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# Research progress on semi-continuous casting of magnesium alloys under external field

**Qi-yu Liao**[2, 3], ***Qi-chi Le**[1], **Da-zhi Zhao**[2, 3], **Lei Bao**[1], **Tong Wang**[1], **and Yong-hui Jia**[4]
*1. Key Laboratory of Electromagnetic Processing of Materials, Ministry of Education, Northeastern University, Shenyang 110819, China*
*2. School of Materials Science and Engineering, Northeastern University, Shenyang 110819, China*
*3. Key Laboratory of Lightweight Structural Materials, Liaoning Province, Northeastern University, Shenyang 110819, China*
*4. Key Laboratory of Light-weight Materials, Nanjing Tech University, Nanjing 210009, China*

**Abstract:** High-performance magnesium alloys are moving towards a trend of being produced on a large scale and in an integrated manner. The foundational key to their successful production is the high-quality cast ingots. Magnesium alloys produced through the conventional semi-continuous casting process inevitably contain casting defects, which makes it challenging to manufacture high-quality ingots. The integration of external field assisted controlled solidification technology, which combines physical fields such as electromagnetic and ultrasonic fields with traditional semi-continuous casting processes, enables the production of high-quality magnesium alloy ingots characterized by a homogeneous microstructure and absence of cracks. This article mainly summarizes the technical principles of those external field assisted casting process. The focus is on elaborating the refinement mechanism of different types of electromagnetic fields, ultrasonic fields, and combined physical fields during the solidification of magnesium alloys. Finally, the development prospects of producing high-quality magnesium alloy ingots through semi-continuous casting under the external field were discussed.

**Keywords:** semi-continuous casting; electromagnetic field; ultrasonic field; magnesium alloys; refinement mechanism

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***Qi-chi Le**

Ph. D., Professor. His research interests mainly focus on casting and solidification, plastic deformation of magnesium alloys, and development of new wrought magnesium alloys. To date, he has published more than 400 peer-reviewed papers and has been granted more than 70 patents. He has hosted over 10 national projects, including the National 863 Program, the National 973 Program, the National Science and Technology Support Program, the National Key R&D Program, and the National Natural Science Foundation of China. He has won the second prize of National Science and Technology Progress Award and multiple provincial and ministerial level science and technology awards.

E-mail: qichil@mail.neu.edu.cn

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## 1 Introduction

Magnesium alloys are widely used in fields such as aerospace, national defense and military industry, and rail transit due to their advantages of low density, high specific strength, good damping, and good electromagnetic shielding [1]. At present, magnesium alloy structural components are increasingly developing towards large-scale, integrated, and lightweight. The stable production of high-quality and large-sized ingots is the key to improve the comprehensive performance of magnesium alloys.

Semi-continuous casting is an effective method for large-scale, efficient, and stable production of magnesium alloy ingots, which can effectively solve the problems of porosity, cracks, segregation, and low production efficiency caused by traditional casting [2]. Semi-continuous casting is also called direct cold casting (DC casting). It is currently the mainstream method for producing magnesium alloy ingots. Due to the characteristics of low heat capacity and low thermal conductivity of magnesium alloys, it is difficult to dissipate heat during the solidification process. The large temperature difference between the center and edge of the molten pool results in problems such as centre shrinkage, coarse and uneven microstructure, severe segregation, poor surface quality, large cutting amount, and serious tendency for solidification cracking [3]. With the improvement of product specifications and quality requirements, traditional DC casting technology as the main method for magnesium alloy billets can no longer meet the needs of fine-grained and homogeneous microstructure.

Applying physical field during the DC casting process can achieve the goals of degassing, refining grain size, and improving the mechanical properties of the ingot through vibration, such as mechanical stirring, electromagnetic stirring, ultrasonic treatment, etc [4]. Due to the impurities generated during the mechanical stirring process, electromagnetic stirring and ultrasonic treatment of magnesium alloy melt are currently commonly used in DC casting.

Research has shown that applying physical field during the solidification process, such as electromagnetic stirring, electromagnetic oscillation, ultrasonic treatment, electric pulse technology, etc., can significantly improve the solidification conditions of the melt, thereby achieving the goal of refining the microstructure and improving casting defects [5, 6]. This method mainly achieves the goals of degassing, refining grain size, improving ingot density and mechanical properties by introducing appropriate stirring or fluctuation during the solidification process of the melt. Le et al. [7, 8] from Northeastern University has conducted in-depth research on the solidification behavior of magnesium alloy ingots under external physical fields for over twenty years. The research has shown that applying different types of electromagnetic fields can effectively change the flow field and temperature field during the solidification process, achieve effective control of solidification cavities and mushy zone, and significantly refine the solidification structure, suppress macroscopic segregation, reduce cracking trends, and improve the surface quality of ingots. In addition, applying ultrasound during the solidification process can effectively change the nucleation and growth behaviors, significantly refine the solidification structure, and effectively remove gas, thereby improving formability and various properties including mechanical properties. At the same time, Le's team has harnessed the synergistic effects of ultrasound and electromagnetic fields to develop a magnesium alloy refining technology that combines ultrasonic and electromagnetic external fields [9-12]. An ultrasonic amplitude lever was inserted into the center of the melt to regulate the structure of the ingot center, and the electromagnetic field was applied to the edge area. The magnetic induction convection of the electromagnetic field expands the range of the ultrasonic field and achieves precise control of the solidification area of magnesium alloy melt through synergistic effects. By combining this technology with magnesium alloy DC casting, the fine and uniform microstructure of the entire ingot can be achieved.

