

A review on approaches to evaluate quality of molten aluminum alloys

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Abstract: The performance and integrity of final Al castings are intrinsically governed by the quality of the molten metal, with hydrogen content and inclusions being the two most critical yet challenging parameters to control. To evaluate these parameters, the industry employs a range of techniques broadly categorized into ex-situ and in-situ methods. This paper provides a systematic review of these approaches. For the ex-situ analysis of Al melt cleanliness, established methods including reduced pressure test (RPT), K-mold test, metallographic analysis, porous disc filtration analysis (PoDFA), liquid metal analyser for inclusions and solids (LAIS), and the Prefil pressure filtration method are thoroughly described. A comparative evaluation of their underlying principles, measurement accuracy, and suitability for laboratory-based quantification is also presented. For real-time monitoring, in-situ techniques such as solidification curve analysis, ultrasonic attenuation sensors for hydrogen, and the liquid metal cleanliness analyzer (LiMCA) for inclusions are examined, focusing on their application in process control. This review conducts a critical comparative analysis of these two paradigms, highlighting the inherent trade-off between the high precision of ex-situ methods and the real-time feedback provided by in-situ monitoring systems. By mapping the capabilities, limitations, and complementary roles of each technique, this work serves as a practical guide for method selection in both quality assurance and process optimization contexts.

Keywords: molten Al alloys; inclusion detection; ex-situ detection; in-situ monitoring

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1 Introduction

With the growing emphasis on energy conservation and emissions reduction, aluminum (Al) alloys have been widely adopted in automotive, aerospace, and rail transportation industries owing to their lightweight nature, high strength, and high corrosion resistance^[1,2]. Particularly, the lightweight properties of Al alloys can effectively reduce energy consumption while enhancing equipment performance, which makes them a research focus in both academic and industrial fields^[3,4].

Based on processing methods, Al alloys are categorized

into wrought and cast alloys^[5]. Wrought Al alloys are produced through plastic deformation processes like rolling, extrusion, and forging, producing plates, profiles, and rods^[6-9]. Typical wrought Al alloy systems include Al-Cu, Al-Mg^[10], Al-Mg-Si, and Al-Zn-Mg-Cu, which combine high strength and high toughness with excellent formability and surface quality. These properties make them ideal for aerospace, transportation, and construction applications^[11]. Cast Al alloys are directly shaped via casting processes, with common systems being Al-Si, Al-Cu, and Al-Mg. These alloys exhibit high strength, hardness, corrosion resistance, and excellent castability, making them suitable for complex components such as engine blocks and automotive wheels^[12-14]. However, both wrought and cast Al alloys face production challenges such as melt cleanliness control, microstructure regulation, and process optimization. Among these challenges, melt cleanliness control is especially crucial because even minute impurities can significantly compromise

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material performance. Therefore, precise monitoring of the molten metal quality during processing becomes a key step in guaranteeing product reliability.

The melting process is crucial in Al alloy casting. Small changes in alloy composition or process parameters can greatly impact the casting's mechanical uniformity and surface quality, which directly affects casting yield^[15]. However, molten Al alloys easily absorb hydrogen and trap inclusions (non-metallic oxides, carbides, borides, etc.) during melting and pouring. Treatments such as grain refinement, flux refining, dross removal, and degassing can cut down gaseous and particulate impurities, but some trace defects still remain in the final cast ingots^[16, 17].

As shown in Fig. 1^[24], the gas pores observed on the fracture surface are mainly caused by air entrapped during the melting process. The oxide inclusions, such as Al_2O_3 , MgO , and MgAl_2O_4 , marked by red circles are the products caused by the reaction between the entrapped air and molten Al, and such

inclusions will significantly reduce the density and mechanical properties of Al alloy castings^[18-20]. The detrimental effect of inclusions on an alloy's structural integrity depends on their type, size, and concentration. Excessive inclusions lead to stress concentration, acting as crack initiation sites which greatly degrade the alloy's tensile strength, ductility, and fracture toughness^[21-23]. Furthermore, these inclusions adversely affect fatigue strength, corrosion resistance, and surface quality, ultimately increasing rejection rates, reducing manufacturing efficiency, and thereby rising production costs^[15]. Current quality control methods face two key challenges: the difficulty in detecting submicron or ultra-trace inclusions and dissolved gases, and the complexity in maintaining consistent melt quality across multi-step processes (melting, refining, pouring), where fluctuations in any single stage can propagate through the process chain, ultimately degrading casting integrity.

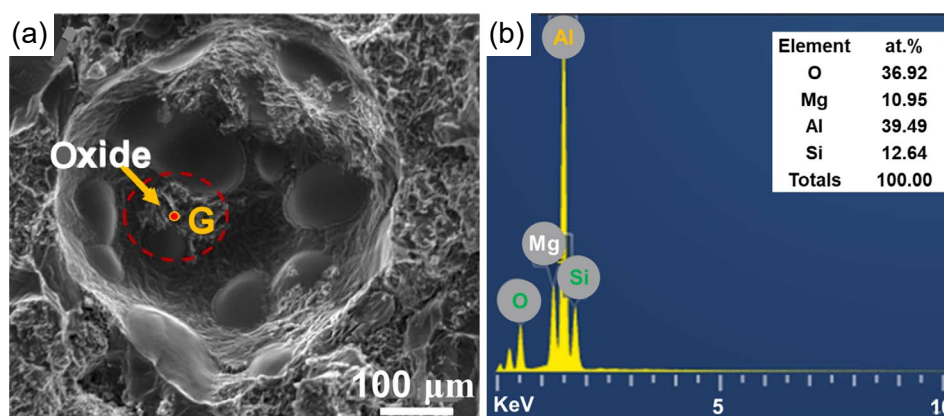


Fig. 1: Analysis of gas pores on fracture surface of A356 Al alloy tensile specimens^[24]: (a) morphology of gas pores; (b) EDS analysis at Point G

Therefore, ensuring molten Al alloy quality necessitates strict control of trace element concentrations and effective detection of entrained gases and inclusions^[25]. In practice, foundries employ various melt quality monitoring techniques to optimize pouring parameters, enhance casting yield, and reduce production costs^[26].

Given the variety of techniques developed to assess molten Al quality, a systematic review comparing their underlying principles and practical applicability is still lacking. This article aims to fill this gap by providing a comprehensive analysis of current quality evaluation methods. The review is structured around a fundamental distinction between ex-situ and in-situ techniques, systematically examining the working principles, advantages, and limitations of each approach to guide optimal method selection in both industrial practice and research settings.

2 Ex-situ detection methods

2.1 Metallographic analysis

Metallographic analysis, a fundamental method for evaluating the quality of molten Al alloy, involves specimen preparation and microscopic examination of grain size, inclusions, and

porosity. While it provides clear insights, it has several drawbacks: the preparation process is time-consuming, the sampled area is limited, and the identification of inclusions relies on manual operator judgment^[27, 28]. These constraints hinder rapid on-site furnace testing, rendering conventional metallography insufficient for industrial efficiency requirements.

