Review on approaches to evaluating the quality of molten aluminum alloys

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Abstract: The quality of molten aluminum (Al) alloys is closely related to the performance of final Al casting products. With the rapid advancement of Al alloy casting technology, various inspection methods have emerged, ranging from traditional ex-situ techniques to modern in-situ detection systems. However, the lack of a systematic review of these detection methods makes it challenging to select the most suitable technical solution for specific applications. This paper comprehensively reviews the approaches to analyzing the quality of molten Al alloys, providing a detailed analysis of their principles, advantages, limitations and applicable scenarios. Furthermore, the differences between ex-situ and in-situ detection methods are discussed, along with their complementary roles in industrial applications. This study systematically reviews the current research status of quality inspection technologies for molten Al alloys, providing a reference basis for technical selection in industries, while also offering insights into future development trends toward intelligent and high-precision detection methods.

Keywords: Molten aluminum alloys; Analyzing approach; Inclusions; Mechanical property

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, high strength, and corrosion resistance[1,2]. Particularly, the lightweight properties of Al alloys can effectively reduce energy consumption while enhancing equipment performance, making them a research focus in both academic and industrial fields[3,4].

Based on the processing methods, Al alloys can be classified into wrought and cast alloys[5]. Wrought Al alloys are produced through plastic deformation processes like rolling, extrusion, and forging, yielding plates, profiles, and rods[6-9]. Typical systems include Al-Cu, Al-Mg[10], Al-Mg-Si, and Al-Zn-Mg-Cu, which combine high strength and 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 offer high strength, hardness, corrosion resistance, and castability, making them suitable for complex components like engine blocks and automotive wheels[12-14]. Both alloy types face production challenges such as melt cleanliness control, microstructure regulation, and process optimization. Among these, precise melt quality monitoring during smelting is key to product performance.

In Al alloy casting, the melting process is crucial. Small changes in composition or parameters can greatly impact the casting's mechanical uniformity and surface quality, directly affecting yield.[15]. However, Molten Al alloys easily absorb hydrogen and trap inclusions (oxides, carbides, borides) 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 ingot.[16, 17].

As illustrated in Fig. 1, hydrogen absorption induces the formation of gas pores in Al alloy castings, significantly compromising their density and mechanical properties. Simultaneously, entrapped air reacts with the molten Al to generate non-metallic oxide inclusions (e.g., Al_2O_3, MgO, SrO, and $MgAl_2O_4$), which exist as solid particles, films, or droplets[18-20]. The harm inclusions cause to an alloy's structural integrity depends on their type, size, and concentration. Too many inclusions lead to stress concentration, which can trigger cracks and defects, greatly reducing the alloy's tensile strength, ductility, and toughness.[21-23]. Furthermore, these inclusions adversely affect fatigue strength, corrosion resistance, and surface quality, ultimately increasing production costs, rejection rates, and reducing manufacturing efficiency[15].

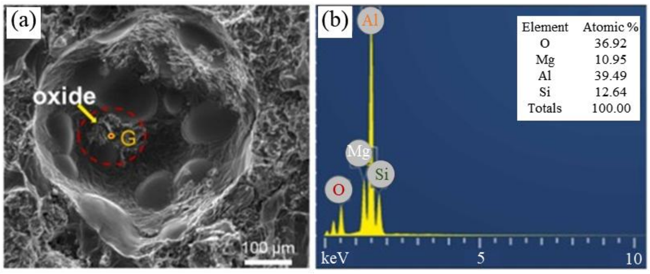


Fig. 1 Analysis of gas pores on fracture surface of A356 Al alloy tensile specimens [24]:
(a) Morphology of gas pores; (b) EDS analysis at Point G

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

Despite great progress in reducing gas and inclusions in molten Al alloys, there is no comprehensive review of quality evaluation methods. This study analyzes current quality monitoring techniques, focusing on their fundamental principles and application boundaries.

2 Ex-situ detection methods

2.1 Metallographic Analysis

Metallographic analysis, a basic way to evaluate molten Al alloy quality, involves preparing specimens and microscopically examining grain size, inclusions, and porosity. While it provides clear insights, it has drawbacks: the preparation is slow, the sampled area is small, and identifying inclusions manually depends on the operator.[27-28]. These constraints hinder rapid furnace-front testing, making conventional metallography insufficient for industrial efficiency requirements.

To solve this technical problem, Northeastern University developed an automated metallographic image analysis system. It uses a complex process including grayscale conversion, illumination correction, edge detection, and morphological operations to accurately segment inclusions, thus enhancing analysis efficiency and accuracy (Fig. 2). The system automatically recognizes and classifies inclusions in molten Al alloys by analyzing their grayscale values, morphology, size, and attributes verified by EPMA. This helps quickly assess alloy quality.[29].

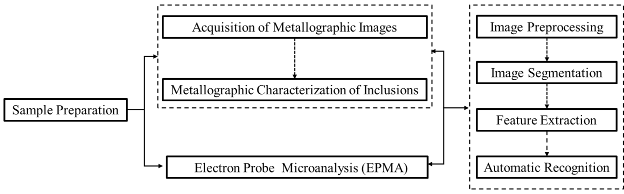


Fig. 2 Flowchart of automated metallographic analysis method [28]

2.2 Filtration methods

2.2.1 Porous disk filtration apparatus (PoDFA)

Conventional metallographic analysis faces inherent limitations in assessing melt cleanliness due to the extremely low inclusion density observable on polished surfaces. To overcome this constraint, Atkinson et al.[30] pioneered the non-metallic inclusions (NMIs) concentration enrichment methodology, which physically or chemically concentrates dispersed inclusions into localized regions to enhance detection statistics. This enrichment approach substantially improves upon conventional methods by expanding the effective sampling volume while increasing measurement reliability through statistically representative data accumulation. Notably, the PoDFA technique has successfully implemented this principle for Al alloy quality control, with its schematic diagram illustrated in Fig. 3, representing a significant advancement in melt cleanliness assessment technology[31].

