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Research Progress on Uneven Cooling in Horizontal Direct Chill Casting of Aluminum Alloys

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Abstract: Traditional vertical direct chill (VDC) casting faces challenges such as discontinuous production and safety risks. In contrast, horizontal direct chill (HDC) casting has gained attention for its continuous operation, enhanced safety, and cost-effectiveness. However, fundamental studies on HDC of aluminum alloys remain limited, particularly concerning quality defects caused by asymmetric cooling within the mold. This article reviews the origins of cooling inhomogeneity in aluminum alloy HDC and the strategies developed to mitigate it, with emphasis on mold design optimization, process parameter control, and modification treatments. Research shows that optimized casting speeds, low-frequency electromagnetic fields, combined magnetic fields, and power ultrasonic techniques can refine grains, reduce surface segregation layer thickness, and suppress solute segregation. Despite these advances, challenges remain, including microstructural defects from uneven cooling, limited effectiveness of grain refiners, and an incomplete understanding of multi-field synergistic mechanisms. Future research should focus on developing multi-physics numerical models to establish quantitative links between external field parameters and solidification structures, creating rare-earth-enhanced composite modification methods for greater compositional flexibility, designing modular external field devices to improve energy field uniformity in large ingots, and applying AI-driven multi-objective optimization for precise process control.

Keywords: aluminum alloys; horizontal direct chill casting; cooling heterogeneity; grain refinement; research progress

1. Introduction

Aluminum alloys are widely used in aerospace, automotive manufacturing, and other industries due to their excellent stamping formability, strong paint-bake hardening response, and superior corrosion resistance, making them indispensable in modern applications [1-3]. According to China's Energy-Saving and New Energy Vehicle Technology Roadmap (MIIT), the per-vehicle aluminum usage targets are set at 250 kg by 2025 and 350 kg by 2030 [4]. This highlights the rapid growth in aluminum alloy ingot production and processing technologies.

Aluminum alloy ingots serve as the primary material for manufacturing automotive body panels. Among aluminum alloy production processes, the Vertical Direct Chill Casting (VDC) has long dominated the preparation of aluminum alloy billets and slabs due to its large single-machine capacity and broad alloy adaptability [5,6]. However, this traditional process has several limitations. First, its discontinuous nature requires stopping the casting cycle once the ingot length reaches several meters, which seriously restricts efficiency. Second, the process requires casting wells tens of meters deep, which greatly increases infrastructure costs and introduces serious safety risks. In addition, relocating and maintaining such large-scale equipment is highly challenging.

In contrast, Horizontal Direct Chill Casting (HDC) offers unique competitive advantages. It enables continuous production, significantly improving efficiency while eliminating the need for deep casting wells. This not only reduces infrastructure costs but also improves operational safety. Furthermore, the modular equipment design improves site adaptability and facilitates flexible production layouts [6]. However, it is worth noting that fundamental research on HDC of aluminum alloys remains relatively undeveloped. In particular, systematic theoretical analysis and effective solutions for quality defects caused by asymmetric mold cooling are still lacking. This gap has become a major bottleneck restricting the broader industrial application of HDC.

This paper reviews recent research trends and key technological advancements in controlling cooling uniformity during aluminum alloy HDC. It focuses on three main areas: mold structure optimization, process parameter adjustment, and modification treatments. The mechanisms and engineering practices reported in current studies are analyzed in depth. Finally, future research directions are proposed, emphasizing multi-scale collaborative process optimization and intelligent regulation models, with the aim of providing theoretical support and innovative approaches for improving ingot uniformity and defect control.

2. Technological Process and Characteristics of Horizontal Direct Chill Casting for Aluminum Alloys

2.1. Process Flow of Horizontal Direct Chill Casting (HDC) for Aluminum Alloys

Figure 1 shows a schematic diagram of the horizontal direct chill casting process for aluminum alloys. The melt enters the casting area from the inlet and is first cooled in the mold, where heat exchange between the melt and the mold forms a solid shell around the billet. However, the central region of the billet still contains high-temperature melt. At this stage, the billet consists of three zones: liquid, mushy (semi-solid), and solid. As the solid shell is continuously pulled out of the mold at a uniform speed by the ingot rod, secondary cooling water is directly sprayed onto the billet surface. Direct contact between the water and the hot ingot surface causes nucleate boiling, which accelerates the cooling rate until solidification is complete. The casting process continues until the billet reaches the predetermined length [7,8].