To address this technical challenge, researchers at Northeastern University developed an automated system for metallographic image analysis^[28]. This system employs a sophisticated process involving grayscale conversion, illumination correction, edge detection, and morphological operations to precisely segment inclusions, thereby enhancing the efficiency and accuracy of analysis (Fig. 2^[28]). Subsequently, Shan et al.^[29] conducted systematic tests on multiple metallographic images of Al alloy inclusions using an in-house developed automatic recognition program. Their results demonstrated that the program achieved an automatic recognition accuracy exceeding 80% for inclusion types, with notably perfect recognition (100%) for refractory materials and MgAl_2O_4 . The system automatically recognizes and classifies inclusions in molten Al alloys by analyzing their grayscale values, morphology, size, and EPMA-verified attributes. This capability enables rapid assessment of alloy quality^[30].

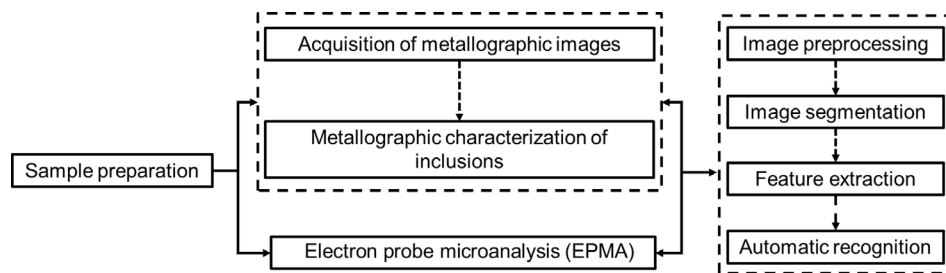


Fig. 2: Flowchart of automated metallographic analysis method for Al alloy inclusions^[28]

2.2 Filtration methods

2.2.1 Porous disk filtration apparatus

Conventional metallographic analysis faces inherent limitations in assessing melt cleanliness due to the extremely low density of inclusions observable on polished surfaces. To overcome this constraint, Atkinson et al.^[31] pioneered a methodology for enriching the concentration of non-metallic inclusions (NMIs), which physically or chemically aggregates dispersed inclusions into localized regions to improve detection sensitivity and statistical reliability. This approach substantially improves upon conventional methods by expanding the effective sampling volume and increasing measurement reliability through the accumulation of statistically representative data. Notably,

the porous disk filtration apparatus (PoDFA) technique has successfully applied this principle to control inclusions in molten Al. Its schematic diagram is shown in Fig. 3^[28], and it represents a significant advancement in melt cleanliness assessment technology^[32].

As an established technique for assessing Al alloy melt quality, the PoDFA method employs a combined filtration and microscopy approach to systematically characterize the distribution of NMIs. Its core technology involves forcing molten alloy through a precision microporous filter under controlled pressure, which results in the formation of an inclusion-enriched filter cake (Fig. 4^[33]).

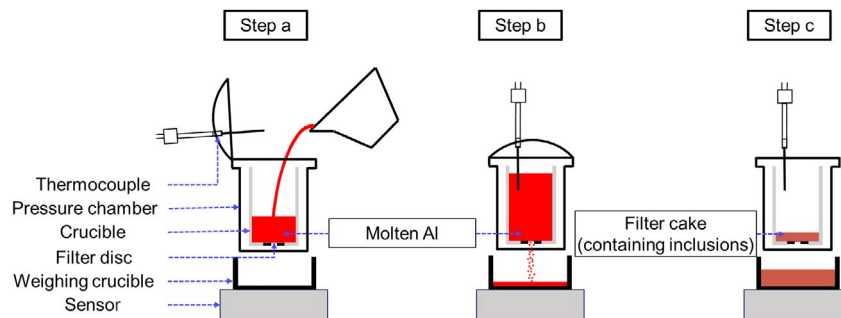


Fig. 3: Schematic diagram of the PoDFA principle^[28]

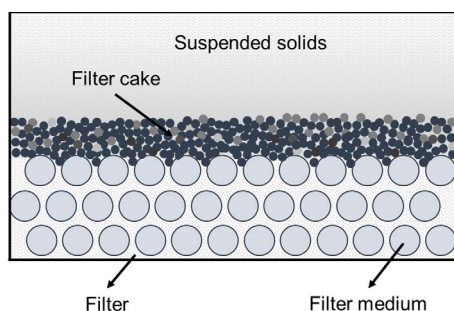


Fig. 4: Microscopic mechanism of filter cake formation^[33]

Subsequent analysis using metallographic microscopy and scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS) provides comprehensive morphological and compositional characterization of the captured inclusions (Fig. 5)^[32, 34]. By quantifying key parameters such as inclusion type, size distribution, and number density, PoDFA enables reliable quantitative evaluation of melt cleanliness^[25]. In a study of A356.2 alloy melts using PoDFA analysis, Liu et al.^[35] detected inclusions ranging in size from 10 to 100 μm . The identified inclusion types mainly include TiB_2 ,

Al_4C_3 , $\alpha\text{-Al}_2\text{O}_3$, MgO , oxide films, as well as complex oxides such as spinel-type compounds and MgAl_2O_4 . This constituent profile is consistent with the known impurity sources in this alloy system.

However, current research indicates that this technique still exhibits significant limitations in practical applications. Through an integrated approach combining numerical simulation and experimental validation, Li et al.^[32] systematically demonstrated the inadequacy of PoDFA technology in quantitatively characterizing the mass fraction of inclusions. Specifically, when analyzing NMIs in molten Al alloy using PoDFA, only values with units of $\text{mm}^2 \cdot \text{kg}^{-1}$ can be obtained, which precludes the direct and accurate determination of the actual inclusion mass fraction in the melt. During statistical analysis, the actual mass fraction of inclusions must therefore be estimated empirically from the PoDFA values. Due to the randomness of inclusion deposition and statistical deviations during filtration, the directly measured PoDFA values cannot precisely correspond to the actual inclusion concentrations in the bulk molten alloy^[36]. Consequently, this empirical conversion approach

