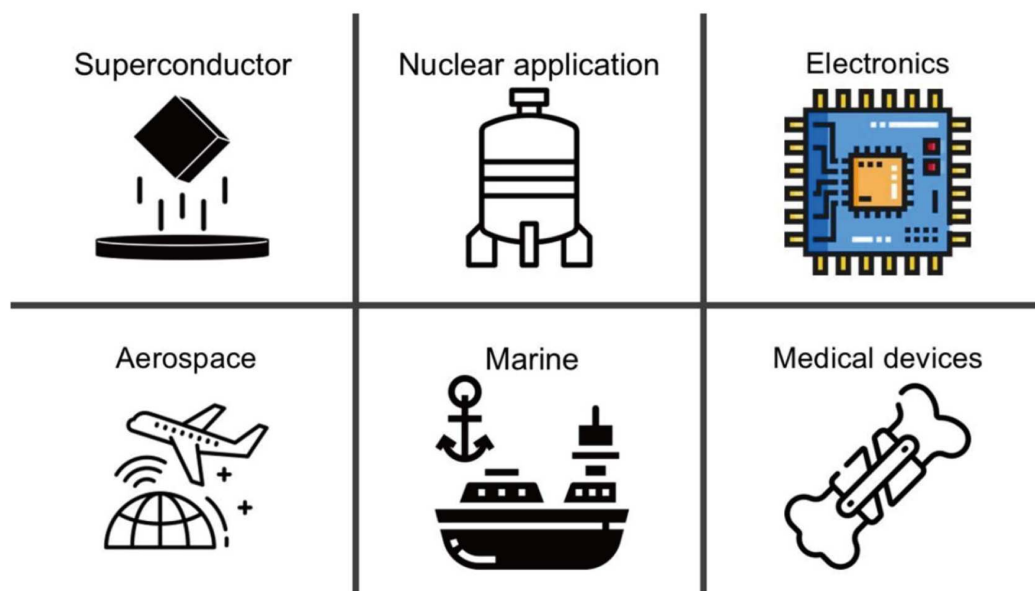


Figure 15 Applications of high purity alloys.

the harmful effects of impurities. These include forming protective coatings, trapping impurities in harmless phases, and using elements that react with impurities to prevent damage. At the same time, advanced tools like APT, SIMS, and ICP analysis help detect and measure impurities at the atomic level. These techniques are important for improving manufacturing processes and ensuring that high-purity alloys meet industry standards.

In the future, the development of high-purity alloys will progress from “impurity removal” to “impurity engineering”. A deeper understanding of impurity behavior under thermo-mechanical and service conditions will play a critical role in alloy guiding alloy design and application.

(1) Extending impurity engineering across the entire metallurgical processing cycle. Future research on high-purity alloys should progress from “melting-stage purification” toward “processing-integrated impurity control”, establishing impurity-engineering strategies throughout the entire metallurgical processing cycle. In addition to melting and solidification, subsequent thermomechanical and heat-treatments significantly influence the morphology, size, and spatial distribution of impurity-containing phases. For example, high-temperature solution treatment can dissolve and redistribute impurity-rich phases; an optimized heat-treatment sequence can incorporate impurities into thermodynamically stable secondary phases; and deformation during mechanical processing (forging, extrusion, rolling, etc.) can mechanically fragment impurity-enriched particles, altering their morphology, size, and interface characteristics—thus converting harmful coarse inclusions into dispersed phases. Future studies should systematically investigate how heat treatments and deformation modes influence impurity evolution and redistribution under coupled thermo-mechanical conditions. These insights will be essential for developing effective impurity-engineering strategies across the full processing route.

(2) Revealing multi-impurity interaction mechanisms. Future research should move beyond the tolerance of single impurities and focus on understanding multi-impurity interactions, identifying their coupled effects and nonlinear influences. In practical alloy systems, multiple residual elements commonly coexist, and their interactions can lead to strongly nonlinear property responses. For instance, an impurity that is only mildly detrimental in isolation may induce significant embrittlement when co-segregating with another impurity, whereas in other cases, specific impurities may partially offset harmful effects. Therefore, it is essential to elucidate multi-impurity interaction mechanisms to establish acceptable impurity limits under service conditions.