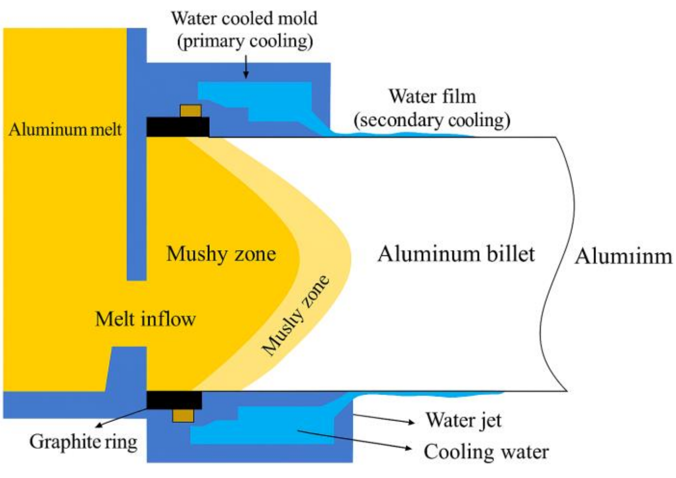

Figure 1. Schematic diagram of the horizontal direct chill casting process for aluminum alloys [7].

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2.2. Characteristics of Horizontal Direct Chill Casting (HDC) for Aluminum Alloys

Horizontal direct chill casting technology was first applied industrially in the early 1950s, mainly for producing non-ferrous metals such as copper and aluminum. However, early equipment suffered from technical limitations, including low heat conduction efficiency, limited billet pulling speed, and insufficient control of the temperature field. As a result, billets often had coarse microstructures and relatively high surface defect rates. These shortcomings prevented the technology from meeting industrial standards for cost-effectiveness and quality stability [9,10]. With advances in materials genome engineering and process control theory, along with the increasing demand for precise regulation of melt purification and solidification paths, the development of continuous casting systems with directional solidification and low segregation has become essential in materials processing. Compared with traditional vertical continuous casting, the main advantages of HDC are [11-13]: (1) Low investment and infrastructure costs, with convenient equipment relocation; (2) Smaller front-box aluminum storage, no need for deep casting wells, higher safety, and reduced accident risk; (3) Continuous casting capability, high automation, and low maintenance costs; (4) Reduced loss of billet head and tail, leading to higher product yield; (5) Use of shorter molds, which enhances the counter-current heat conduction effect of secondary cooling. Direct water cooling forms a solidified shell layer, significantly reducing surface segregation and improving billet quality. Although HDC of aluminum alloys has unique advantages for industrial production, it still faces challenges such as uneven cooling caused by gravity (leading to surface cracks, cold laps, segregation, and structural inhomogeneity), relatively low production efficiency, and limitations on billet size (making it difficult to produce large-section or irregular billets) [14-16]. Nevertheless, some of these issues have been alleviated through process optimization and technological improvements. Further research is still needed to enhance the overall performance and economic competitiveness of HDC.

3. Improvement Methods for Uneven Cooling in Horizontal Direct Chill Casting of Aluminum Alloys

3.1. Mold structure optimization

Horizontal direct chill casting of aluminum alloys is a complex process system involving multiple technologies. Its core framework includes key technical modules such as regulation of the melt flow field, thermodynamic coupling design of the mold, and dynamic control of secondary cooling. Among these, the mold serves as the solidification core unit, and collaborative optimization of its structural parameters and thermodynamic field distribution is crucial for billet uniformity and defect control. Studies have shown that adjusting the position of idler rollers [17] or optimizing mold cooling intensity [18] can improve billet crystallization symmetry, refine microstructure, and reduce segregation. R. A. D. Amir [7] further demonstrated, through finite element simulations of different melt inlet positions, that vertical downward movement of the inlets can significantly improve melt flow uniformity and reduce asymmetry in cavity separation. Collectively, these results suggest that solving uneven cooling in HDC requires a combination of structural design and dynamic process matching to achieve multi-scale collaborative optimization of solidification.