As a pivotal technique for Al alloy melt quality assessment, the PoDFA method employs an integrated filtration-microscopy approach to systematically characterize the distribution of NMIs. The core technology involves forcing molten alloy through a precision microporous filter under controlled pressure to form an inclusion-enriched filter cake (Fig. 4).

Subsequent analysis utilizing metallographic microscopy, SEM (scanning electron microscopy)/EDS (energy dispersive spectroscopy). provides comprehensive morphological and compositional characterization of the captured inclusions (Fig. 5)[31, 33]. By quantifying key parameters such as inclusion type, size distribution and number density, PoDFA enables reliable quantitative evaluation of melt cleanliness[25].

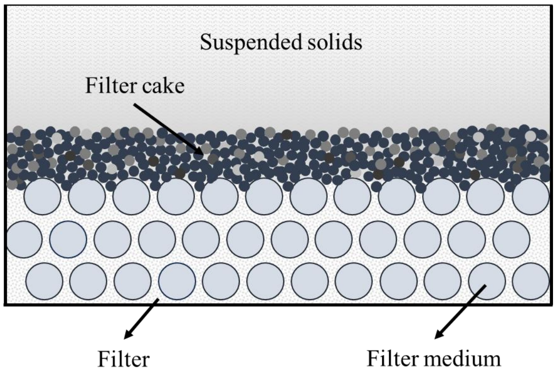


Fig. 4 Microscopic mechanism of filter cake formation[32]

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.[31] 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 [mm²/kg] can be obtained, making it impossible to directly and accurately determine the actual mass fraction of inclusions in the melt. During statistical analysis, the actual mass fraction of inclusions must be empirically derived from PoDFA values. Due to the randomness of inclusion deposition and statistical deviations during the filtration process, the directly measured PoDFA values cannot precisely correspond to the actual inclusion concentration in the bulk molten Al alloy[34]. Consequently, this empirical data conversion approach may introduce systematic errors, compromising the accuracy and universality of the test results. Furthermore, the process of pouring metal into a PODFA crucible may introduce some oxide inclusions.

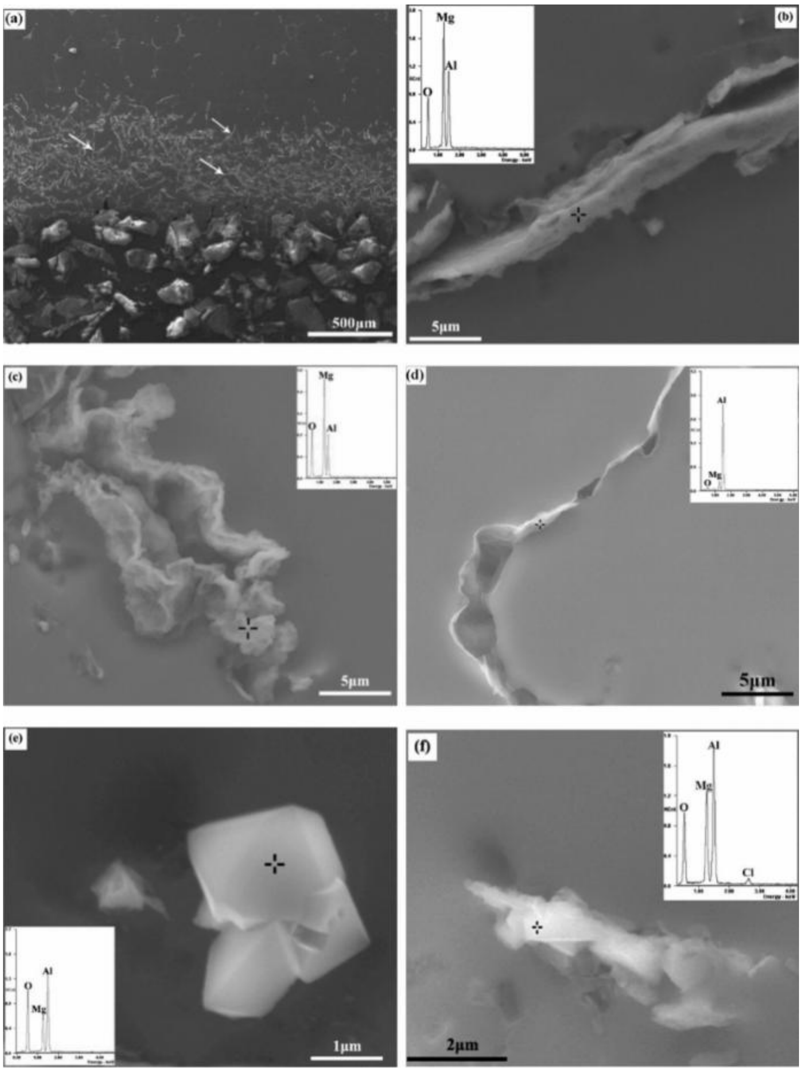


Fig. 5 SEM micrographs showing [31]: (a) overview of collected inclusions, white arrows mark thick oxide films; (b) stringer like oxide film; (c) nodule-like oxide film; (d) curled oxide film; (e) cuboid oxide particle; (f) cuboid oxide nucleates upon oxide film. Inserts are result of spot EDS analysis performed at target symbol.

Despite its limitations, PoDFA is a key technique for analyzing inclusion characteristics in Al alloy metallurgy. By combining filtration enrichment with microscopic quantification, it can precisely characterize micron - sized inclusions in Al alloy melts.[35]. Consequently, PoDFA analysis remains crucial in labs and high-end manufacturing to identify inclusion types and properties.