This article summarizes the principles and latest research progress of magnesium alloy DC casting technology under external field, elucidates the mechanism of external field in the casting process, and looks forward to the development trend of external field assisted DC casting magnesium alloy.

# 2 Research on heat transfer behavior of magnesium alloy during DC casting process

## 2.1 DC casting process and solidification characteristics of magnesium alloy

Figure 1 shows the schematic diagram of the DC casting process for magnesium alloys. Before DC casting, the dummy bar device, including the dummy bar head, is lifted into the mold. Subsequently, the cooling water circulation system is activated. Following this, the molten magnesium is poured into the mold through the guide pipe. After the molten metal is cooled by the mold, also known as primary cooling, to form a solid shell billet and is then extracted from the bottom of the mold, cooling water is applied to the surface of the billet in either a spray or a film form, establishing secondary cooling. Ultimately, the solidified billet is completely submerged in water, further intensifying the cooling process. Secondary cooling can significantly reduce the depth of the molten pool, improve the solidification structure, increase the solidification rate of castings, and improve production efficiency. When the ingot reaches a certain length, casting process is terminated.

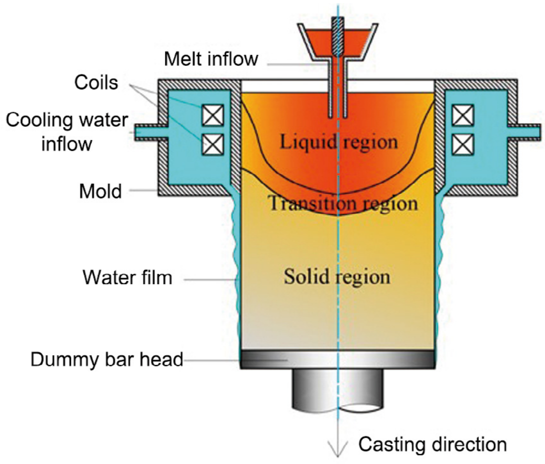


Fig. 1: Schematic diagram of DC casting of magnesium alloy [10]

Due to the characteristics of low heat capacity, low melting heat, and low thermal conductivity of magnesium alloys, it is difficult to dissipate heat during the solidification process, resulting in a faster initial solidification rate, wider overall solidification range, and larger thermal gradient in the DC casting process. This makes it more prone to segregation, cracking, and other casting defects. During the solidification process of magnesium alloys, there are three main regions with different characteristics, namely the liquid phase region, transition region, and solid phase region, as shown in Fig. 1. The transition region is a two-phase region where solid and liquid phases coexist.

## 2.2 Heat transfer during DC casting of magnesium alloy

The DC casting establishes a balance between the heat input into the casting crystallizer and the heat exported from the molten metal to produce the desired shape and quality of casting products. The casting crystallizer is essentially a strong heat exchanger, and its internal melt flow, heat transfer, solidification, and shell stress state are very complex. The heat transfer during the DC casting process of magnesium alloys mainly includes the heat exchange between the crystallizer wall and the initial shell and air gap formed by primary cooling of the melt, and the heat exchange between the billet and the cooling water after the ingots leaving the crystallizer (secondary cooling), as shown in Fig. 2(a) [8].

The heat exchange between the billet and the crystallizer wall is closely related to the formation of casting stress, and they interact with each other. As shown in Fig. 2(b), at the meniscus, due to the fast cooling rate, the metal melt quickly solidifies to form an initial solidified shell [13]. As the temperature decreases, shrinkage stress is generated inside the billet shell, causing it to detach from the crystallizer wall. This separation creates an air gap between the two interfaces, increases thermal resistance, slows down the growth rate of the solidified shell. At the same time, the continued export of melt heat and solidification latent heat in the liquid cavity causes the solidified shell to heat up again, reducing the cooling intensity. As the billet moves downwards, the gradually increasing static pressure of the melt will cause it to detach from the wall and press back against the crystallizer wall, reducing the air gap and potentially re-establishing contact [14]. For flat ingot casting, the corner areas of the crystallizer experience two-dimensional heat transfer, resulting in the fastest and earliest formation of the solidified shell. This contraction leads to the creation of air gaps that slow down heat transfer and delay the solidification process. As the condensation shell moves downwards, the air gap extends from the corner to the center. Due to the static pressure of the melt, the air gap at the center is smaller than that at the corner, resulting in the thinnest condensation shell at the corner. This uneven thickness of the condensation shell is often the main cause of cracks and leakage. The above process is repeated continuously until the condensation shell leaves the crystallizer. In summary, the heat transfer process of primary cooling is very complex and crucial, which directly determines whether the casting process can proceed smoothly.