3.2. Process parameter optimization

In HDC, precise control of process parameters—such as pouring temperature, cooling intensity, and casting speed—is critical to ingot quality. By regulating the temperature gradient and grain nucleation and growth kinetics during solidification, these parameters directly influence microstructural uniformity, mechanical properties, and defect formation (e.g., shrinkage cavities, segregation, and cracks). Thus, they are essential for balancing production efficiency and product quality [19]. Casting speed, in particular, plays a decisive role. While higher speeds improve efficiency, they also strongly affect solidification structures and defect evolution. Optimization, therefore, requires balancing efficiency and quality. Increasing casting speed can shorten solute migration time, but studies show associated risks. D. Bartocha et al. [20] found that increasing casting speed (30-80 mm/min for 30 mm ingots) reduces the temperature gradient at the crystallization front, resulting in coarse

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grains and lower adaptability to plastic deformation. Similarly, Q. F. Zhu et al. [21] reported that higher speeds in 7075 HDC ingots increase surface segregation while reducing dendrite layer thickness. A. Larouche et al. [22] suggested combining higher speeds with lower temperatures to maintain structural uniformity. Further, G. Yang et al. [6] observed that, for 6061 aluminum alloy, increasing speed within a certain range improves surface quality (by weakening cold barriers and thinning the fine-grained zone), but exceeding a critical threshold leads to more severe cracks and surface defects. P. M. Nuckowski [23,24] showed that synergistic control of casting speed and cooling flow rate influences grain surface area (from 0.037 mm^2 at 30 mm/min to 0.1 mm^2 at 100 mm/min) and mechanical properties, with higher speeds reducing hardness but increasing elongation.

3.3. Modification Treatment in Aluminum Alloy Casting

Grain refinement of aluminum alloys through modification treatment is a key approach that involves adding modifiers or applying physical methods to regulate the solidification of the melt, thereby refining grains and optimizing the microstructure [25]. Current techniques can be broadly divided into two categories: physical methods and chemical methods. Physical methods include electromagnetic stirring, ultrasonic treatment, and severe plastic deformation, while chemical methods primarily involve introducing exogenous nucleation particles into the melt to promote grain refinement through heterogeneous nucleation [26]. Among available modification treatments, Al-Ti-B master alloys are the most widely used grain refiners. Z. Fan et al. [27] systematically investigated their mechanism, showing that the effectiveness of Al-5Ti-1B arises from a two-dimensional (112) Al_3Ti compound monolayer that forms on the surface of TiB_2 particles during preparation, which greatly enhances the heterogeneous nucleation ability of TiB_2. In addition, free Ti solute in the melt promotes the columnar-to-equiaxed transition via the growth restriction effect. J. Wannasin et al. [28] compared the effects of modification treatment (Al-Ti-B addition) and dynamic nucleation (GISS technology, which induces forced convection and localized cooling through gas injection) on A356 alloy. The study showed that dynamic nucleation generates a high density of secondary nuclei in the melt, significantly increasing the solid fraction and particle distribution density. When combined with modification treatment, a synergistic effect occurs, producing a finer and more uniformly dispersed equiaxed grain structure. This combined approach reduced the as-cast grain size from 114.2 μm in conventional casting to 32.9 μm.

Currently, most research on grain refinement of aluminum alloys focuses on traditional casting processes, while studies on horizontal direct chill casting—a highly efficient continuous forming process—remain limited. Because the solidification behavior in HDC differs fundamentally from conventional casting, the mechanisms and effectiveness of modifiers under these conditions require systematic review and deeper analysis. Therefore, it is essential to comprehensively summarize recent advances in modification treatments for aluminum alloys in HDC, in order to address theoretical gaps and provide a scientific basis for industrial applications.

