

Article

Effect of Electromagnetic Power on the Microstructure and Properties of 2219 Aluminum Alloy in Electromagnetic Continuous Casting Technology

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Abstract: Electromagnetic continuous casting technology serves as a significant means for enhancing the casting performance of 2219 aluminum alloy. Investigating the influence of electromagnetic field variations on the solidification process is crucial for studying the microstructure and mechanical properties of electromagnetic cast billets. Through experimental research, variations in the microstructure and mechanical properties were examined for ordinary direct chill casting, as well as three different electromagnetic power casting ingots. The COMSOL software (COMSOL Multiphysics 6.0) was utilized to simulate the temperature and flow field, enabling an explanation of the resulting performance changes. The results showed the effect on electromagnetic continuous casting technology by the electromagnetic field generated by the Lorentz force and melt stirring, improving the melt flow and temperature distribution so that the melt center and the edge of the melt forcible convection were enhanced, thus realizing the tissue refinement, mechanical properties, and Cu element segregation of the improvement. With an increase in electromagnetic power, the distribution of the temperature field was more homogeneous, the segregation phenomenon was more alleviated, and the improvement in mechanical properties was more significant. The optimal microstructure and mechanical properties were achieved at a power of 20.0 kW, with a 74.7% improvement in grain refinement in the center and a tensile strength increase of 30.8%. Additionally, significant improvements were observed in segregation phenomena.

Keywords: electromagnetic continuous casting; 2219 aluminum alloy; COMSOL multiple; electromagnetic power



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1. Introduction

The 2xxx series of Al-alloys have gained significant recognition due to their remarkable high strength, excellent toughness, and impressive resistance to stress corrosion cracking, and have found extensive application within the aerospace sector [1–4]. As a typical 2xxx aluminum alloy, 2219 aluminum alloy can be used at temperatures ranging from 250 °C to 300 °C, and can be used as a welding structural material for launching rocket oxidizer tanks, skins, and structural components, as well as components of supersonic aircraft. Its unique combination of properties makes it invaluable in ensuring the structural integrity and performance of these aerospace components [5–8].

Direct cooling casting technology (DC) is a commonly employed method in the mass production of deformed aluminum ingots. Its appeal lies in its uncomplicated design and straightforward application [9]. However, during the direct chill (DC) process, several defects can arise as a result of the gradual cooling and solidification of the aluminum alloy melt. These defects include segregation, cold shuts, and hot cracks. These defects become more severe as the ingot size increases, which ultimately affects the processability and

strength of the ingots [10,11]. In the direct cooling casting process of 2219 aluminum alloy, there are defects such as the coarse second phase of Al_2Cu , poor grain uniformity, and macro-partitioning. In macro-partitioning, the main element that needs to be solved is Cu partitioning.

Numerous studies have shown that the use of electromagnetic stirring (EMS) in DC processes can solve the aforementioned problems [12,13]. Electromagnetic continuous casting technology has always been a very attractive method in aluminum alloy production. By applying an alternating magnetic field to generate Lorentz forces on the flowing melt [14], the liquid metal can be stirred during solidification under the action of Lorentz forces, resulting in denser and more uniform microstructures. This leads to effectively improving the mechanical properties and improving the segregation phenomenon. Wang et al. [15] conducted a study about the microstructure and solid solubility of 2A97 Al-Li alloys using electromagnetic casting. The findings demonstrated that the electromagnetic field led to remarkable microstructure refinement and solid solubility of the alloying elements within the grain boundaries. In addition, more T1 phases were obtained, resulting in improved mechanical properties. In a study conducted by Zhao et al. [16], the application of the internal electromagnetic stirring technique in 2219 aluminum alloy was investigated. The main focus of the study was to assess the impact of the stirring current and frequency on the homogeneity of the microstructure and macroscopic segregation in the ingot. Through their experiments, the researchers observed that the use of the internal electromagnetic stirring process during the solidification of the melt resulted in forced convection. This forced convection played a crucial role in reducing the average grain size and mitigating the formation of macro-segregation. Consequently, the billets prepared through this technique exhibited a finer and more uniform grain structure. During the semi-continuous casting process, Wang et al. [12] extensively studied the impact of an electromagnetic field on the segregation of 5A90 alloy ingots at both the microstructural and macroscopic levels. The findings emphasized the remarkable improvement in the microstructure of the ingots and the decrease in the width of the zone with columnar grains, which were successfully achieved using electromagnetic casting techniques. The above research results indicate the importance of investigating the variations in electromagnetic fields for the microstructure and mechanical properties of electromagnetically cast billets.