Although the surface defects of DC casting billets are mainly affected by the solidification process of the melt in the crystallizer stage, when the secondary cooling is not ideal, these defects will continue to expand after the solidification shell leaves the crystallizer. For example, the thickness of the oxide layer on the surface of the billet is related to the strength of the secondary cooling, and weak cooling leads to excessively high surface temperature of the billet and intensifies oxidation. Strong cooling can lead to an increase in temperature gradient on the surface of the billet, increasing its sensitivity to cracking [15]. As shown in Fig. 3 [16], the heat transfer during the secondary cooling stage after the billet leaves the crystallizer includes four states: stable film boiling at high temperature (>350 °C), film boiling (150–350 °C), nucleate boiling (100–150 °C), and convective heat transfer (<100 °C) [16]. Under standard atmospheric pressure, there is no boiling below 100 °C, and heat dissipation only occurs through convection. Above this temperature, nucleate boiling occurs in the unwetted gaps on the surface of the billet, and steam bubbles nucleate. The release of these bubbles enhances the stirring of cooling water near the surface of the billet, leading to an increase in heat flux. If the water temperature is low enough to cause the bubbles to rupture, steam will not escape. As the surface temperature increases, the generation of more bubbles will increase the heat flux to the critical value. If the surface temperature of the casting billet is high enough, many steam bubbles will accumulate, forming an unstable steam layer that periodically collapses on the casting billet's surface. This process is known as unstable film boiling. During this process, the low thermal conductivity of the steam layer reduces the heat flux density. When the temperature is higher than the Leiden Frost temperature, the vapor layer tends to become completely stable and limits heat flow. During the stable casting process, most ingots exhibit unstable thin film boiling in the impact zone with a surface temperature of around 350 °C. However, the surface temperature of the billet will rapidly drop below the critical temperature and nucleate boiling will occur in the falling film. As the surface cools further, boiling ceases and only convective cooling occurs.

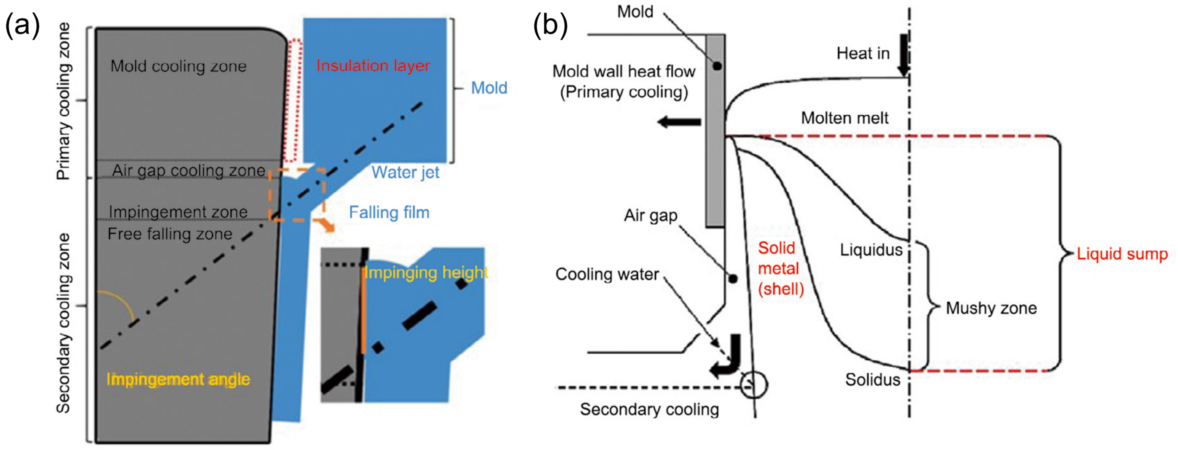


Fig. 2: Schematic illustration of primary cooling zone and secondary cooling zone (a) [8], and the cold shut at the corner of flat ingot (b) [13]

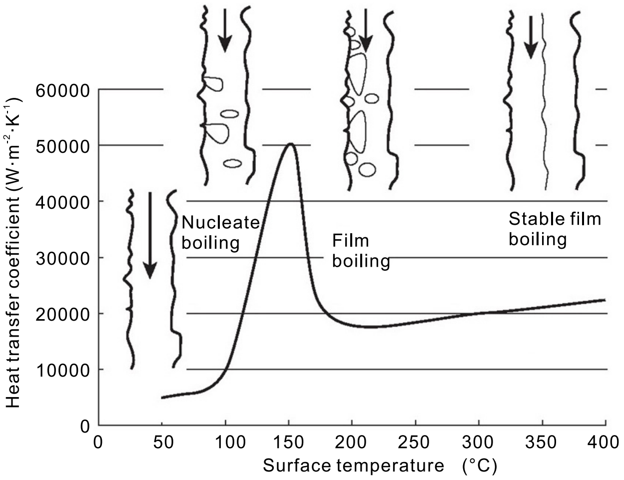


**Fig. 3: Schematic diagram of relationship between surface temperature of slab and heat transfer coefficient in the second cooling zone of semi-continuous casting [16]**

# 3 Application of external field in DC casting of magnesium alloy

## 3.1 Electromagnetic field

Electromagnetic DC casting is achieved by equipping an electromagnetic induction coil in the crystallizer and connecting it to an electromagnetic generating device, thereby generating electromagnetic force in the crystallizer and achieving stirring effect on the melt. Electromagnetic fields have the advantages of being clean and pollution-free, not changing the composition of the melt, significantly controlling the solidification structure, and significantly improving the surface quality of the ingot [17]. Therefore, research on the improvement of metal solidification structure by electromagnetic fields has been continuously developing and improving. At present, common types of magnetic fields include conventional vibration electromagnetic field (VMF), differential phase vibration electromagnetic field (DP-VMF), conventional low-frequency electromagnetic field (LFEF), and differential phase low-frequency electromagnetic field (DP-LFMF) [4]. Different forms of magnetic fields have different effects on metal melts, and their effects on solidification structures are also different.