3.3.1. Modifiers for Aluminum Alloy Casting

In studies on optimizing the microstructure and properties of HDC aluminum alloys using modifiers, J. Zhang [29] employed Fine-grained Structural Materials (FSM) with the same composition to improve HDC Al-Si alloys. The results showed significant refinement of the microstructure, elimination of shrinkage cavities, and improvement of mechanical properties. Later, J. Zhang et al. [30] reported that the amount of FSM added has a threshold effect. With 30% FSM, eutectic silicon transforms from coarse needle-like to fine rod-like, leading to simultaneous improvements in strength and elongation. However, when the FSM content increases to 50 %, eutectic silicon coarsens, causing a decline in performance (Figure 2(a)). Furthermore, J. Zhang et al. [31] found through microscopic analysis that the addition of 30 % FSM also induced crystal defects such as twins and stacking faults in eutectic silicon, further clarifying the correlation between microstructure and properties (Figures 2(b) and 2(c)). The introduction of other master alloys has also shown differentiated effects. M. Jabłoński et al. [32] added Fe and Si to HDC aluminum wire and found that Fe, combined with casting speed, refined grains and increased tensile strength, though at the cost of plasticity and electrical conductivity. Q. F. Zhu et al. [33] studied the effect of the Al-Ti-B grain refiner on the microstructure of 7075 aluminum alloy ingots in HDC. Their results showed that the addition of Al-Ti-B reduced grain size and modified grain morphology. However,

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the Al-5Ti-B refiner exhibits a refinement limit (about 120 μm) and refinement fading caused by TiB_2 particle sedimentation [34-36]. More importantly, in alloys containing elements such as Zr and Si, Al-Ti-B shows poor refinement efficiency and is prone to "poisoning" phenomena [37,38], restricting its use in high-performance alloys. To address these issues, current optimization of Al-Ti-B refiners focuses on three directions: (1) improving composition design through rare earth (RE) doping, (2) regulating second-phase distribution using external fields, and (3) optimizing particle dispersion through plastic deformation [26].

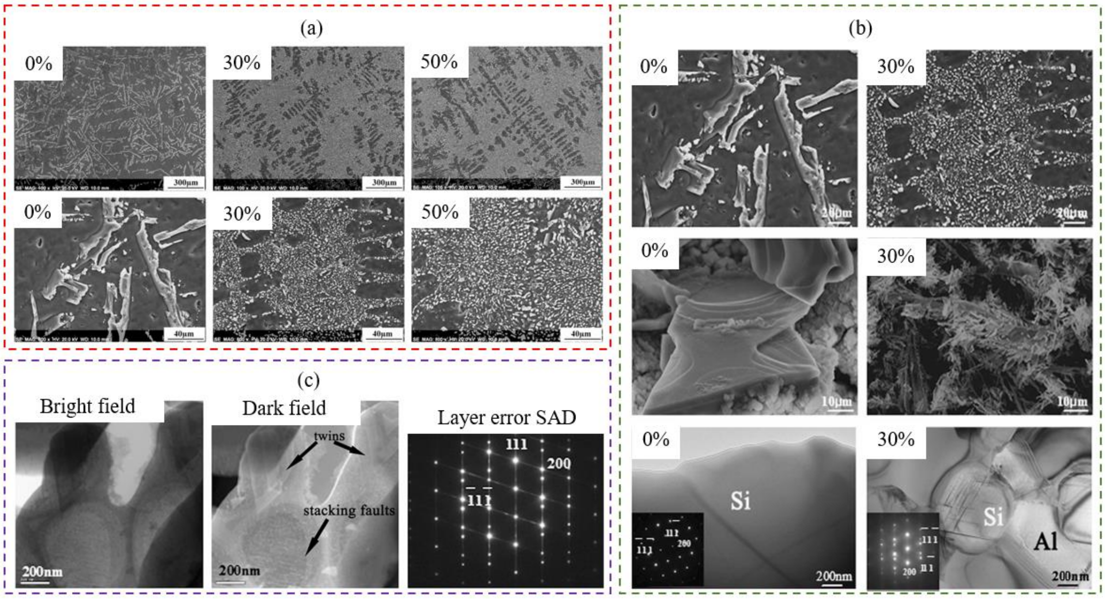

Figure 2. (a) Microstructure of HDC Al–12%Si alloy billets with different contents of fine-grained raw material[30]; (b) Microstructure of eutectic silicon in HDC Al–12%Si alloy; (c) Morphology of eutectic silicon and diffraction pattern of the modified Al-12%Si alloy with FSM intermediate alloy [31].