2.2.2 Liquid Al alloy inclusion sampler (LAIS）

Building on the PoDFA technique, Union Carbide Corporation, using its materials science and high - temperature tech knowledge, developed the LAIS as an improved version of PoDFA. The LAIS keeps the basic working principles of PoDFA but has major upgrades, including a simpler sampling mechanism that can precisely control the immersion depth in molten Al alloy [20].

The working principle of LAIS is illustrated in Fig. 6. 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 Al alloy through a porous graphite crossover into the sampling cup. During this process, NMIs are effectively captured by the filter while purified Al alloy continues flowing into the sampling cup [26]. Following sample collection, the vacuum pump is deactivated and the sampling device is retrieved. After solidification of the Al alloy in the sampling cup, comprehensive analysis of inclusion typology, size distribution, and spatial characteristics can be conducted. This methodology demonstrates high efficiency and precision, providing reliable technical support for stringent quality control of molten Al alloy.

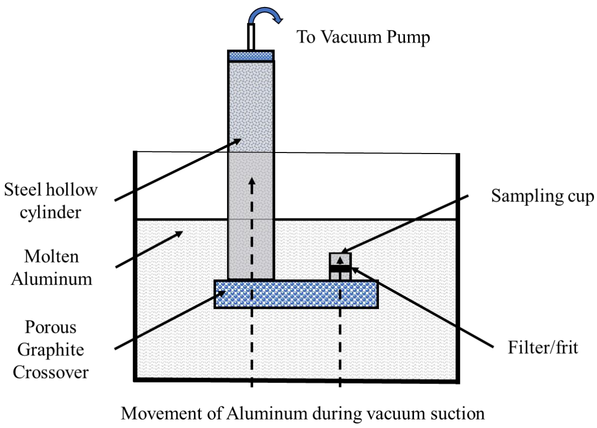


Fig. 6 Schematic diagram of the LAIS system [20]

2.2.3 Pressure filtration method-Prefil

Based on the technical principle of LAIS for assessing melt quality through inclusion enrichment in molten Al alloy, N-Tec (UK) conducted systematic experimental research in pressure filtration to establish correlation models between inclusion content and filtration rate while improving the cleanliness database of Al alloy melts. The test results revealed significant correlations between filtration velocity and both: (a) physical parameters of the molten Al alloy (temperature, density) and (b) characteristic parameters of inclusions in the filter cake (type, size, morphology) during the multi-porous filtration process[36]. These findings enabled N-Tec to successfully develop the Prefil method - a quantitative evaluation technology for molten metal cleanliness with enhanced metrological performance, marking a significant advancement in inclusion analysis techniques.

Compared to the two filtration analysis techniques of PoDFA (Porous disk filtration **a**pparatus) and LAIS (Liquid Al alloy Inclusion Sampler), Prefil is an Al alloy melt quality inspection method that rapidly evaluates inclusion content through dynamic pressure difference analysis, capable of providing direct analytical results while supporting subsequent metallographic analysis with sample preparation[37]. As shown in Fig. 3 and Fig. 4, the Prefil method exhibits operational similarities with PoDFA during initial procedural stages. During experimental operation, the Al alloy melt flows through a precision microporous ceramic filtration unit under dynamic pressure, forming a filter cake on its surface (Fig. 7), with the filtered melt subsequently entering a high-accuracy electronic weighing assembly positioned below the crucible.

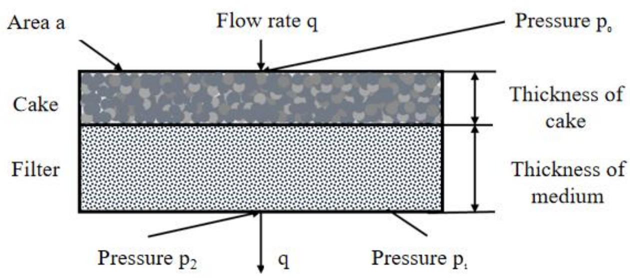


Fig. 7 Schematic illustration of filter cake and filtration medium microstructure [38, 39]

The system automatically generates characteristic cumulative filtration volume versus time curves through real-time monitoring of temporal filtration data, while establishing a quantitative model correlating the curvature variation rate of filtration curves with inclusion content[38, 40]. Steeper curve slopes indicate higher melt cleanliness levels and correspondingly faster flow rates through the microporous filter medium (Fig. 8)[39, 41]. This innovative model achieves simultaneous multiparameter determination of inclusion equivalent size distribution, aspect ratio, and volumetric concentration, while enabling quantitative assessment through rapid calculation of the Cleanliness Index (CI), demonstrating excellent measurement repeatability and minimal systematic error.

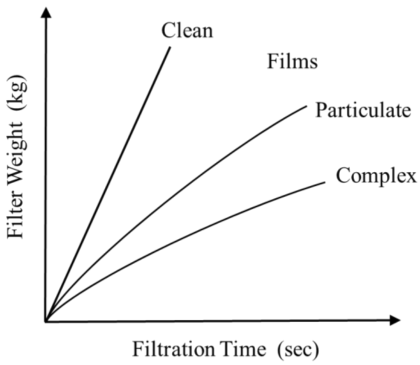


Fig. 8 Schematic diagram of Prefil curves corresponding to the filtration behavior of molten Al alloys containing different types of inclusions [37]

Currently, the Prefil method employs two standardized ceramic filter configurations: the permeability-type (90 μm) and high-permeability-type (130 μm), with their fundamental differences manifesting in the balancing mechanism between permeability performance and filtration precision[37,42]. The standard configuration uses smaller pores for high - precision filtration, meeting conventional cleanliness needs. The high - permeability version enlarges pores to cut flow resistance, ideal for high - flow, large - throughput conditions. This graded filtration offers flexible choices for different processes, and in practice, selection should match melt features, flow demands, and cleanliness standards.