The researchers found that the as-cast microstructure of magnesium alloys can be significantly refined by applying an electromagnetic field. Le et al. [18] found that the electromagnetic DC process can refine the microstructure, improve the grain size uniformity in cross-section of the magnesium alloy billet, and inhibit the generation of macroscopic segregation and cracks. Bao [19], Hu [20], Bai [21], and Guo [22] studied the effects of current intensity and frequency of low-frequency electromagnetic casting on electromagnetic field, heat transfer behavior, and solidification structure of magnesium alloys. The results showed that the forced convection of melt caused by LFEF could change the flow field and temperature field during solidification, realize effective regulation of solidification cavity and mushy zone, and thus significantly refine the solidification structure and inhibit macro-segregation. Guo et al. [23] found that under the action of low-frequency alternating magnetic field, the microstructure of the entire cross-section of AZ91 alloy transformed from columnar dendrites to equiaxed dendrites, thereby improving the hardness of the billet and reducing the trend of hot tearing. Jia et al. [24] experimentally investigated the effect of oscillating electromagnetic fields generated by low-frequency pulse currents on grain refinement and second phase formation in AZ31B magnesium alloy during DC casting. As shown in Fig. 4 [24], they found that the effect of grain refinement was significant after applying magnetic field, and the best effect was achieved at the frequency of 15 Hz. At the same time, the area fraction of eutectic $Al_8Mn_5$ phase gradually decreases from the center to the edge of the billet, and its distribution is more uniform under the action of electromotive force.

In recent years, the Le's team has further developed the magnetic field type of magnesium alloy electromagnetic DC casting and proposed differential pulse magnetic field (DPMF). Jia et al. [25] studied the effects of harmonic magnetic field (HMF), pulsed magnetic field (PMF), differential harmonic magnetic field (DHMF) and DPMF on liquid region and transition region by numerical simulation. They found that pulsed current generates a stronger magnetic field than harmonic current under the same conditions. Single coil magnetic field is easy to cause radial vibration of molten metal, and differential magnetic field not only causes radial vibration, but also produces axial convection. Wang et al. [26, 27] analyzed and compared the fluid flow and solidification characteristics under three conditions: conventional DC casting, PMF, and DPMF. It was found that under the action of DPMF, the z-component of the Lorentz force, the circulation area of the melt, the maximum velocity, and the fluctuation amplitude were the largest. Moreover, under DPMF, the temperature distribution of the melt was more uniform, the undercooling was higher, and the temperature gradient was smaller. Jia et al. [4, 28] used numerical simulation to study the melt flow, heat transfer, and solidification characteristics of AZ31 alloy under the same casting conditions under the action of DPMF and differential LFEF. It was found that differential magnetic field can effectively reduce the temperature of the melt in the liquid pool, and a shallow liquid pool depth can be obtained under the action of differential magnetic field. However, DPMF has both a larger velocity vibration amplitude and lower temperature, making the temperature distribution more uniform. In recent years, the Institute of Metals, Chinese Academy of Sciences has proposed the low voltage electric current pulses (LVECP) grain refinement method. It is found that LVECP fields have significant refining effects on AZ31, AZ91D, AZ80, AM60, AS31, and Mg-Gd-Y-Zr magnesium alloys [29-31].

In summary, different electromagnetic field technologies can achieve the effect of reducing macroscopic segregation and obtaining ingots with uniform microstructure and fine grains. Compared to traditional DC casting, electromagnetic casting produces high-quality ingots, smooth surfaces, and high density. Low-frequency electromagnetic casting possesses strong magnetic field penetration capabilities, induces significant liquid level disturbances, and offers an effective melt stirring effect. This method notably refines the grain structure and also enhances the crack resistance of the cast billet. However, when the size of the ingot is too large, due to the skin effect of the magnetic field, the electromagnetic force of the low-frequency electromagnetic field drives the convection and oscillation of the melt to be difficult to penetrate the center of the liquid cavity, and the electromagnetic stirring effect will be correspondingly weakened, resulting in limited control of heat transfer and solidification process. The DMF has a greater action depth than traditional electromagnetic fields, and shows great potential in refining the microstructure and suppressing columnar crystals in large-sized ingot casting. DMF is also good for small-sized ingot castings. The application of a differential pulse/low-frequency magnetic field can effectively reduce the temperature and cavity depth of the molten metal, allowing the metal melt in the crystallizer to simultaneously achieve larger velocity oscillations and a lower, more uniform temperature distribution.