Overall, research indicates that the introduction of master alloys can significantly regulate the microstructure and properties of HDC aluminum alloys. However, the effectiveness is strongly dependent on the addition amount, process parameters, and alloy composition. For example, adding FSM in appropriate amounts optimizes the eutectic silicon morphology and mechanical properties of Al-12 % Si alloys, but excessive additions deteriorate performance. Similarly, while Fe and Si additions can refine grains, they create a trade-off between strength and plasticity. Meanwhile, the traditional Al-Ti-B refiner faces application bottlenecks due to refinement limits, particle sedimentation, and poisoning effects. Future breakthroughs will require multi-dimensional innovation in composition design, preparation processes, and post-treatment technologies to overcome these limitations and advance high-performance aluminum alloy continuous casting.

3.3.2. Electromagnetic casting technology

Electromagnetic casting is a cutting-edge process based on magnetohydrodynamics. Its core mechanism involves inducing a three-dimensional Lorentz force in the conductive melt using an alternating magnetic field, which drives controlled forced convection. This dynamic flow disrupts solute diffusion barriers during natural solidification, suppresses macroscopic segregation, and improves solidification structure by enhancing heat and mass transfer [39,40]. T. Wróbel et al. [41] systematically studied high-purity aluminum (99.5 %, 99.8 %) and AlSi2 alloys and found that a horizontal electromagnetic field powered by high-frequency current effectively refined the casting structures. However, the refinement effect of the horizontal magnetic field was weaker than that of grain refiners, likely due to reduced melt kinetic energy from insufficient electromagnetic stirring intensity. However, a major advantage of the horizontal magnetic fields is that they avoid competitive grain boundary adsorption by elements such as Ti, B, and Sr [42,43], for example, the antagonistic effect of Ti and Sr on eutectic silicon morphology. This provides a clean, pollution-free alternative for refining high-purity and component-sensitive alloys.

Traditional electromagnetic casting often requires complex processes and expensive equipment. To simplify and reduce costs, Z. H. Zhao et al. [44] developed a low-frequency electromagnetic casting method (LFEF), shown in Figure 3 (a). Their study on 7075 aluminum alloy demonstrated that LFEF effectively reduces surface defects and improves ingot microstructure. Further work [45] confirmed that LFEF enhances surface quality and reduces heterogeneous structures and segregation in HDC. Q. F. Zhu et al. [46] applied LFEF to 2024 aluminum alloy, showing that it reduced macroscopic segregation and produced a more uniform Cu distribution, as shown in Figure 3(b). Their subsequent research [47] revealed that LFEF promoted the transformation of ingots from columnar/plumes to equiaxed grains (Figure 3(c)). Similarly, L. Li et al. [48] studied the transitional structures of 7075 aluminum alloy after LFEF was turned off, finding that equiaxed grains transformed into columnar grains and then pinnate grains, with finer equiaxed grains forming a transition zone. Multiple twins were also observed between adjacent pinnate grains (Figure 3(d)).