The electromagnetic continuous casting process mainly occurs through interaction with the melt to generate the Lorentz force, the Lorentz force of the shear drive, and the melt changing the flow mode, thus changing the temperature distribution, etc. The input power of the electromagnetic coil directly affects the distribution of the electromagnetic field, which influences the melt flow and temperature distribution. This is a key concern in the solidification process of alloys, which affects the solute distribution, solid-liquid interface, and microstructure of the alloy. However, detecting the flow and temperature distribution of molten metal in the DC process is challenging as a result of the molten metal's high temperature and opaqueness, making it arduous to conduct experimental analyses. Therefore, numerical simulation has become a viable alternative method [17]. Qiu et al. [18] conducted a simulation to investigate the influence of cooling intensity on the casting process in 2219 aluminum alloy using the internal electromagnetic stirring technique. The simulation results revealed that increasing the intercooling heat transfer coefficient expanded the affected region by intercooling. Similarly, Zhou et al. [19] performed a simulation study on the electromagnetic casting process of magnesium alloys. They examined the variations in molten metal shaping effects under different currents and found that the application of a magnetic field can reduce temperature gradients, significantly enhance molten metal flow, and mitigate the depth of liquid cavities.

Previous research on electromagnetic continuous casting has predominantly concentrated on the impact of casting speed, cooling intensity, and other experimental parameters on the microstructure and properties. However, there is limited understanding of how changes in the input power of the electromagnetic coil affect the flow of the melt and temperature distribution, subsequently influencing the distribution of solutes in the alloy,

the solid–liquid interface, and the morphology of the castings. This investigation primarily centers on examining how different electrical powers impact the microstructure and characteristics of 2219 Al-alloy, which has a 180 mm diameter. Additionally, we utilize the COMSOL software to examine the distribution of multiple physical fields under an intermediate-frequency electromagnetic field. By combining experimental and simulation approaches, our study aims to comprehensively explore the impact of temperature and flow field variations on the microstructure of the alloy.

2. Materials and Methods

2.1. Experimental

The alloy melting process was conducted using an AL-Q-1000 crucible resistance furnace (Shandong Aolang Energy Technology Co. Ltd., Weifang, China). Experimental 2219 aluminum alloys were produced from pure Al, Al-50Cu, Al-10Mn, Al-5V, Al-5Ti, and Al-5Zr, and Table 1 lists the chemical compositions of the 2219 aluminum alloys.

Table 1. Chemical composition of 2219 aluminum alloy (mass fraction, %).

Cu	Mn	Zr	Ti	V	Fe	Si	Mg	Zn	Al
5.80–6.80	0.20–0.40	0.10–0.25	0.02–0.10	0.05–0.15	≤0.30	≤0.20	≤0.02	≤0.10	Bal.

Figure 1a illustrates a schematic diagram of the continuous casting system utilizing electromagnetic technology. The smelting process involved preheating, slag skimming, stirring, and refining. After the refining process, the aluminum melt was poured into the launder through a downward flow pipe and entered the crystallizer, keeping the pouring temperature at 715 °C.

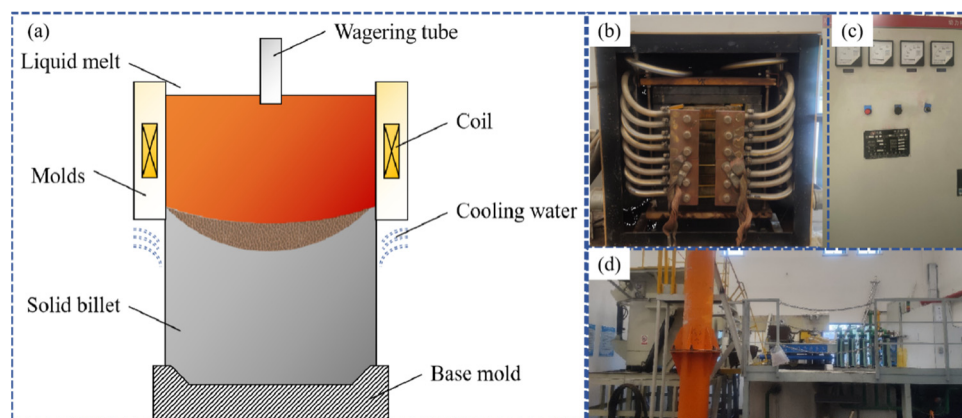


Figure 1. (a) Schematic representation of electromagnetic continuous casting system; (b) transformer; (c) intermediate frequency power cabinet; and (d) casting experiment platform.