2.3 Reduced pressure test (RPT)

Hydrogen (H) is one of the gaseous element known to form solid solutions in molten Al alloys, making hydrogen concentration measurement fundamentally equivalent to gas content assessment in Al melts[43]. Current investigations indicate that over twenty distinct analytical techniques have been developed for hydrogen content determination in both molten Al alloy and Al alloy ingots, with particularly significant advancements achieved in hydrogen measurement methodologies for solid Al alloy products[44]. Among these, the Reduced Pressure Test (RPT) has emerged as the industry standard due to its ability to directly visualize pore morphology and establish precise hydrogen content-porosity correlations[45].

The Reduced Pressure Test (RPT), alternatively termed the Reduced Pressure Test, Vacuum Solidification Test (VST), Vacuum Density Test (VDT), or Straube-Pfeiffer Test[46], represents a classical methodology for characterizing hydrogen content and porosity defects in molten Al alloy, widely employed in Al alloy melt metallurgical quality assessment[33]. As illustrated in Fig. 9, the testing apparatus involves introducing a quantified Al alloy melt into a preheated graphite crucible, with coordinated control via a shut-off valve and vacuum pump to establish negative pressure conditions within the sealed chamber formed by the glass cover and base plate. Vacuum pumping ceases when the vacuum gauge reaches predetermined thresholds, allowing the crucible's molten Al alloy to solidify under reduced pressure. During this process, dissolved hydrogen in the melt partially escapes as surface bubbles due to decreased solid solubility, while the remainder forms subsurface pinhole defects through solute redistribution at solidification fronts, concurrently generating characteristic surface bulges from constrained melt shrinkage. Post-solidification, the Al alloy ingot specimen undergoes standardized longitudinal sectioning after degassing, followed by metallographic analysis comparing against reference standards for semi-quantitative porosity evaluation. Concurrent density measurement via water displacement or density index calculation establishes mathematical models correlating hydrogen content with physical parameters, ultimately enabling multidimensional characterization of molten Al alloy hydrogen content[45, 47].

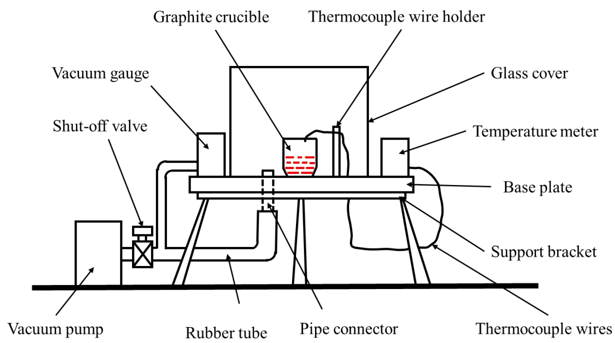


Fig. 9 Schematic diagram of reduced-pressure solidification principle [45]

RPT has become a widely adopted technique for hydrogen content assessment in Al alloy melts, owing to its simple apparatus and standardized procedure. However, this method demonstrates limited sensitivity for ingots with low hydrogen concentrations. More importantly, systematic studies by Dispinar et al.[46,48,49] have demonstrated that inclusions in molten Al significantly influence pore distribution in solidified samples, disrupting the linear correlation between pore characteristics and actual hydrogen content. Further research by Jang et al.[50] revealed that minimizing atmospheric exposure during melting reduces the density index (DI) by 5.6%, while employing a ladle-scooping sampling method (Al_s), as opposed to conventional pouring(Al_p), further decreases the DI by an additional 1.9% . The porosity exhibited a similar trend to the DI variation between the two samples (Fig. 10). Subsequent SEM-EDS analysis (Fig. 11) confirmed that inclusions in the melt are the primary factor affecting DI values. Such interference caused by inclusions substantially degrades the measurement accuracy of RPT, thereby limiting its reliability in certain applications.

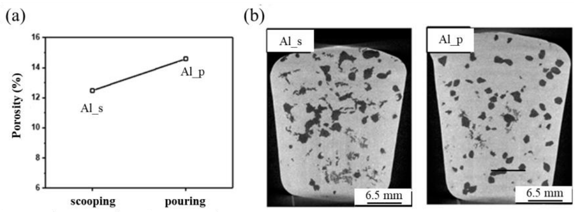


Fig. 10 Analysis of Al-Si alloy samples collected by two sampling methods under RPT [50]: (a) Porosity comparison, (b) 2D cross-sectional X-ray CT image

In recent years, with breakthrough advancements in digital image processing technology, intelligent hydrogen content evaluation methods based on solidification defect morphology characteristics have emerged as a research focus. Current studies employ high-resolution optical microscopy to acquire solidification microstructure images of Al alloy ingot longitudinal sections for statistical analysis. Campbell et al.[51] pioneered the incorporation of the Bifilm Index into hydrogen content assessment systems while conducting image analysis of porosity in Al alloy ingot longitudinal sections. Subsequently, El-Sayed's research team[52] utilized quantitative indicators including the quantity and size of pores generated by bifilms in ingot cross-sections to qualitatively evaluate hydrogen content in molten Al alloy. These studies have overcome the technical limitation of reduced pressure solidification tests being prone to heterogeneous - phase interference in complex melt systems, laying a technical foundation for optimizing melt purification processes and refining detection models.