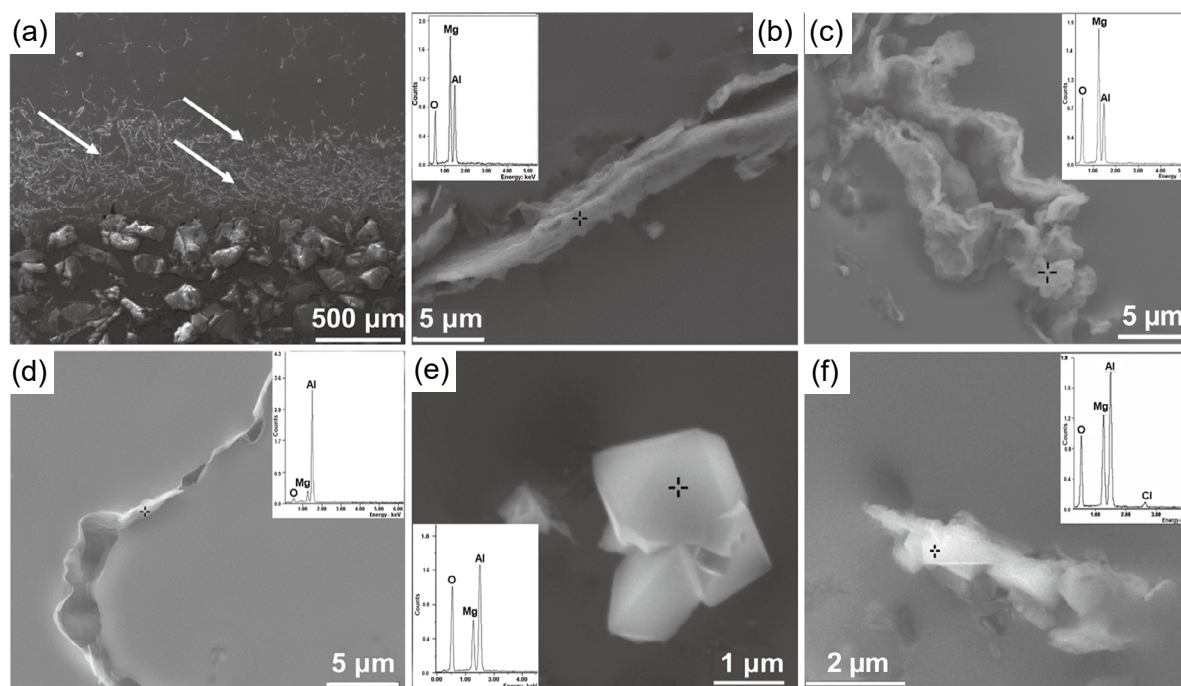


Fig. 5: SEM micrographs showing^[32]: (a) overview of collected inclusions, white arrows mark thick oxide films; (b) stringer like oxide film; (c) nodule-like oxide film; (d) curled oxide film; (e) cuboid oxide particle; (f) cuboid oxide nucleates upon oxide film

may introduce systematic errors, compromising the accuracy and universality of the results. Furthermore, the process of pouring metal into a PoDFA crucible may introduce exogenous oxide inclusions.

Nevertheless, PoDFA remains a key technique for analyzing inclusion characteristics in Al alloy metallurgy. It can precisely characterize micron-sized inclusions in aluminum alloy melts through the combination of filtration enrichment and microscopic quantification^[37]. Thus, PoDFA analysis continues to play a crucial role in laboratories and high-end manufacturing for identifying inclusion types and properties.

2.2.2 Liquid Al alloy inclusion sampler

Building on the PoDFA technique, Union Carbide Corporation leveraged its expertise in materials science and high-temperature processing to develop the liquid Al inclusion sampler (LAIS) as an improved version. A significant advantage of LAIS over PoDFA is that its probe assembly can be directly immersed into the liquid metal within the launder. This design avoids the introduction of oxides that occurs with PoDFA when metal is poured into a crucible^[20].

The working principle of LAIS is illustrated in Fig. 6^[20]. After assembly and verification of proper sealing, the sampling device is immersed into the molten Al alloy bath. Upon activation of the vacuum pump, a negative pressure environment is created within the sampler, drawing the molten alloy through a porous graphite crossover into the sampling cup. During this process, NMIs are effectively captured by the filter, while the purified alloy flows into the cup^[26]. Following sample collection, the vacuum pump is deactivated and the device is retrieved. After the alloy in the sampling cup solidifies, comprehensive analysis of inclusion typology, size distribution, and spatial

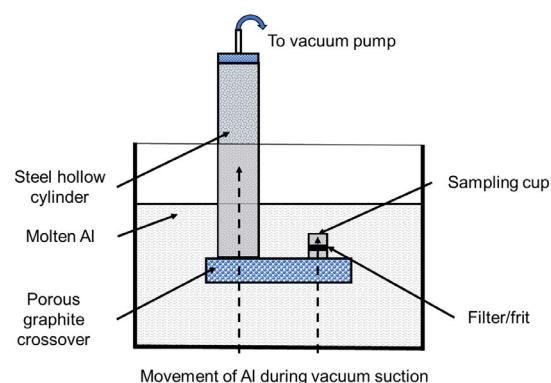


Fig. 6: Schematic diagram of LAIS system^[20]

characteristics can be conducted. This methodology is precise and provides reliable technical support for stringent quality control.

However, the LAIS operation is complex and time-consuming. Specifically, it requires waiting for the metal to solidify and cool within the sampling cup, followed by disassembly of all components to remove the filtered Al sample. A new sampling unit must then be prepared by installing a fresh carbon liner and reassembling the parts while ensuring an airtight seal. Even under optimal conditions, only one test can be completed per hour. Additionally, the consumables used in LAIS are relatively expensive. In contrast, the PoDFA technique is simpler, faster, and more user-friendly. For these reasons, LAIS is now rarely used.

2.2.3 Pressure filtration method–Prefil

Building upon the LAIS principle of assessing melt quality by enriching inclusions, the UK company N-TEC conducted systematic research on pressure filtration. This work aimed

to establish correlation models between inclusion content and filtration rate while expanding the cleanliness database for Al alloy melts. The results demonstrated significant correlations between filtration velocity and both the physical parameters of the molten alloy (temperature, density) and the characteristic parameters of inclusions in the filter cake (type, size, morphology) during the multi-porous filtration process^[38]. These findings enabled the successful development of the Prefil method. This quantitative molten metal cleanliness evaluation technology offers enhanced metrological performance and represents a significant advancement in inclusion analysis.

Compared to the PoDFA and LAIS techniques, Prefil is a method that rapidly evaluates inclusion content through dynamic pressure difference analysis. It provides direct analytical results and can also provide prepared samples for subsequent metallographic examination^[39]. As shown in Fig. 7, the Prefil method shares some initial operational similarities with PoDFA. During testing, the Al alloy melt is forced through a precision microporous ceramic filter under dynamic pressure, which forms a filter cake on the surface. The filtered melt then enters a high-accuracy electronic weighing assembly positioned below the crucible.

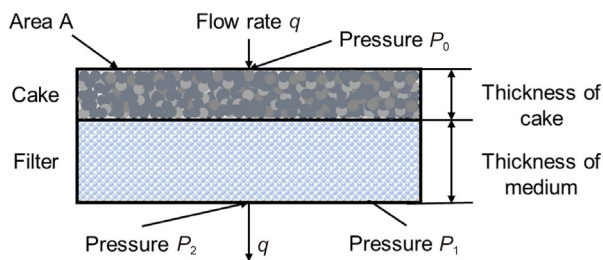


Fig. 7: Schematic illustration of filter cake and filtration medium microstructure^[40, 41]

The system automatically generates characteristic cumulative filtration volume versus time curves by monitoring real-time filtration data, while establishing a quantitative model that correlates the curvature variation rate of filtration curves with inclusion content^[40, 42]. Steeper curve slopes indicate higher melt cleanliness levels and correspondingly faster flow rates through the microporous filter medium (Fig. 8)^[39, 41, 43]. This innovative model achieves the simultaneous multiparameter determination of inclusion equivalent size distribution, aspect ratio, and volumetric concentration. It also enables quantitative assessment through rapid calculation of the cleanliness index (CI), demonstrating excellent measurement repeatability and minimal systematic error. Luo et al.^[44] systematically explored the evolution of various typical inclusions in 3104 Al alloy melts under different heating and holding treatment durations using the Prefil method. The results show that for durations of 30, 60, and 120 min, the size of most detected inclusions ranged from 40 to 300 μm . The cleanliness index calculated by this method shows high consistency with the expected quality standards of this alloy grade, demonstrating the value of the Prefil method in accurately controlling melt quality and ensuring alloy performance.