(3) Identifying critical impurity-content transition ranges and beneficial utilization thresholds. Future studies should clarify whether different impurities exhibit beneficial-to-detrimental transition regimes, where properties may be enhanced within a certain compositional range but deteriorate beyond it. Impurity effects are not linear or monotonic, but often involve critical phenomena. Key questions include which impurities can be exploited for strengthening or stabilization, what the critical compositional ranges are, and whether alloying or processing can shift these transition regimes to expand the usable range. Developing a comprehensive understanding of these transitions may enable traditionally detrimental impurities to be strategically utilized as controllable mechanisms for performance opti-

mization.

(4) Broadening performance evaluation of high-purity alloys under service conditions. Beyond corrosion and fatigue, future attention should focus on how impurities affect other performance characteristics, such as strength, electrical and thermal conductivity, high-temperature creep, low-temperature toughness, irradiation response, and high-strain-rate behavior. Furthermore, extreme service conditions markedly intensify impurity-induced degradation, yet systematic evaluation of these performance dimensions remains limited and warrants further exploration.

(5) Enabling recycling, green manufacturing, and high-value reuse through purification. High-purity alloys offer significant potential in sustainable manufacturing by improving the quality of recycled metals, extending recycling lifetimes, and reducing resource consumption. High-purity alloys provide solutions on two levels: (i) primary purification slows the accumulation of residual elements across multiple recycling cycles, thereby prolonging alloy recyclability; and (ii) impurity trapping and secondary separation strategies can actively remove impurities from recycled streams. Such a “purification + circular utilization” framework may enable high-value, multi-cycle closed-loop metal systems, particularly in critical lightweight alloys such as aluminum, magnesium, and titanium alloys.

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Conflict of interest The authors declare that they have no conflict of interest.



Bing-Qiang Wei is a professor at the Department of Materials Science and Engineering, Hebei University of Technology. His research mainly focuses on the effects of impurity elements on the mechanical properties of metallic materials.



Jia-Ning Zhu is a researcher at the Department of Materials Science and Engineering, Delft University of Technology. His research primarily focuses on laser additive manufacturing of advanced alloys.



Hui-Yuan Wang is a professor at the School of Materials Science and Engineering, Yanshan University. His research focuses on the development of high-purity alloys and the design of high-performance light alloys.

高洁净金属与合金的制备策略、性能提升机制与前景展望

徐新宇^{1,2}, 刘翕嘉¹, 魏兵强^{1*}, 邓敏¹, 朱家宁^{3*}, 王慧远^{1,4*}

摘要 面向高端装备与极端服役环境对高可靠性材料的迫切需求, 高洁净金属与合金已成为新一代关键技术中不可或缺的基础材料。大量研究表明, 即使是ppm级含量的杂质, 仍会显著影响金属材料的强度、耐腐蚀性和疲劳等关键性能。因此, 发展高洁净金属与合金对提升材料可靠性与服役稳定性具有重要意义。本文系统概述了近年来高洁净金属与合金的主要研究进展, 梳理了高洁净金属与合金的制备工艺策略, 讨论了铝、镁、钛等典型合金体系的杂质敏感性及其去除方法, 探讨了先进微观表征技术在微量杂质检测、定量分析及机制揭示中的关键作用, 阐明了微量杂质对组织演化和性能的影响规律及作用机制。本文分析了高洁净金属在先进结构材料领域的关键作用, 提出了未来研究亟需从全流程杂质调控、多元杂质交互作用、杂质含量的双面效应、服役性能影响因素, 以及金属材料在循环利用与绿色制造中的净化策略等方面持续突破, 以推动高洁净金属体系的设计方法与工程应用迈向更加可控、高效与可持续的发展阶段。