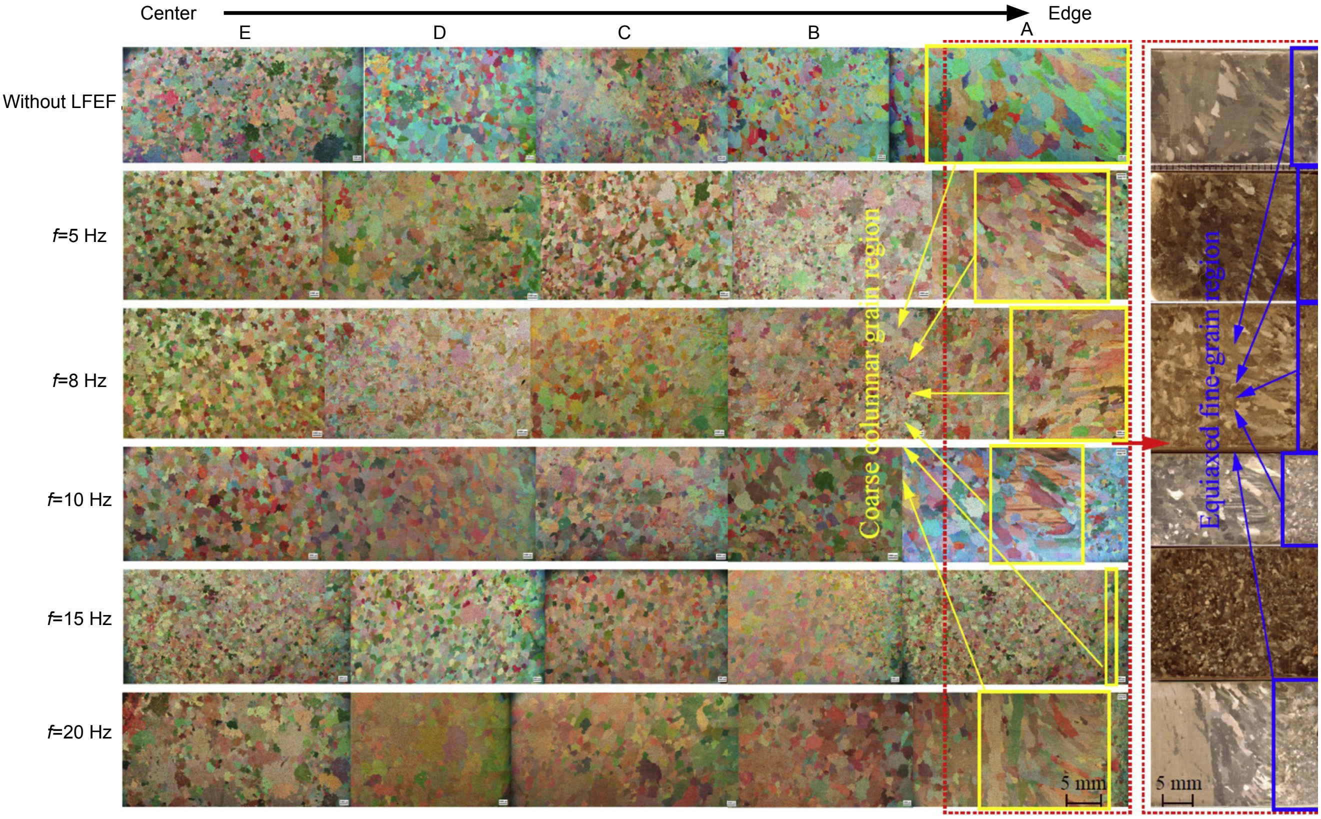


**Fig. 4: Macrostructures of DC casting AZ31B billet near the mold showing fine crystalline zone, at ~5 mm from edge showing coarse columnar crystal zone, coarse equiaxed grain region, and enlarged fine equiaxed grain area [24]**

## 3.2 Ultrasonic field

Applying power ultrasound to magnesium alloy melt can promote degassing, refine microstructure, and so on. It is generally believed that ultrasonic fields can refine the solidification structure of metals, because the cavitation effect and acoustic flow effect generated by the introduction of ultrasonic waves into the melt can change the solidification behavior of the melt [32]. As shown in Fig. 5 [33], when the ultrasonic wave propagates in the liquid, the liquid molecule will vibrate periodically under the action of the ultrasonic field, and there are positive and negative pressure zones in the medium. Liquid molecules in the positive and negative pressure regions are subjected to stress and form cavitation bubbles. The rapidly collapsing cavitation bubbles will instantly release the energy absorbed during the previous growth process, generating high temperature and pressure fluctuations in small local spaces. This series of dynamic processes is called ultrasonic cavitation. The acoustic flow effect refers to a macroscopic fluid flow phenomenon formed by the pressure gradient caused by amplitude attenuation during the propagation of ultrasonic waves. Sound flow is a mixture of circulation and turbulence, and this high-speed flow plays a crucial role in breaking the boundary layer, accelerating mass and heat transfer, promoting the dispersion distribution of fine particles, and accelerating interfacial reactions.

The refining effect of power ultrasound on the melt can be applied in the casting of magnesium alloys. Shao et al. [32] used ultrasonic treatment in AZ80 alloy melt with different intensities and found that as the ultrasonic intensity increased, the sound pressure increased and the grain size decreased. Aghayani et al. [34] found that ultrasound treatment has an impact on the size and sphericity of α-Mg dendrites, as well as the size, continuity, sphericity, and distribution of intermetallic particles formed during alloy cooling and solidification. Chen et al. [35] found that traditional single-frequency ultrasound has problems such as difficult resonance and serious attenuation in metal melt. On this basis, they developed a way to apply dual-frequency ultrasound combinations. They compared the as-cast microstructure and mechanical properties of ZK60 magnesium alloy melt treated by traditional single frequency ultrasonic field (SUF) and dual frequency ultrasonic field (DUF), and found that the as-cast microstructure was significantly refined after DUF treatment. Moreover, the yield strength, ultimate tensile strength and elongation after 1,400 W DUF treatment reached 153 MPa, 239 MPa and 13.9%, respectively, which were 20.5%, 20.7% and 30.0% higher than those after SUF treatment, as shown in Fig. 6. To clarify the effects of DUF and SUF on magnesium alloy melt, Chen et al. [36, 37] used numerical simulation methods to study the sound pressure distribution and related cavitation regions of single/dual frequency ultrasound fields in magnesium melt. It was found that compared with SUF, DUF weakened sound attenuation, thereby expanding the latent cavitation area and improving grain refinement efficiency. Chen et al. [33] further investigated the influence of ultrasonic flow field on the physical field of AZ80 magnesium alloy during DC casting process, and systematically discussed the effects of input sound pressure, insertion depth, and ultrasonic horn shape on the physical field. Compared with DC casting, ultrasonic casting exhibits a more turbulent melt flow, uniform temperature gradient, and shallower liquid pool, and has a significant grain refinement effect, as shown in Figs. 7 and 8.