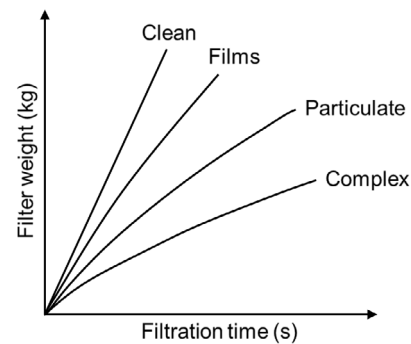


Fig. 8: Schematic diagram of Prefil curves corresponding to filtration behavior of molten Al alloys containing different types of inclusions^[39]

Currently, the Prefil method employs two standardized ceramic filter configurations: a standard permeability type (90 μm pore size) and a high-permeability type (130 μm pore size). Their fundamental difference lies in the balance between permeability and filtration precision^[39, 45]. The standard configuration uses smaller pores for high-precision filtration to meet conventional cleanliness requirements. The high-permeability version enlarges larger pores to reduce flow resistance, making it suitable for high-flow, high-throughput conditions. This graded design provides operational flexibility for different process requirements. In practice, the selection should be based on specific melt characteristics, flow rate demands, and target cleanliness standards.

2.3 Reduced pressure test

Hydrogen (H) is one of the gaseous elements that forms solid solutions in molten Al alloys. Consequently, measuring its concentration is closely related to assessing the overall gas content in the melt^[46]. Current research indicates that over twenty distinct analytical techniques have been developed for determining hydrogen content in both molten and solid Al alloys, with significant advancements particularly in methods for solid products^[47]. Among these, the reduced pressure test (RPT) has become an industry standard due to its ability to directly visualize pore morphology and establish precise correlations between hydrogen content and porosity^[48].

The RPT, also known as the vacuum solidification test (VST), vacuum density test (VDT), or straub-pfeiffer test^[49], is a classical method for characterizing hydrogen content and porosity defects in molten Al alloys. It is widely used for metallurgical quality assessment^[34]. As illustrated in Fig. 9, the test procedure is as follows: A measured quantity of molten Al alloy is introduced into a preheated graphite crucible within the apparatus. A shut-off valve is then closed, and a vacuum pump is activated to establish a negative pressure inside the sealed chamber formed by the glass cover and base plate. Vacuum pumping continues until a predetermined pressure threshold is reached, after which the molten alloy is allowed to solidify under this reduced pressure. During solidification, the decreased solubility of hydrogen causes a portion of the dissolved gas to escape as surface bubbles, while the remainder forms subsurface pinhole defects due

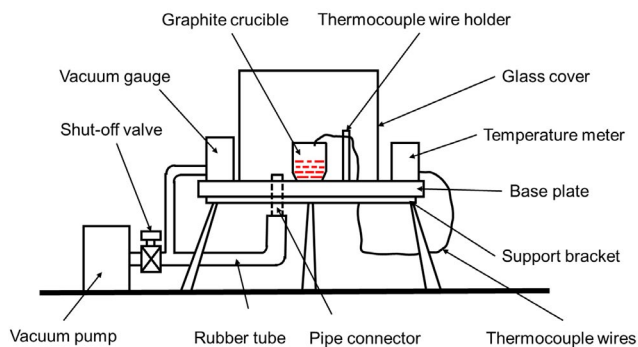


Fig. 9: Schematic diagram of reduced-pressure solidification principle^[48]

to solute redistribution at solidification fronts. This process also generates characteristic surface bulges from constrained melt shrinkage. After solidification, the resultant ingot is longitudinally sectioned. The exposed surface is then examined against reference standards through metallographic analysis for semi-quantitative porosity evaluation. Concurrently, density measurement via water displacement or density index calculation is performed. These data are used to establish mathematical models correlating hydrogen content with physical parameters, enabling a multifaceted assessment of the melt's hydrogen content^[48, 50].

RPT has become a widely adopted technique for assessing hydrogen content in Al alloy melts due to its simple apparatus and standardized procedure. However, this method has limited sensitivity for ingots with low hydrogen concentrations. More

importantly, systematic studies by Dispinar et al.^[49, 51, 52] have demonstrated that inclusions in molten alloy significantly influence pore distribution in solidified samples, thereby disrupting the linear correlation between pore characteristics and actual hydrogen content. Further research by Jang et al.^[53] revealed two key factors affecting measurement: minimizing atmospheric exposure during melting reduced the density index (DI) by 5.6%, and employing a ladle-scooping sampling method (Al_s) instead of conventional pouring (Al_p) further decreased the DI by 1.9%. The porosity exhibited a trend similar to the DI variation between the two samples (Fig. 10^[53]). Subsequent SEM-EDS analysis (Fig. 11^[53]) confirmed that inclusions in the melt are the primary factor affecting DI values. Such interference substantially degrades the measurement accuracy of RPT, limiting its reliability in certain applications.

Recent breakthroughs in digital image processing have spurred the development of intelligent hydrogen evaluation methods based on solidification defect morphology. Current approaches typically involve acquiring high-resolution optical microscopes of longitudinal sections from Al alloy ingots for statistical analysis. Campbell et al.^[54] pioneered this field by incorporating the bifilm index into hydrogen assessment systems through image analysis of porosity. Subsequently, El-Sayed's research team^[55] used quantitative indicators, such as the quantity and size of bifilm-induced pores in cross-sections, to qualitatively evaluate hydrogen content. More recently, Zhang et al.^[56] applied the RPT method to evaluate melt quality for ductility prediction in a 46000-series alloy, specifically

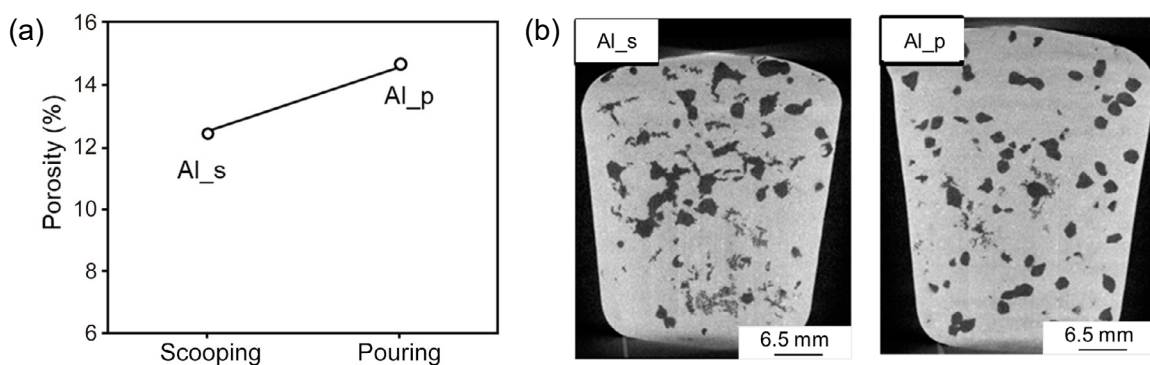


Fig. 10: Analysis of Al-Si alloy samples collected by two sampling methods under RPT: (a) porosity comparison; (b) 2D cross-sectional X-ray CT images^[53]