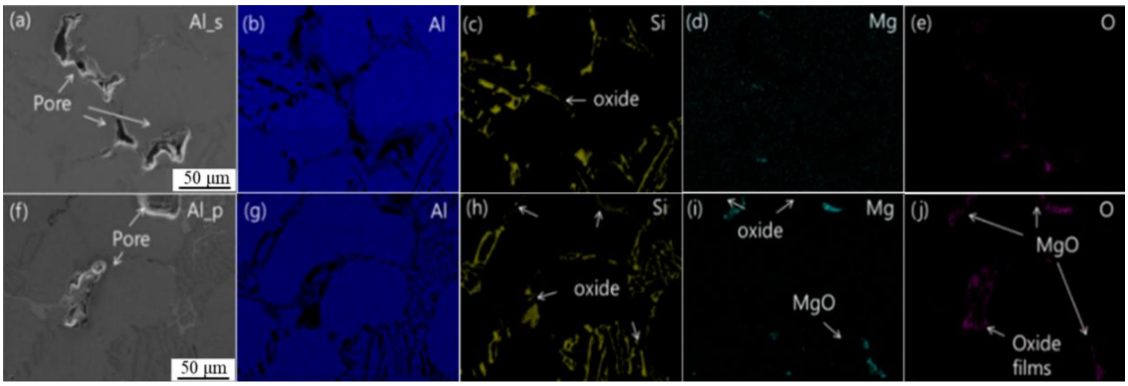


Fig. 11 SEM microscope images (a,f) and EDS-mapping results (b-e,g-j) of pores and oxide films in the reduced pressure test samples of Al-Si alloys collected by two different sampling methods[50]

2.4 K-mold method

The K-mold method, alternatively termed the fracture surface observation test, represents an Al alloy melt cleanliness assessment technique based on as-cast fracture morphology examination. Originally proposed by Yuan Xiaodong [53], this methodology involves extracting a representative melt sample from the furnace prior to casting and pouring it into a waffle mold (Fig. 12) to produce standardized waffle-shaped specimens (K-mold, Fig. 13) measuring 40 mm × 36 mm × 8 mm [54]. Following solidification, specimens are manually fractured along pre-designed breaking lines, with inclusion distribution characteristics on fracture surfaces examined using stereomicroscopy.

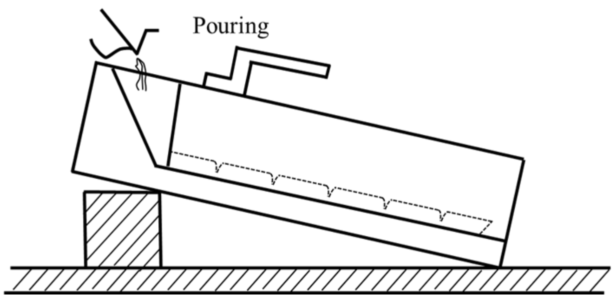


Fig. 12 Waffle ingot mold [54]

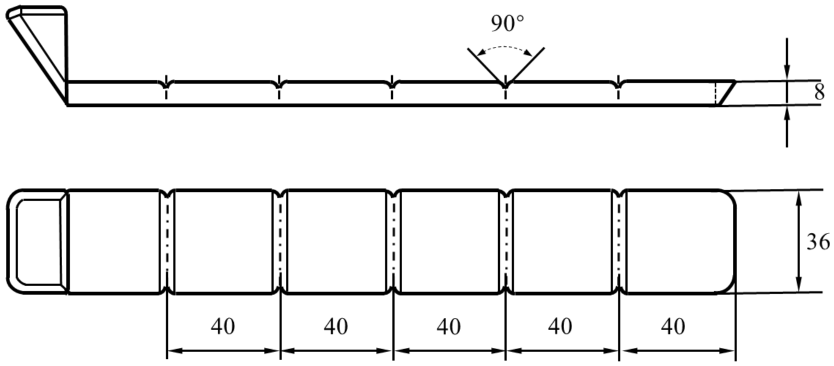
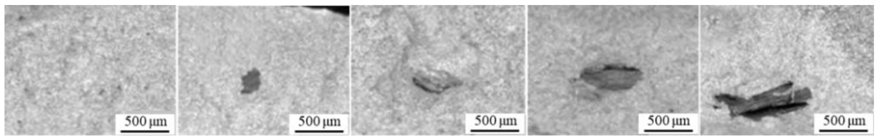


Fig. 13 Waffle-patterned Al alloy ingot [54]

Table 1 Correlation between Fracture Inclusion Size Grades [56]

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

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

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

where: K is inclusion content ratio, M is total inclusion content, N is number of fracture surfaces, Count(i) is quantity of inclusions with size grade i, Y is weighting factor for size grade i, i is inclusion size grade.

The inclusion content (K-value) is then calculated according to the size-grade correlation specified in Table 1, incorporating both formula (1) and (2)[29,55,56]. Per industry standards, the K-value exhibits an inverse correlation with melt cleanliness - lower K-values indicate higher melt purity, thereby enabling semi-quantitative Al alloy melt quality evaluation.

The conventional K-mold method provides a fundamental solution for Al alloy melt cleanliness assessment due to its cost-effectiveness and operational simplicity, yet demonstrates significant limitations in detection accuracy and data processing capacity. Specifically, manual fracture preparation introduces operational deviations while microscopic observation depends on subjective empirical judgment, and the traditional K-value calculation formula inadequately quantifies inclusion morphology and size distribution characteristics. To overcome these limitations, Li et al.[57] innovatively developed an intelligent detection system based on deep learning, constructing a cascaded dual-network model integrating Convolutional Neural Network (CNN) and Error Back-Propagation (BP) networks. This system utilizes CNN for intelligent identification of inclusion-containing regions on fracture surfaces, followed by BP network-based quantitative calculation of inclusion content, achieving substantial improvement in detection accuracy. This advancement represents a paradigm shift from experience-dependent to data-driven quality evaluation, significantly enhancing detection efficiency while effectively reducing human error to meet industrial precision requirements. Future developments through algorithm iteration and multimodal data fusion are expected to further break through technical barriers, providing more efficient and reliable quantitative tools for precision casting process control.