Ultrasonic treatment has significant refining effect on the as-cast microstructure, which can lead to improvement in the mechanical properties, corrosion resistance, and other properties of the as-cast alloy. Hu et al. [38] studied the hot extrusion mechanical properties of the Mg-6Al-0.8Zn-2.0Sm alloy after ultrasonic treatment and found that the coarser $Al_2Sm$ phase in the alloy was in petal shape. However, after ultrasonic vibration treatment, the $Al_2Sm$ phase morphology changed to small particles, and the tensile strength increased by 15%. Lu et al. [39] found that ultrasonic vibration treatment can effectively modify $Al_2NiY$ phase into short flakes and distribute uniformly in the matrix, improving the mechanical properties of $Mg_{98}Y_{1.0}Ni_{0.5}Al_{0.5}$ alloy: the ultimate tensile strength and elongation of the alloy treated with ultrasonic vibration increased by 21.4% and 105.7%, respectively. Chen et al. [40] compared the deformation performance and behavior of as-cast AZ80 with and without ultrasonic processing during hot rolling using both experimental and numerical simulation methods. They found that this method can refine as-cast grains and improve the formability of AZ80 during subsequent deformation processes. Yin et al. [41] studied the corrosion resistance and mechanical properties of ZW61 treated with DUF and found that dense oxide film layer formed on the surface, which prevented the continuous penetration and corrosion of corrosive fluids on the substrate, and thus had a shielding effect on corrosion. At the same time, its grain refinement effect improved the mechanical properties of the alloy, as shown in Fig. 9.

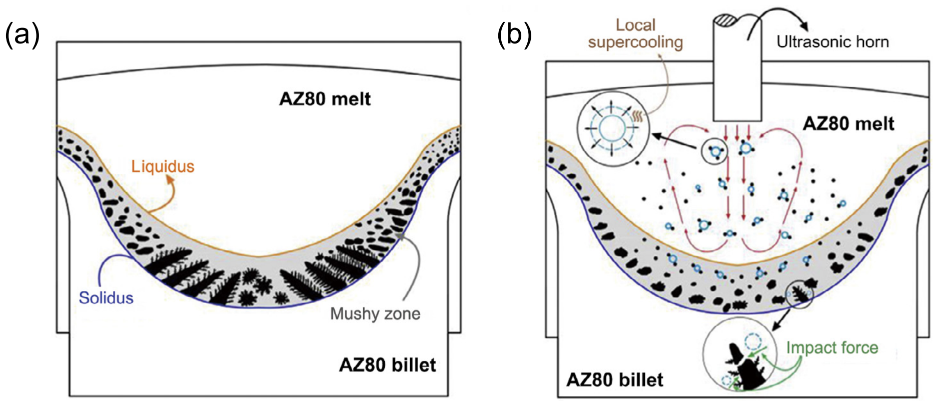
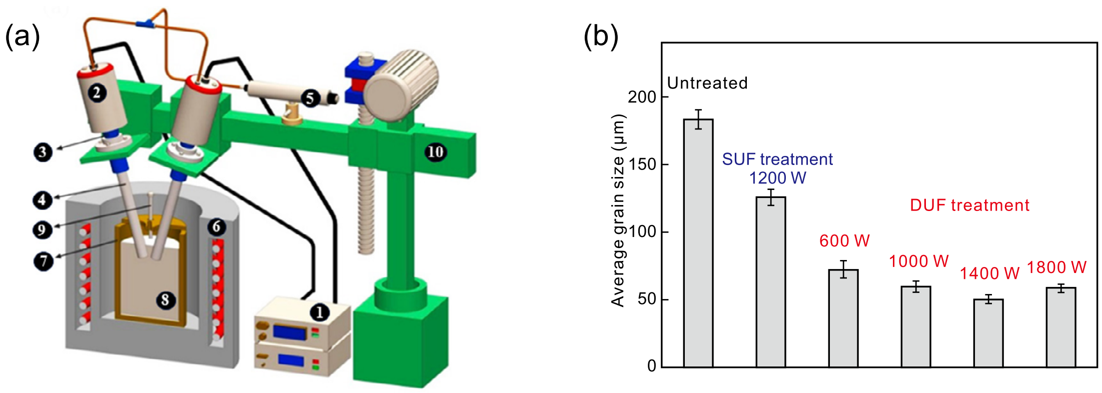


Fig. 5: Schematic diagram of ultrasonic cavitation and acoustic streaming [33]