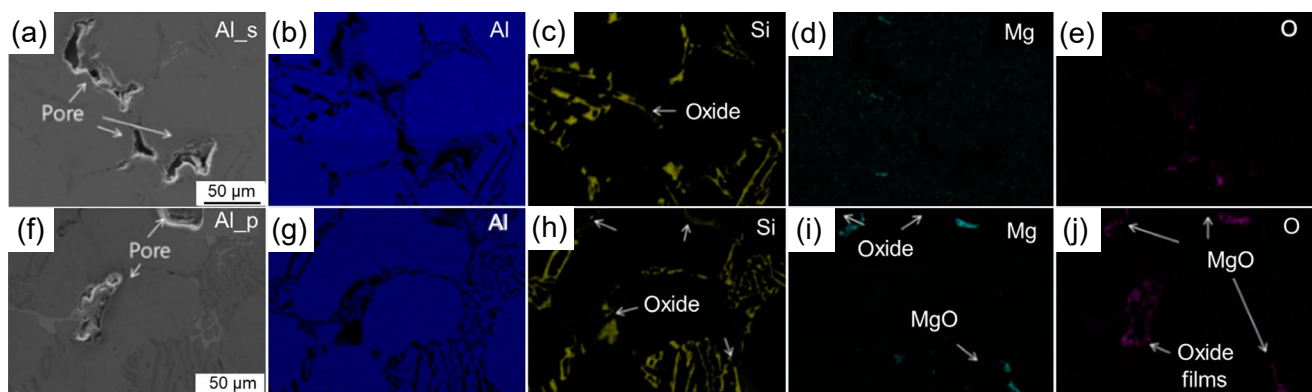


Fig. 11: Microstructure of pores and oxide films in Al-Si alloy samples from RPT collected by two sampling methods: (a, f) SEM images; (b-e, g-j) EDS results^[53]

investigating the influence of pore morphology and distribution. Their study identified various pore types, with linear pores ranging in size from 2 to 6 mm. Pore distribution varied between melts from different heats, and distinct correlation patterns were observed between the sizes and areas of pores with different morphologies. This work underscores the value of RPT in supporting accurate melt quality assessment and reliable ductility prediction. Collectively, these studies have helped overcome a key limitation of reduced-pressure solidification tests, namely, their susceptibility to interference from heterogeneous phases in complex alloy melts. This progress provides a technical basis for optimizing melt purification processes and refining detection models.

2.4 K-mold method

The K-mold method, also known as the fracture surface observation test, is a technique for assessing Al alloy melt cleanliness by examining the morphology and quantity of inclusions on as-cast fracture surfaces. Originally developed by Yuan et al.^[57], the procedure involves extracting a representative melt sample and pouring it into a waffle mold (Fig. 12^[58]) to produce standardized specimens (K-molds, Fig. 13^[58])

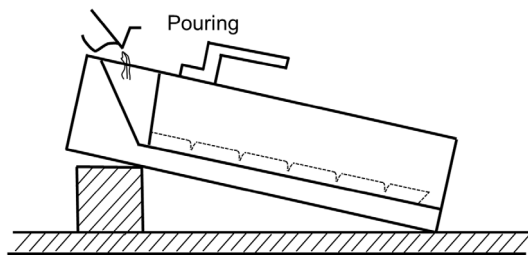


Fig. 12: Waffle ingot mold^[58]

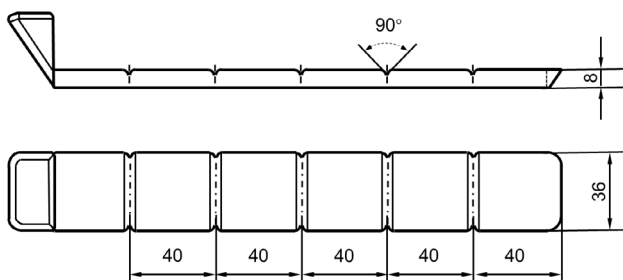


Fig. 13: Waffle-patterned Al alloy ingot (Unit: mm)^[58]

measuring 40 mm×36 mm×8 mm^[58]. After solidification, specimens are manually fractured along predefined lines, and the inclusion distribution on the fracture surfaces is examined using stereomicroscopy.

The inclusion content, expressed as the K -value, is then calculated according to the size-grade correlation specified in Table 1, using Eqs. (1) and (2)^[30, 59, 60].

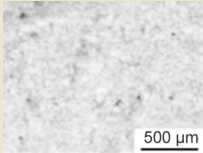
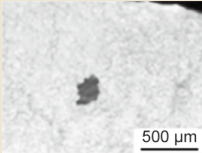
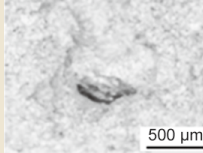
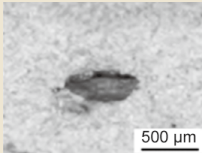
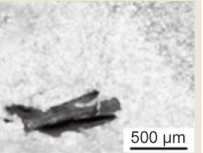
$$M = \sum_{i=1}^5 \text{Count}(i) \cdot Y_i \quad (1)$$

$$K = M \cdot N^{-1} \quad (2)$$

where K is the inclusion content ratio, M is the total inclusion content, N is the number of fracture surfaces examined, $\text{Count}(i)$ is the number of inclusions belonging to size grade i , and Y_i is weighting factor for size grade i . According to industry standards, the K -value is inversely correlated with melt cleanliness; lower values indicate higher purity, enabling a semi-quantitative quality evaluation.

The conventional K-mold method offers a cost-effective and operationally simple solution for assessing Al alloy melt cleanliness. However, it has significant limitations in detection accuracy and data processing capacity. Specifically, manual fracturing introduces variability, microscopic observation relies on subjective empirical judgment, and the traditional K -value calculation fails to fully quantify the morphological and size distribution characteristics of inclusions. To overcome these limitations, Liu et al.^[61] developed an intelligent detection system based on deep learning. Their system employs a cascaded dual-network model that integrates a convolutional neural network (CNN) with an error back-propagation (BP) network. The CNN intelligently identifies inclusion-containing regions on fracture surfaces, and the BP network then performs the quantitative calculation of inclusion content. This approach achieves a substantial improvement in detection accuracy, representing a paradigm shift from experience-dependent to data-driven quality evaluation. It significantly enhances detection efficiency while reducing human error, thereby meeting stringent industrial precision requirements. Future developments through algorithm iteration and multimodal data fusion are expected to address remaining challenges, providing more efficient and reliable quantitative tools for precision casting process control.