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 Al alloy melt composition and quality, yet they demonstrate inherent limitations in characterizing the dynamic solidification processes of molten Al alloy. Solidification curve analysis, a subset of thermal analysis techniques, is a well-validated method capable of real-time monitoring of the metallurgical properties of aluminum alloy melts during processing without the need for conventional metallographic examinations.[58]. Chen et al.[59] established that the characteristic profiles of thermal analysis cooling curves directly correlate with the solidification kinetics of Al-Si alloy melts, wherein the solidification zone parameters serve as quantitative indicators for melt quality assessment, allowing comprehensive evaluation through systematic comparison of cooling curve morphological features.

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 - through recording and analyzing the temperature-time curve during Al alloy melt solidification[60, 61]. In foundry applications, the monitoring and adjustment of solidification parameters significantly influence casting quality. Currently, Computer-Aided Cooling Curve Thermal Analysis (CA-CCTA) has been extensively employed for evaluating alloy composition[62], crystallization latent heat[63], and other relevant parameters, while enabling comprehensive monitoring and analysis of solidification behavior in multi-component alloy systems[64-66].

Solidification curve analysis method achieves these functions primarily through thermocouple-based examination of Al alloy melt solidification curves. As depicted in Fig. 14, the thermocouple is centrally positioned within the sampling cup at 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[67], with operational details shown in Fig. 15. This methodology provides not only real-time solidification monitoring but also critical process optimization data, establishing itself as an essential tool for Al alloy melt quality evaluation.

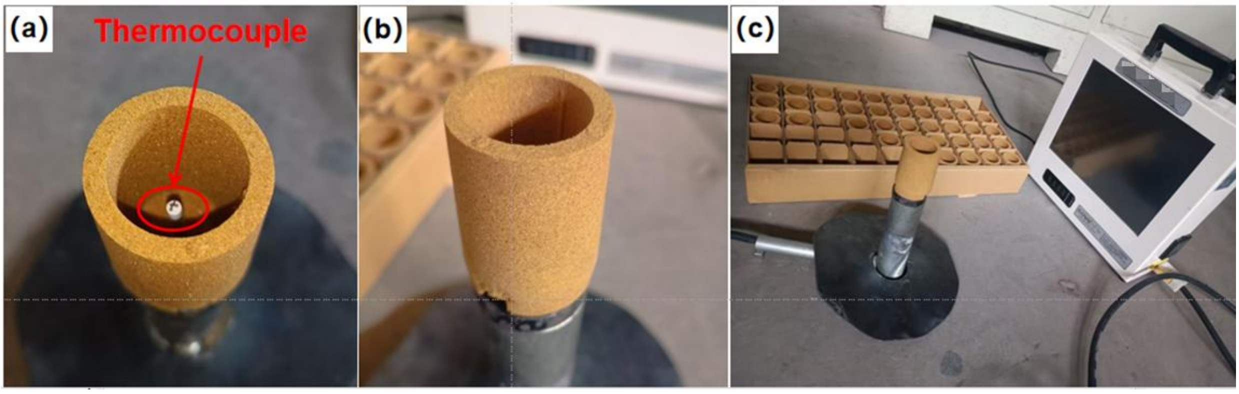


Fig. 14 Thermal analysis equipment (Figures captured by authors): (a) Thermocouple in sampling cup; (b) Front view of sampling cup; (c) Solidification curve display.

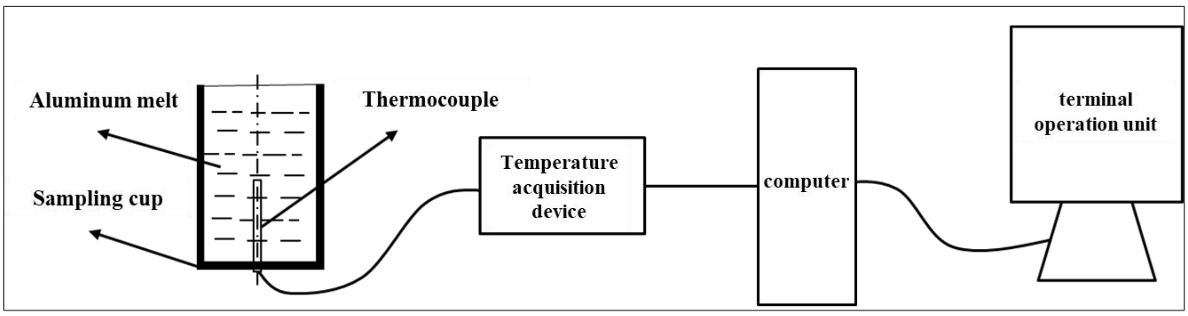


Fig. 15 Simplified Thermal Analysis Equipment [68]

3.2 Liquid metal cleanliness analyser（LiMCA）

Compared to thermal analysis, LiMCA demonstrates superior precision in Al alloy melt quality assessment. In 1950, the electrical sensing zone method was first developed by Coulter to address erythrocyte measurement challenges, leading to the invention of the Coulter Counter[69,70]. By 1985, McGill University adapted this electrical sensing zone theory to metallurgical applications, enabling direct quantification of inclusion count and size distribution in molten metals[70,71], which led to the successful development of the LiMCA system[72]. ABB Corporation subsequently commercialized LiMCA technology for metallurgical cleanliness evaluation, and through continuous technical refinement, has introduced multiple generations of LiMCA series products[73,74].

Therefore, the Liquid Metal Cleanliness Analyzer (LiMCA) is an in-situ detection device developed based on the electric sensing zone principle, primarily used for detecting NMIs in Al alloy melt and assessing melt quality[70]. As shown in Fig. 16, the system mainly consists of three components: a sensor, current source, and signal processing system. The sensor's core assembly comprises two electrodes and an electrically insulated sampling tube containing a micro-aperture in its wall[15,26,75,76]. Based on hydrodynamic principles, liquid metal can be pumped or discharged by applying a pressure differential across the sampling tube[77]. When a strong DC current is applied between the two electrodes, the potential difference becomes concentrated in the micro-aperture and its immediate vicinity. Since inclusions' electrical properties (e.g., conductivity) typically differ significantly from the Al alloy melt, particles with different conductivity passing through the micro-aperture generate resistance pulse signals (Electrical Resistance Pulse, ERP) superimposed on the voltage drop[71]. The amplitude and duration of these signals directly correlate with the inclusions' size and conductivity characteristics, thereby providing the theoretical basis for quantitative inclusion detection[41].