1 - Ultrasonic power supply, 2 - Ultrasonic transducer, 3 - Acoustical wave-guide,
4 - Acoustic radiator/horn, 5 - Vortex tube cooler, 6 - Resistance furnace,
7 - Iron crucible, 8 - Magnesium melt, 9 - Thermocouple, 10 - Positioning device

Fig. 6: Schematic of the experimental set-up (a), and average grain size of as-cast ZK60 alloys with different ultrasonic treatment (b) [35]

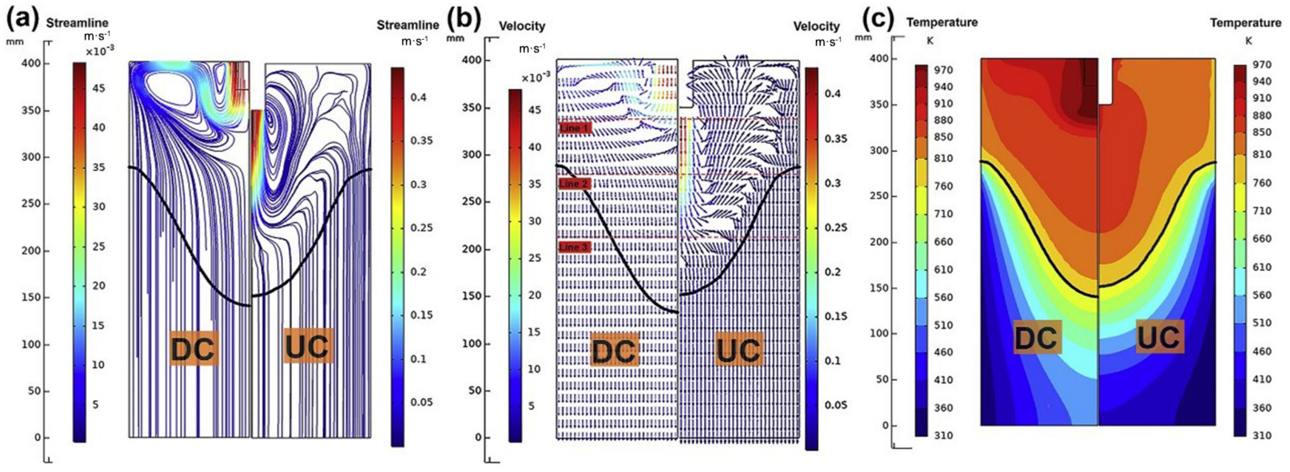


Fig. 7: Comparison between DC and UC in terms of streamline (a), velocity field (b), and temperature field (c) [36]

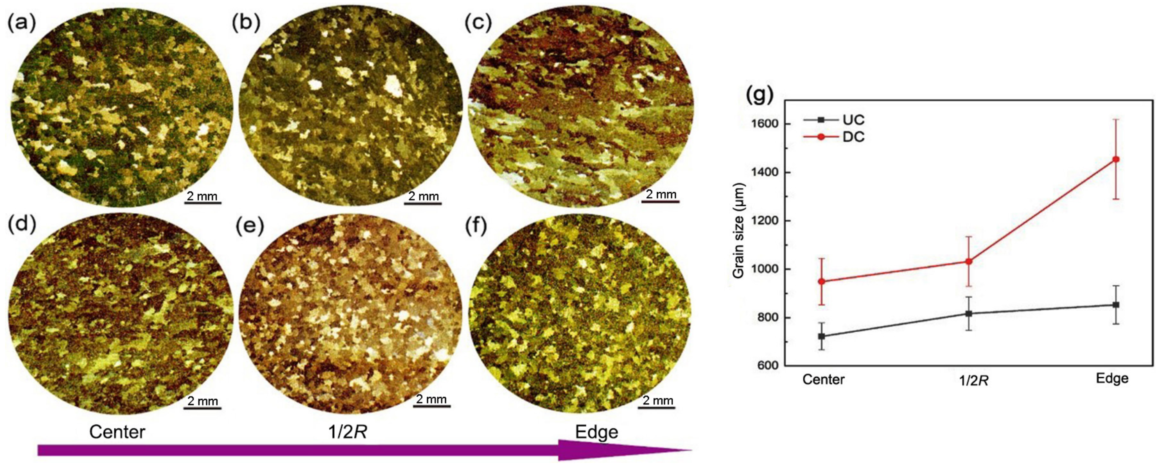


Fig. 8: Microstructure of AZ80 billet from center to edge: (a)–(c) for DC casting; (d)–(f) for UC casting; and (g) grain size [37]