Table 1: Correlation between fracture inclusion size grades^[60]

Slag inclusion size (μm)	(50, 100]	(100, 500]	(500, 800]	(800, 1200]	(1200, ∞)
Grade	I	II	III	IV	V
Legend					
Weighting factor	0.1	0.5	1.0	1.5	2

3 In-situ detection methods

3.1 Solidification curve analysis method

Traditional analytical techniques, including the K-mold method, filtration analysis, and metallographic examination, have provided fundamental references for evaluating the composition and quality of Al alloy melts. However, they exhibit inherent limitations in characterizing the dynamic solidification processes of molten Al alloys. Solidification curve analysis, a subset of thermal analysis techniques, is a well-validated method that can monitor the metallurgical properties of Al alloy melts in real time during processing eliminating the need for conventional metallographic examination^[62]. Chen et al.^[63] established that the characteristic profiles of thermal analysis cooling curves directly correlate with the solidification kinetics of Al-Si alloy melts. In this approach, parameters derived from the solidification zone are used as quantitative indicators to assess melt quality. This enables a comprehensive evaluation through systematic comparison of the morphological features of cooling curves.

Based on the principles of the solidification curve method, this technique provides critical parameters regarding solidification dynamics, including latent heat release and solid fraction evolution, by recording and analyzing the temperature-time curve during the solidification of Al alloy melts^[64, 65]. In foundry applications, monitoring and adjusting solidification parameters significantly influence casting quality. Currently, computer-aided cooling curve thermal analysis (CA-CCTA) has been extensively employed to evaluate alloy composition^[66], crystallization latent heat^[67], and other relevant parameters, while also enabling comprehensive monitoring

and analysis of solidification behavior in multi-component alloy systems^[68-70].

The solidification curve analysis method primarily accomplishes these functions by using thermocouples to record and analyze the cooling curves of solidifying aluminum alloy melts. As depicted in Fig. 14, the thermocouple is positioned centrally within the sampling cup, 25 mm above its base. The test procedure involves pouring molten Al alloy into the thermocouple-equipped sampling cup, performing cooling curve thermal analysis (CCTA), and acquiring data via a computer-interfaced analog-to-digital (A/D) converter^[71]. The operational details are illustrated in Fig. 15^[72]. This methodology not only provides real-time monitoring of the solidification process but also supplies critical data for process optimization. As a result, it has become an essential tool for evaluating and ensuring aluminum alloy melt quality.

3.2 Liquid metal cleanliness analyzer

Compared with thermal analysis, the liquid metal cleanliness analyzer (LiMCA) provides superior precision in assessing the quality of Al alloy melts. The electrical sensing zone method was first developed by Coulter in 1950 to address challenges in erythrocyte (red blood cell) measurement, leading to the invention of the Coulter counter^[73, 74]. By 1985, researchers at McGill University adapted this electrical sensing zone principle to metallurgical applications, enabling direct quantification of inclusion count and size distribution in molten metals^[74, 75]. This work eventually led to the successful development of the LiMCA system^[76]. ABB Corporation later commercialized LiMCA technology for evaluating metallurgical cleanliness. Through continuous technical

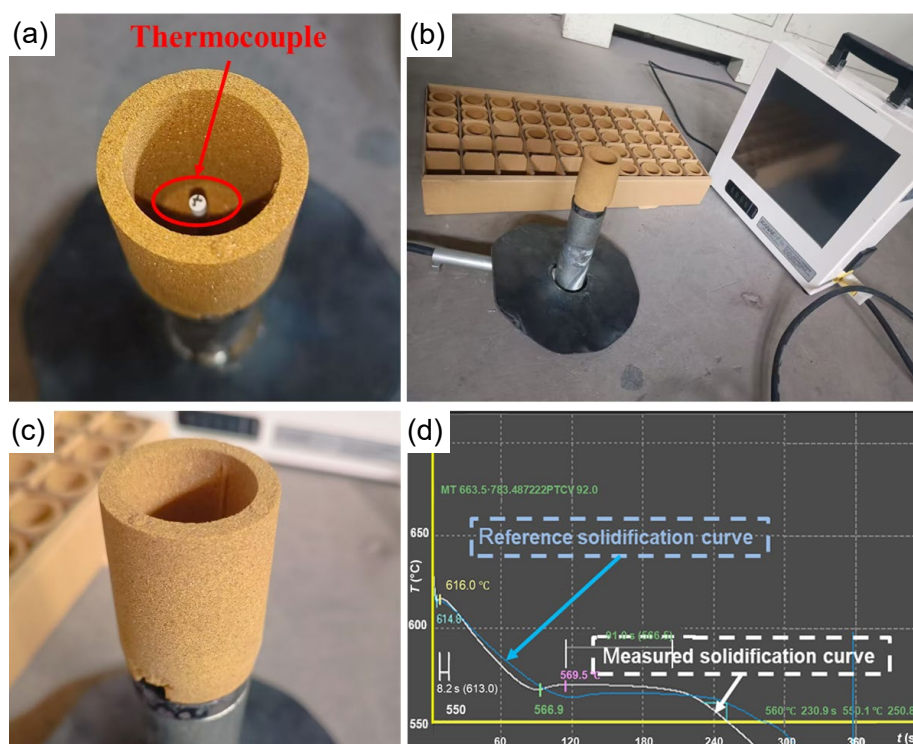


Fig. 14: Thermal analysis equipment: (a) thermocouple in sampling cup; (b) front view of sampling cup; (c) solidification curve testing device; (d) solidification curve display^[71]

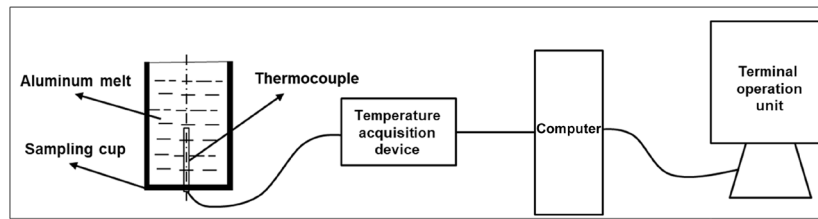


Fig. 15: Simplified thermal analysis equipment^[72]

improvement, the company has released multiple generations of LiMCA series products^[77, 78].

LiMCA is an in-situ detection device based on the electrical sensing zone principle, primarily used for detecting NMIs in Al alloy melts and assessing melt quality^[74]. As shown in Fig. 16^[26, 74], the system mainly consists of three components: a sensor, a current source, and a signal processing unit. The core part of the sensor includes two electrodes and an electrically insulated sampling tube with a micro-aperture in its wall^[15, 26, 79, 80]. Based on hydrodynamic principles, liquid metal can be drawn into or expelled from the tube by applying a pressure differential across its ends^[81]. When a strong direct current is applied between the two electrodes, the electrical potential difference becomes concentrated across the micro-aperture and its immediate surrounding region. Because the electrical properties (e.g., conductivity) of inclusions typically differ significantly from those of the Al alloy melt, particles passing through the micro-aperture generate resistance pulse signals (Electrical Resistance Pulses, ERPs) that are superimposed on the voltage drop^[75]. The amplitude and duration of these pulses correlate directly with the size and conductivity of the inclusions, thereby providing the theoretical basis for quantitative inclusion detection^[43].