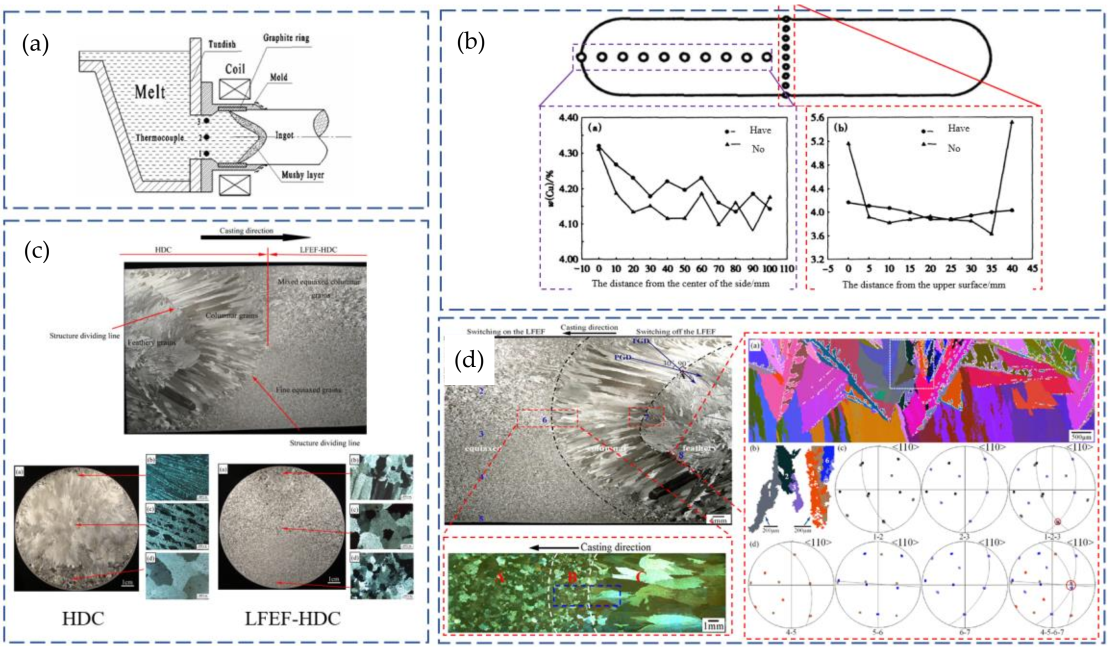

Figure 3. (a) Schematic diagram of low-frequency electromagnetic field horizontal direct chill casting[47]; (b) Cu distribution in a 2024 aluminum alloy flat ingot produced by horizontal direct chill casting [46]; (c) Microstructure of the ingot section [47]; (d) Microstructure of the ingot section in the low-frequency magnetic field transition zone [48].

With the continuous advancement of fundamental research on metal solidification, the traditional single-field regulation mode has gradually shown deficiencies in both the accuracy and uniformity of magnetic field distribution. To address this, researchers have begun to explore combined magnetic field technology, which applies multi-field synergy by breaking through the physical limitations of a single magnetic field through the spatio-temporal coupling design of electromagnetic parameters. The combined magnetic field is generated by two or more interacting electromagnetic fields using multiple excitation coils, which are then applied to the material preparation process. Its structure is shown in Figure 4(a) [49,50]. The main advantages are: (1) Full coverage: The affected area increases, with both the flow channel and the molten pool subjected to the magnetic field. (2) Intensity superposition: As magnetic field intensity increases, coil interactions enhance the intensity at each point. (3) Dynamic adjustability: By combining multiple coils, the axial length can be extended to form a traveling wave magnetic field. However, if the axial length of a single coil is too long, forced convection may not form in the center of the coil, reducing the stirring effect. Q. F. Zhu et al. [51] studied the evolution of the as-cast structure of 5182 aluminum alloy during HDC under the action of a combined magnetic field. The results

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showed that electromagnetic convection fully stirred the melt, enhanced heat and mass transfer, made the liquid cavities shallower, and effectively reduced temperature field differences caused by gravity. The as-cast structure also changed from a coarse, uneven columnar crystal structure under conventional conditions to a fine equiaxed structure. This research group later investigated the influence of the combined magnetic field on the surface quality and floating grains of 5182 aluminum alloy HDC ingots. The results indicated that the combined magnetic field reduced the thickness of the bottom subsurface segregation layer and significantly refined floating dendrites, as shown in Figure 4(b) [50]. Q.F. Zhu et al. [52] also verified the applicability of the combined magnetic field in 2024 aluminum alloy ingots. The refinement effect was evident, and coarse floating dendrites completely disappeared. Similarly, L. Li et al. [53] investigated the influence of the combined magnetic field on the microstructure of 3004 aluminum alloy ingots using crystallographic methods. The results showed that the combined magnetic field improved uneven cooling in HDC, producing smaller, more uniformly distributed grains. A transition zone of fine equiaxed grains also appeared when the electromagnetic field was turned off, as shown in Figure 4(c).