Significant research advancements have been achieved regarding resistive pulse disturbances caused by particles traversing micro-apertures through theoretical analysis and numerical simulations. Maxwell first derived analytical solutions for resistance variations induced by spherical particles in micro-channels, establishing the fundamental theoretical framework for subsequent studies[78]. Subsequent work by Steidley demonstrated that under uniform electric field conditions, when insulating particle dimensions are substantially smaller than the micro-aperture size, the resultant resistance change exhibits proportionality to particle volume[79]. Further developments by Roderick Guthrie et al.[72] combined numerical modeling with Newton's second law to investigate particle dynamics through variously shaped electrical sensing zones, enabling determination of inclusion size and type via signal analysis. These research achievements have provided critical theoretical support for the development and optimization of LiMCA technology in Al alloys, while establishing a scientific foundation for precise detection and quantitative analysis of NMIs in molten metal.

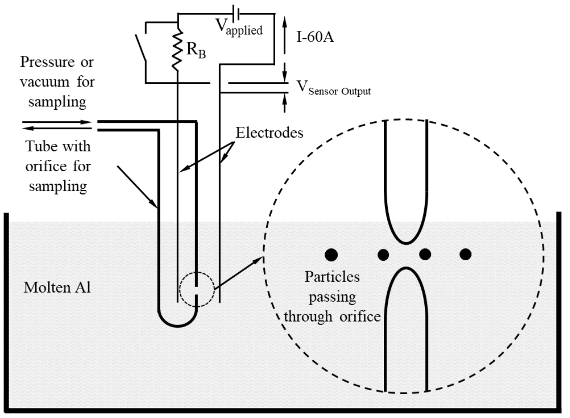


Fig. 16 Schematic diagram of the LiMCA system (R_B,$V_{applied}$,$V_{sensor\ output}$, and I are the resistance, applied voltage, output voltage, and current, respectively) [26,70]

3.3 Ultrasonic

Current ex-situ and certain in-situ methods for Al alloy melt quality assessment require multiple procedural steps including molten metal sampling, specimen preparation, and laboratory analysis. While these approaches satisfy conventional inspection requirements, their protracted analytical cycles result in significant time lag relative to casting operations. When defects emerge in molten metal, delayed data feedback prevents real-time process parameter optimization, substantially compromising the timeliness and precision of quality control, ultimately constraining comprehensive casting performance metrics[80]. In contrast, ultrasonic testing has gained widespread application in molten Al alloy quality monitoring as a mature non-destructive in-situ technique[72]. Building upon this, T.M. Mansfield's team[81] conducted systematic research on ultrasonic melt quality monitoring, combining experimental and theoretical analyses to verify 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 detection accuracy and signal-to-noise ratio, establishing both theoretical frameworks and technical protocols for industrial implementation of ultrasonic melt quality assessment.

The ultrasonic testing method primarily encompasses two detection modalities. The first configuration involves direct ultrasonic wave propagation from transmitter to reflector, enabling inclusion detection solely along the transmission path, as illustrated in Fig. 17 (left). This approach generates relatively simple ultrasonic signals and is suitable for limited melt volumes[82]. The second modality operates without reflectors throughout the detection process, featuring enhanced beam directivity that facilitates inclusion detection at crucible bottoms, shown in Fig. 17 (right), albeit with more complex signal analysis requirements[26]. By integrating these two ultrasonic configurations, comprehensive analysis of large-area non-metallic inclusion distribution in Al alloy melts becomes achievable, with the expanded detection space providing more accurate representation of actual inclusion size and concentration characteristics[83].

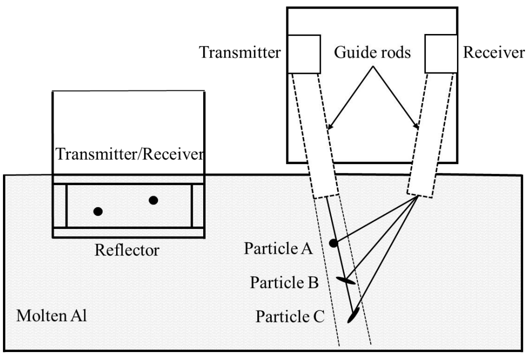


Fig. 17 Schematic diagram of the ultrasonic method for inclusion detection system [26]

The ultrasonic testing method demonstrates significant advantages due to the ability of ultrasonic waves to propagate through molten metals with minimal attenuation. When ultrasonic waves encounter inclusions within Al alloy melts, their propagation characteristics undergo substantial alterations accompanied by measurable energy variations[80]. This unique property enables direct measurement of four distinct parameters in molten Al alloy: attenuation characteristics[84], discontinuity detection, velocity variations, and frequency spectrum analysis. Research shows measuring ultrasonic attenuation in Al alloy melts can assess suspended particles, characterizing inclusions' size, distribution, and type. This ultrasonic - based method offers theoretical and technical support for analyzing inclusions and controlling molten metal quality.

4 Comparison of different evaluating approaches

Currently, the field of Al alloy melt quality inspection has developed a variety of detection methods, as summarized in Table 2. Based on the inspection timeline, these methods can be primarily categorized into ex-situ detection and in-situ detection[70].