Significant research advancements have been achieved through theoretical analysis and numerical simulations regarding the resistive pulse disturbances caused by particles traversing micro-apertures. Maxwell first derived analytical solutions for the resistance variations induced by spherical particles in micro-channels, establishing the fundamental theoretical framework for subsequent studies^[82]. Subsequent

work by Steidley^[83] demonstrated that, under a uniform electric field, when the dimensions of an insulating particle are substantially smaller than the micro-aperture size, the resultant resistance change is proportional to the particle volume. Guthrie et al.^[76] further combined numerical modeling with Newton's second law to investigate particle dynamics through electrical sensing zones of various shapes, enabling determination of inclusion size and type via signal analysis. Subsequently, Samuel et al.^[84] utilized LiMCA technology to study the detection of typical inclusions (Al_2O_3 , Al_4C_3 , MgO , CaO , TiB_2 , and TiAl_3) in an Al-6%Si cast alloy. This technology enables online, real-time monitoring of inclusions with sizes larger than 20 μm , providing data that reveal distinct microstructural characteristics of various inclusions, such as size and agglomeration tendency of Al_2O_3 . LiMCA was shown to efficiently capture TiB_2 agglomerates, thereby overcoming the clogging issues common in conventional technologies. This body of work has provided critical theoretical insights and practical advancements for the development and optimization of LiMCA technology for Al alloys, establishing a scientific foundation for the precise detection and quantitative analysis of NMIs in molten metal. Moreover, it offers a crucial online monitoring tool for alloy melt cleanliness assessment and process optimization, enhancing the reliability and timeliness of quality control in this field.

3.3 Ultrasonic

Current ex-situ and some in-situ methods for assessing Al alloy melt quality involve multiple steps, including molten metal sampling, specimen preparation, and laboratory analysis. Although these approaches satisfy conventional inspection requirements, their lengthy analytical cycles introduce a significant time lag relative to casting operations. When defects arise in the melt, delayed data feedback prevents real-time optimization of process parameters, substantially compromising the timeliness and precision of quality control and thus limiting overall casting performance^[85].

In contrast, ultrasonic testing has gained widespread applications as a mature, non-destructive, in-situ technique for monitoring molten Al alloy quality^[76]. Building on this foundation, Mansfield et al.^[86] conducted systematic research on ultrasonic melt quality monitoring. By combining experimental and theoretical analyses, they verified the technology's effectiveness for real-time detection of inclusion distribution, gas porosity, and microstructural evolution during solidification. Furthermore, they developed enhanced ultrasonic signal processing algorithms that significantly improved

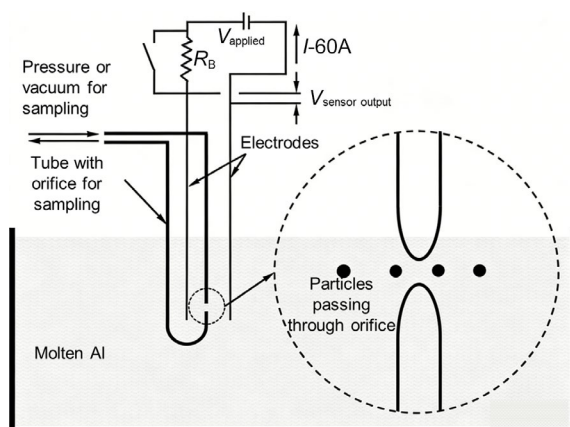


Fig. 16: Schematic diagram of the LiMCA system (R_B , V_{applied} , $V_{\text{sensor output}}$, and I are the resistance, applied voltage, output voltage, and current, respectively)^[26, 74]

detection accuracy and the signal-to-noise ratio, providing both theoretical frameworks and technical protocols for the industrial implementation of ultrasonic melt quality assessment.

Ultrasonic testing method primarily utilizes two detection modalities. The first configuration involves direct propagation of ultrasonic wave from a transmitter to a reflector, enabling the detection of inclusion only along the transmission path, as illustrated in Fig. 17^[26] (left). This approach generates relatively simple signals and is suitable for limited melt volumes^[87]. The second modality operates without reflector and features enhanced beam directivity, which facilitates the detection of inclusions at crucible bottoms, as shown in Fig. 17^[26] (right). However, this modality requires more complex signal analysis^[26]. The integration of these two configurations enables comprehensive analysis of NMIs distribution over larger areas within Al alloy melts. The expanded detection space provides a more accurate representation of the actual inclusion size and concentration^[88].

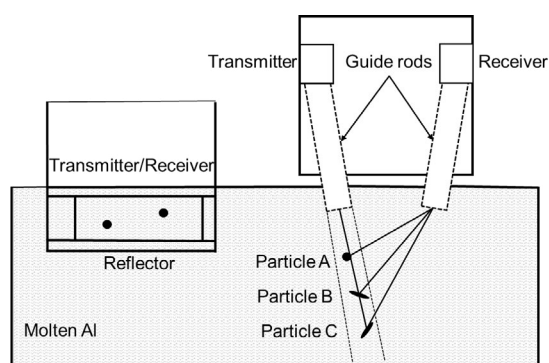


Fig. 17: Schematic diagram of the ultrasonic method for inclusion detection system: (left) transmitter-reflector configuration; (right) reflector-free configuration^[26]

Ultrasonic testing offers significant advantages due to the ability of ultrasonic waves to propagate through molten metals with minimal attenuation. When ultrasonic waves encounter inclusions within the melt, their propagation characteristics change substantially, accompanied by measurable energy variations^[85]. This property enables the direct measurement of four key parameters in molten Al alloy: attenuation characteristics^[89], detection of discontinuities, velocity variations, and frequency spectrum analysis. Research indicates that measuring ultrasonic attenuation in Al alloy melts allows for the assessment of suspended particles and the characterization of inclusions by size, distribution, and type. This ultrasonic-based method provides both theoretical and technical support for inclusion analysis and molten metal quality control. Guo et al.^[90] investigated the detection capability of ultrasonic technology for TiB_2 , AlSr , Al_3Ti , and Al_2O_3 particles in liquid Al and commercial 356 Al alloy. Experiments showed that conventional methods can only detect TiB_2 particles at concentrations lower than 10 ppm (as boron), whereas ultrasonic technology can effectively measure TiB_2 particles at concentrations as high as 90 ppm (as boron). This result demonstrates the significant advantage of ultrasonic technology for inclusion detection in Al alloys.

4 Comparison of different evaluation methods

Currently, various detection methods have been developed for inspecting Al alloy melt quality, specifically targeting gas content and inclusions, as summarized in Table 2. Based on when the inspection is performed, methods for analyzing gas and non-metallic inclusions can be primarily categorized into ex-situ and in-situ detection approaches^[74].