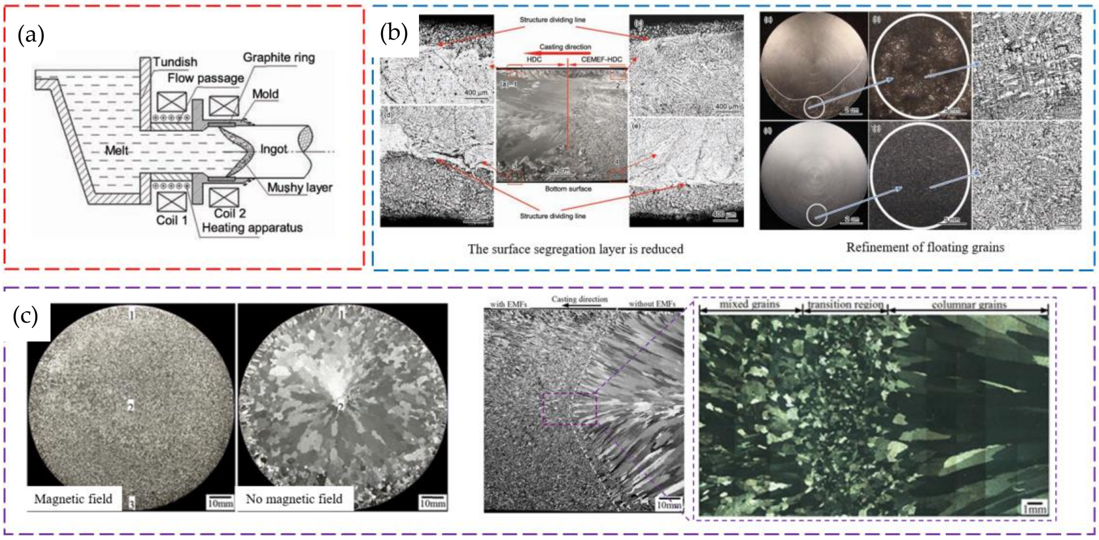

Figure 4. (a) Schematic diagram of the combined magnetic field [50]; (b) Surface structure of a 5182 aluminum alloy ingot produced by horizontal direct chill casting[50]; (c) Surface structure of a 3004 aluminum alloy ingot produced by horizontal direct chill casting [53].

In summary, electromagnetic casting technology has achieved full-chain optimization—from macroscopic segregation suppression to microstructure regulation—through the coupling of multiple physical fields, including magnetic, flow, and temperature fields. The LFEF, with its low cost and high compatibility, may become the core process for improving the surface quality of HDC aluminum alloys. The combined magnetic field technology further breaks through traditional refinement concepts by introducing multi-dimensional energy input, providing a new solution for refining the microstructure. Future research should focus on three key directions: (1) Multi-field coupling modeling: Establish quantitative relationships between magnetic field parameters (frequency, intensity, direction), melt flow state, and solidification structure, and develop intelligent regulation algorithms. (2) Dynamic defect control: Analyze the formation dynamics of defects such as twinning and stacking faults in the transition zone, and develop targeted elimination technologies. (3) Engineering adaptation: Design modular magnetic field generators for large ingots to address issues of limited penetration depth and high energy consumption. Through these advances, electromagnetic casting technology is expected to achieve large-scale application in areas such as integrated die-casting for new energy vehicles and lightweight components for spacecraft.

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3.3.3. Power ultrasonic technology

Power ultrasound, as an efficient external field intervention, has demonstrated distinctive physical and chemical regulation capabilities in material processing. Its mechanism of action arises from the multi-field coupling effects induced by ultrasonic waves propagating in a liquid medium. Specifically, the acoustic cavitation effect causes periodic collapse of micrometer-sized bubbles, the acoustic streaming effect drives macroscopic convection of the melt, and the combined mechanical, thermal, and chemical effects dynamically reconstruct the flow, pressure, and temperature fields [54,55].