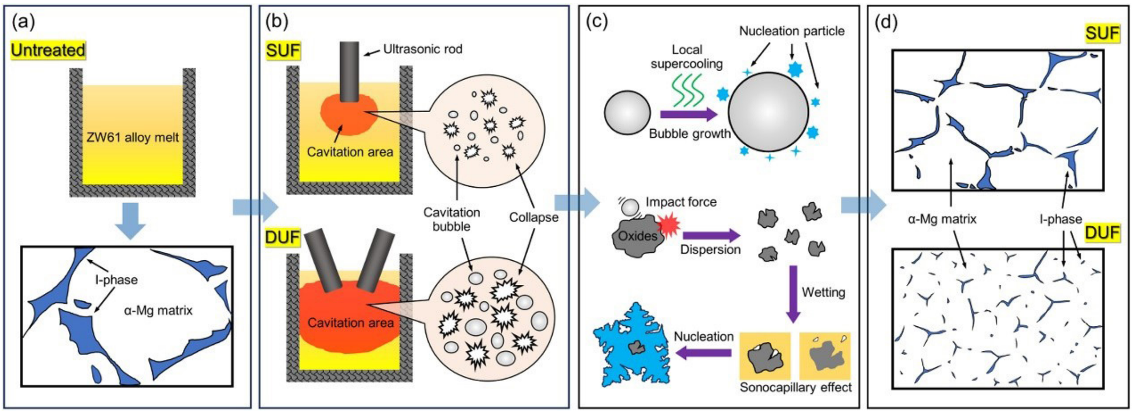
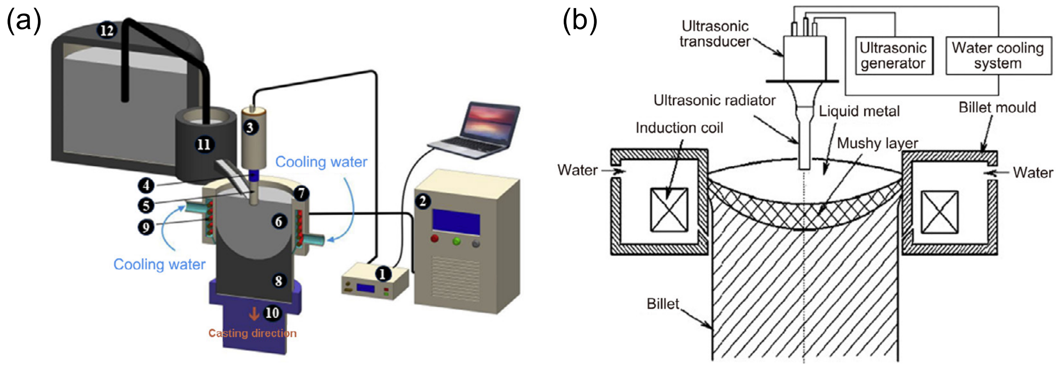


Fig. 9: Schematic illustration of refinement mechanism of ultrasonic vibration: (a) untreated ZW61 alloy; (b) acoustic cavitation of SUF and DUF; (c) local supercooling and heterogeneous nucleation; (d) microstructures with SUF and DUF treatments [41]

## 3.3 Combination of electromagnetic field and ultrasonic field

Due to that both electromagnetic field and ultrasonic field have refinement effect on DC casting magnesium alloys, the researchers applied the two external fields in the magnesium alloy melt at the same time to achieve a better refinement effect. Schematic of the experimental facility and process can be seen in Fig. 10. Cui et al. [42] developed a new DC casting process for electromagnetic ultrasonic (ECUS) castings, which significantly refined the ingot grains, made the overall grains more uniform, and improved the mechanical properties of the ingot. Shao et al. [43] found that during the low-frequency electromagnetic DC casting process of AZ80, simultaneous application of ultrasonic vibration to the melt resulted in significant refinement and uniform distribution of the as-cast macroscopic and microscopic structures, and ultimately improved mechanical properties.



1 - Ultrasonic power supply, 2 - Electromagnetic field control unit, 3 - Ultrasonic transducer, 4 - Acoustical wave-guide, 5 - Acoustic radiator/horn, 6 - Magnesium alloy melt, 7 - Crystalizer, 8 - Billet, 9 - Magnetic coil, 10 - Dummy bar, 11 - Tundish, 12 - Melting furnace

**Fig. 10: Schematic of experimental facility (a), and semi-continuous casting of AZ80 Mg alloy billets under electromagnetic and ultrasonic vibration condition (b) [41]**

Chen et al. [33] studied the effects of traditional fixed frequency ultrasonic field (FUF), LFEF, variable frequency ultrasonic field (VUF), and ultrasonic electromagnetic combination field (VUF+LEF) on the as-cast microstructure of AZ80 magnesium alloy. They found that the combination of ultrasonic and electromagnetic fields had the best refining effect and the grain size refined from 679–1,454 μm to 116–141 μm. Xiang et al. [44] found that ultrasound and electromagnetic fields significantly reduced the grain size in the casting and rolling zone, with the average grain size decreasing from 60–70 μm to 10–15 μm. The tensile strength, yield strength, elongation, and hardness increased by 25%, 44.4%, 120.7%, and 12%, respectively.

## 4 Summary and outlook

(1) Applying external fields during the semi-continuous casting process of magnesium alloys can significantly refine the microstructure, as well as achieve degassing and reduce segregation.

(2) The refinement effect of LFEF is remarkable, but the effect is mostly limited by the size of the ingot. For large-sized ingots, the refinement effect of DPMF on the entire domain is better.

(3) Applying DUF can significantly improve the refining ability of the as-cast microstructure and expand the refining range.

(4) Compared to applying electromagnetic or ultrasonic fields separately, the combination of electromagnetic and ultrasonic fields has the best refining effect on the as-cast microstructure of magnesium alloys.

(5) It is necessary to strengthen the basic research on the external field forming technology of magnesium alloys, and to conduct more in-depth research and exploration on the mechanism of microstructure refinement in physical fields, especially the influence mechanism of electromagnetic/ultrasound types on different solidification characteristics of magnesium alloys. Based on clarifying the refinement mechanism, new intelligent casting processes and equipment should be developed. This involves an in-depth exploration of multi-physical field numerical simulation technologies, combined with composite external field casting techniques, to obtain more optimized process parameters and casting methods.

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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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