Table 2: Comparison of different inspection methods for molten Al alloys^[15]

Detection method	Detection category	Inspection object	Principle/basis	Response time	Accuracy	References
K-mold	Ex-situ	Gas Inclusions	Calculation of the K-value	1–2 h	60–80 μm	[79]
PoDFA	Ex-situ	Inclusions	Microscopic analysis of filter membrane	1–5 d	10–100 μm	[35, 36, 91]
LAIS	Ex-situ	Gas Inclusions	Optical/ultrasonic principle	~1 h	1–10 μm	[20, 26]
Prefil	Ex-situ	Inclusions	Gravimetry/microscopic counting	5–15 min	5–300 μm	[92, 93]
RPT	Ex-situ	Gas	Solidification density	2–3 h	0.1–1 ppm	[94]
Metallographic analysis	Ex-situ	Inclusions	Metallographic microscopy	1–2 h	>1 μm	[27, 28, 30]
Solidification curve analysis method	In-situ	Gas Inclusions	Characteristic curve points	5 min	ppm	[62, 64, 68, 71]
LiMCA	In-situ	Inclusions	Laser scattering or electrical induction signal analysis	Real-time	>20 μm	[26, 43, 79, 84]
Ultrasonic	In-situ	Gas Inclusions	Ultrasonic reflection through-transmission signal analysis	Minutes	10–15 μm	[26]

In the field of ex-situ detection, the metallographic method enables high-resolution observation of microstructures through microscopy. However, it is inherently destructive and time-consuming, with moderate to high costs due to labor-intensive sample preparation and specialized equipment maintenance. These factors limit its cost-effectiveness for large-scale industrial applications. Filtration-based techniques, including LAIS, PoDFA, and Prefil, are commonly employed for inclusion analysis. LAIS is limited by the cumbersome and time-consuming operation of liquid immersion samplers, as well as notably high costs associated with disposable sampler components and labor-intensive handling procedures. These drawbacks restrict its efficiency for on-site rapid sampling. Additionally, it only enables qualitative analysis with limited reliability, further constraining its application in real-time monitoring of molten Al. In contrast, both PoDFA and Prefil offer higher precision for laboratory-based quantitative analysis. They also feature relatively simple instrumentation and significantly lower operational costs, making them more cost-effective for routine testing. The reduced-pressure solidification density method demonstrates unique advantages for gas content evaluation in Al alloy melts through indirect density measurement. It offers a cost-effective solution with low equipment investment, despite its limited accuracy. Similarly, the K-mold method facilitates rapid quality assessment via fast solidification. It features straightforward operation and low associated costs but is restricted to qualitative analysis, lacking the capability for precise quantification of inclusion content or gas concentration^[74, 76, 95, 96].

Ex-situ detection methods offer high flexibility, accuracy, detailed results, and cost-effectiveness in controlled laboratory settings. However, they are plagued by several drawbacks. These include long turnaround times, low throughput, and a lack of real-time monitoring capability, all of which prevent timely production feedback. Furthermore, the requirement for sampling from production lines not only introduces potential measurement errors but also causes operational interruptions, ultimately compromising overall manufacturing efficiency^[97].

To overcome the inherent limitations of ex-situ methods, substantial research has focused on developing advanced in-situ monitoring technologies. Recent advances have driven substantial progress in techniques such as thermal analysis, LiMCA, and ultrasonic testing. These methods now offer effective solutions for real-time, high-efficiency assessment of Al alloy melt quality^[95]. Thermal analysis, primarily used for solidification characterization, is operationally simple and highly cost-effective, requiring minimal consumables and low maintenance costs. However, its capability to detect inclusions and gas content remains limited. In contrast, LiMCA demonstrates superior accuracy for inclusion analysis but exhibits insufficient sensitivity for measuring gas content and evaluating solidification properties. Its cost is moderate, stemming mainly from probe replacement and system calibration. As a non-destructive testing technique, the ultrasonic method enables the detection of microscopic

inclusions. Furthermore, its integration with thermal analysis allows for the comprehensive optimization of both solidification characteristics and inclusion assessment. Although the initial equipment investment for ultrasonic systems is relatively high, their long-term operational costs are low. The elimination of sampling steps also reduces production interruptions, enhancing its cost-effectiveness for continuous industrial monitoring. Collectively, these in-situ techniques represent a significant technological advance in addressing the shortcomings of conventional ex-situ approaches.

In conclusion, among ex-situ detection methods, PoDFA, Prefil, and K-mold methods hold prominent positions due to their low-to-moderate cost advantages, making them particularly suitable for regular quality checks in budget-limited scenarios. Regarding in-situ technologies, thermal analysis demonstrates high cost-effectiveness for basic real-time monitoring; although ultrasonic testing, LiMCA, and solidification curve analysis require higher initial investment, they prove economical in long-term, high-frequency monitoring scenarios because they significantly reduce production interruptions. In contrast, LAIS and metallographic methods exhibit low applicability in cost-sensitive industrial environments due to their high cost and limited efficiency.

The integration of in-situ Al melt monitoring with automation facilitates real-time data collection and precise process feedback, thereby enhancing efficiency, ensuring product consistency and stability, and supporting precision manufacturing. The continuous operation of such integrated systems reduces production interruptions, while their intelligent capabilities enable more efficient and precise control^[25, 79]. However, in-situ techniques are generally less accurate than ex-situ methods, which limits their application in high-precision scenarios such as laboratory research or quality control for special alloys.

Given the distinct advantages and limitations of each approach, the choice of monitoring techniques should be tailored to specific production or research objectives, taking into account their technical characteristics and practical constraints.

5 Conclusions and outlook

This review has systematically examined and compared the principal methods for assessing gas content and inclusions in Al alloy melts, categorizing them into ex-situ and in-situ paradigms. The analysis reveals their distinct characteristics and complementary roles, leading to the following conclusions:

(1) Ex-situ methods, such as metallography, PoDFA, Prefil, and RPT, provide high-precision, detailed characterization that is essential for research and development. These techniques excel in laboratory environments, offering invaluable data on inclusion morphology, type, size distribution, and gas porosity for fundamental studies and alloy design. However, their reliance on sampling, lengthy preparation, and offline analysis introduces a significant time lags, preventing real-time feedback and limiting their utility in dynamic

production control.

(2) In-situ techniques, including solidification curve analysis, LiMCA, and ultrasonic testing, enable real-time monitoring critical for industrial process stability and optimization. These methods allow for the immediate detection of trends in melt quality, facilitating rapid interventions to maintain process stability. Although they generally offer lower resolution and less detail than ex-situ methods, their key strength lies in providing continuous, real-time data on inclusion counts, hydrogen levels, and solidification behavior directly from the molten metal, thereby enabling proactive process control, improving production consistency, and increasing yield.

(3) A hybrid approach, intelligently integrating ex-situ precision with in-situ immediacy, represents the future of melt quality control. The ideal quality management system will leverage the strengths of both paradigms: using ex-situ methods for periodic calibration, validation, and in-depth root-cause analysis, while employing in-situ sensors for continuous, real-time monitoring and control. Technological advancements in automation, data fusion, and smart sensor systems are key to achieving this seamless integration.

In summary, the selection of an appropriate assessment method depends on the specific objective, for high-precision R&D or for real-time production control. Future progress in the field will be driven by the convergence of sensor technology, data analytics, and automation to create intelligent, integrated monitoring systems. Such systems will not only provide comprehensive insights into melt quality but also enable predictive control, ultimately advancing toward more precise, efficient, and reliable Al casting processes.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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