In metal solidification engineering, ultrasonic treatment can significantly refine the solidification structure. X. P. Gao et al. [55,56] successfully applied power ultrasound to the HDC system, as shown in Figure 5(a), and quantitatively studied the solidification behavior of Al-1 wt.%Si billets. The results confirmed that power ultrasound increases the crystallization temperature interval of the alloy. When the ultrasound power was increased to 1000 W, the average grain size of the cast billet was refined from 94.1 μm in the reference state to 31.2 μm, representing a 66.8 % reduction. Additionally, solute solubility and distribution uniformity in the matrix were improved, while solute segregation was effectively inhibited, as shown in Figure 5(b) [57,58]. Similarly, X. W. Xie et Al. [59] investigated the synergistic mechanism of casting temperature (720 ℃), billet pulling speed (100 mm/min), and cooling water flow rate (40 L/h) under 1000 W ultrasonic power for HDC casting of Al-1 wt.%Si alloy. The results indicated that this combination produced billets with uniform, fine microstructures and optimal mechanical properties. Furthermore, X. T. Li et al. [60] confirmed the refining effect of ultrasound on billet solidification structures and clarified its mechanism. The study also reported that higher ultrasonic power not only refined the solidification structure but also suppressed Si grain boundary segregation. Theoretical analysis suggests that at an ultrasonic frequency of 22.3 kHz, the maximum cavitation bubble radius capable of sustaining cavitation is 1.02×10^{-4} m. As ultrasonic power increases, the number of cavitation bubbles increases. The collapse of these bubbles generates localized high temperature and pressure, thereby enhancing grain refinement and improving Si element distribution.

Overall, power ultrasound provides a precise physical pathway for regulating the solidification structure of metals through the collaborative mechanism of cavitation-acoustic flow-thermal effects. Research confirms its universal benefits in grain refinement, solute homogenization, and mechanical strengthening of Al-Si alloys. Establishing the process–structure–property relationship not only advances the manufacturing technology of bonding-line materials but also lays the foundation for the quantitative application of cavitation dynamics theory in solidification engineering. Future research should further explore the compatibility between ultrasonic parameters and multi-component alloy systems to broaden its large-scale application in horizontal direct chill casting.

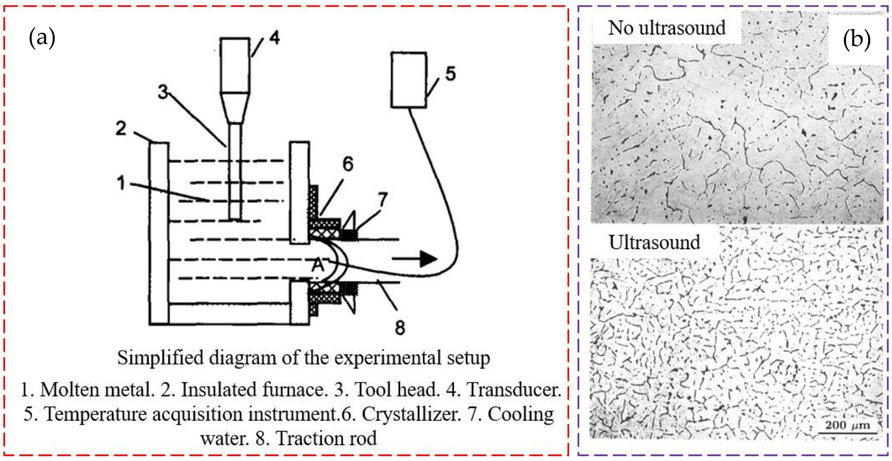

Figure 5. (a) Schematic diagram of power ultrasonic technology [55]; (b) Solidified structure of the casting billet before and after ultrasonic treatment [57].

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4. Conclusions

Aluminum alloy horizontal direct chill (HDC) casting technology has markedly enhanced ingot quality and production efficiency through innovations such as mold optimization, addition of FSM master alloy (30 % addition transforms eutectic silicon from needle-like to short rod-like), application of electromagnetic fields, and power ultrasound (1000 W reduces grain size by 66.8 %). Despite these advances, several challenges remain unresolved, including the performance limits of grain refiners, insufficient electromagnetic field energy, and microstructural inhomogeneity caused by uneven cooling. Future research should focus on developing multi-field coupled numerical models, novel rare-earth grain refiners and composite processing techniques, modular external field devices, and the integration of artificial intelligence for process parameter optimization. These efforts will accelerate the application of HDC technology in areas such as integrated die-casting for new energy vehicles and aerospace lightweighting, thereby supporting green manufacturing and sustainable development.

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