In the field of ex-situ detection, the metallographic method enables high-resolution microstructure observation through microscopy, yet it is inherently destructive and time-consuming. Filtration-based techniques, including the LAIS, PoDFA, and Prefil , are commonly employed for inclusion analysis. LAIS offers operational simplicity and low cost, making it suitable for on-site rapid sampling, though limited to qualitative analysis with moderate accuracy. In contrast, both PoDFA and Prefil provide higher precision suitable for laboratory-based quantitative analysis, albeit requiring sophisticated instrumentation at elevated costs. The reduced-pressure solidification density method demonstrates unique advantages for gas content evaluation in Al alloy melts through indirect density measurement, offering a cost-effective solution despite its limited accuracy. Similarly, the K-Mold Method facilitates rapid quality assessment via fast solidification, featuring straightforward operation while being restricted to qualitative analysis[70,72,90,91]. Although ex-situ detection methods offer high flexibility, accuracy, detailed results, and cost - effectiveness in controlled settings. However, they have drawbacks like long turnaround times, low throughput, and lack of real-time monitoring, preventing 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[92].

To overcome the inherent limitations of ex-situ detection methods, substantial research efforts have been devoted to developing advanced in-situ monitoring technologies. Recent technological advancements have facilitated significant progress in in-situ detection techniques such as thermal analysis, LiMCA , and ultrasonic testing, which now provide effective solutions for real-time and high-efficiency Al alloy melt quality assessment[90]. Thermal analysis, primarily employed for solidification characterization, offers operational simplicity and cost-effectiveness, though its capability for detecting inclusions and gas content remains limited. In contrast, LiMCA demonstrates superior accuracy in inclusion analysis, yet exhibits insufficient sensitivity for gas content measurement and solidification property evaluation. The ultrasonic method, as a non-destructive testing technique, enables simultaneous detection of microscopic inclusions and gas concentrations, and its integration with thermal analysis allows for comprehensive optimization of both solidification characteristics and inclusion assessment, establishing it as a critical methodology for Al alloy melt quality monitoring. These in-situ techniques collectively represent a significant technological breakthrough in addressing the shortcomings of conventional ex-situ detection approaches.

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

Detection method	Detection type	Inspection content	Principle/Basis	Response time	Accuracy	References
K-Mold	Ex-situ	Gas Inclusions	K-value	1-2 h	60-80 μm	[75]
PODFA	Ex-situ	Inclusions	Microscopic analysis of filter membrane	1-5 d	20-50 μm	[34, 85]
LAIS	Ex-situ	Gas Inclusions	Optical/Ultrasonic principle	Real-time	1-10 μm	[20, 26]
Prefil	Ex-situ	Inclusions	Gravimetry/Microscopic counting	5-15 min	5-20 μm	[86, 87]
RPT	Ex-situ	Gas	Solidification density	2-3 h	0.1-1 ppm	[88]
Metallographic analysis	Ex-situ	Inclusions	Metallographic microscopy	1-2 h	>1 μm	[27-29]
Thermal analysis	In-situ	Gas Inclusions	Characteristic curve points	5 min	ppm	[58, 60, 64, 67]
LIMCA	In-situ	Inclusions	Laser scattering or electrical induction signal analysis	Real-time	15-20 μm	[26, 41, 75, 89]
Ultrasonic	In-situ	Gas Inclusions	Ultrasonic reflection Through-transmission signal analysis	Minutes	10-15 μm	[26]

Integrating in-situ Al alloy melt quality monitoring systems with automation allows real-time data collection and precise feedback for process adjustments. This boosts inspection efficiency, ensures product consistency and production stability, and supports precision manufacturing. Furthermore, the continuous operation design of these systems significantly mitigates production interruption risks, while their enhanced intelligent capabilities establish a robust foundation for efficient and precise production control[25,75]. Conversely, when compared with ex-situ detection methods, in-situ monitoring techniques demonstrate relatively inferior detection accuracy, rendering them inadequate for applications demanding stringent precision requirements, such as laboratory research, novel material development, or quality control of specialty alloys.

In view of the distinct advantages and limitations inherent in both ex-situ and in-situ detection methodologies, the selection of appropriate monitoring techniques in practical applications should be systematically determined based on specific production requirements and research objectives, with due consideration given to their respective technical characteristics and operational constraints.

5 Conclusions and outlook

This paper reviews several common Al alloy melt quality inspection methods, covering two major categories: ex-situ inspection and in-situ inspection. Through systematic analysis of these two types of inspection methods, the study finds that:

(1)Ex-situ methods exhibit superior precision in laboratory settings, enabling detailed microstructure characterization critical for R&D of novel alloys. In contrast, in-situ techniques prioritize real-time process monitoring to enhance production stability, though their resolution may limit applicability in nanoscale research.

(2)Ex-situ and in-situ inspection methods complement each other in Al alloy melt quality control. Ex-situ inspection aids process development and quality analysis, in-situ inspection ensures real-time industrial quality, and their combined use enables a comprehensive quality management system.

(3)Future Al alloy melt inspection should merge ex-situ precision with real-time online detection through smart integration, driving innovation. This study provides critical insights for optimizing casting quality control systems, offering both theoretical and industrial value.

The findings suggest that with further development of inspection technologies, the integration between ex-situ and in-situ inspection methods will become more seamless, providing a more comprehensive solution for intelligent and precise Al alloy melt quality control. This study offers theoretical foundations and practical guidance for the selection and application of Al alloy melt quality inspection technologies, holding important significance for promoting technological advancement in the Al alloy casting industry.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Nos. 52301197; 52071262), the Research Fund of the State Key Laboratory of Solidification Processing (NPU), China (Nos. 2024-ZD-06; 2024-TS-06), the Young Talent Fund of Xi'an Association for Science and Technology (No. 959202413014), the Natural Science Foundation of Chongqing, China (No. CSTB2022NSCQ-MSX0945) and the Fundamental Research Funds for the Central Universities (No. D5000240144).

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