The electromagnetic system consisted of a medium-frequency power and a transformer, as shown in Figure 1b–c. To provide the necessary electromagnetic power for the experiment, KGPS-120 medium-frequency power with an output frequency of 2500 Hz was used. During the experiment, 10.6 kW, 14.5 kW, and 20.0 kW output powers were selected to explore the impact of different electromagnetic powers. The base mold, made from 6061 aluminum alloy, was positioned within the induction coil in a way that its top surface aligned with the location of the maximum magnetic field intensity. The platform housing the bottom mold was moved vertically using a hydraulic system. When the partially suspended liquid column reached a certain height, the billet pulling mechanism was activated. This led to a stable phase where the elevation of the liquid column remained constant until the casting procedure was completed.

The positioning along the radial direction of the four plates, as depicted in Figure 2, involved extracting samples for a microstructural analysis and mechanical testing. The

specifications and sampling positions of the tensile specimens are shown in Figure 2. Three tensile specimens were taken at each position for testing. The samples were mechanically ground and polished to facilitate metallographic observation (400#, 800#, 1000#, 1200#, 1500#, 2000#, and 5000# grit sandpapers were used in sequence, followed by w1.0 size diamond polishing paste polishing). Subsequently, the specimens were polished and anodization was performed in 4 vol.% HBF_4 and 96 vol.% H_2O [20]. The metallographic structure was examined using a ZEISS- Axio Observer optical microscope (Carl Zeiss Management GmbH, Shanghai, China). The alloy composition was analyzed using an XRF-1800 X-ray fluorescence spectrometer (Shimadzu Corporation, Kyoto, Japan). The grain size was analyzed using the linear intercept method (ASTM E112-10) [21]. The precipitation phase was analyzed using scanning electron microscopy (SEM SU5000) (Hitachi, Ltd., Shanghai, China) and energy-dispersive spectroscopy (EDS) (Hitachi, Ltd., Shanghai, China). The tensile test used an electronic universal material testing machine UTM-5105 (Shenzhen Sansi Zongheng Technology Co., Ltd., Shenzhen, China) (room temperature), and the test speed was 0.5 mm/min.

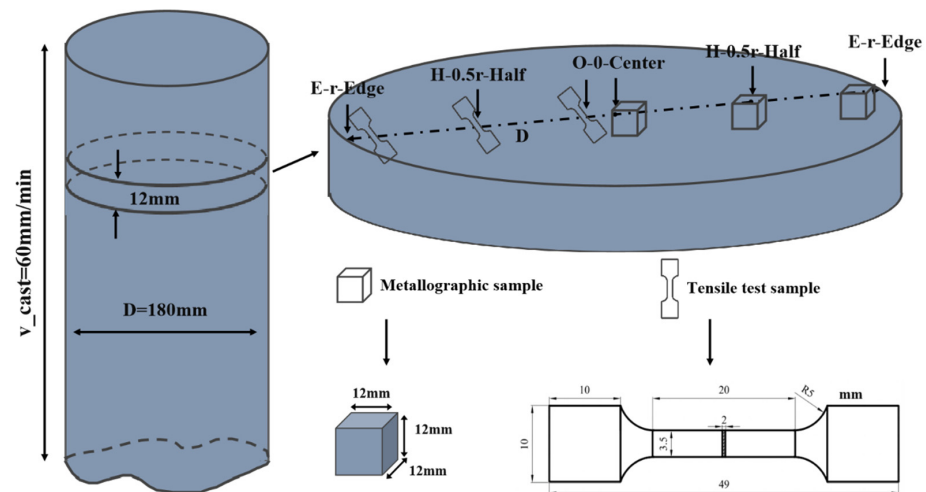


Figure 2. Sampling positions and dimensions.

2.2. Governing Equations

The geometric model and meshing of the simulation process are shown in Figure 3. To streamline the simulation process and minimize the computational requirements, a two-dimensional axisymmetric model was employed, with a more detailed mesh configuration in the boundary and corner areas. Several assumptions were taken into consideration: (1) the displacement current was not taken into account; (2) the impact of velocity fluctuations in the molten material on the distribution of the electromagnetic field was disregarded; (3) the 2219 aluminum alloy was treated as an incompressible fluid in a molten state; (4) all melts were assumed to be in a homogeneous state; and (5) the minimal magnitude of temperature changes caused by induced heat allowed them to be disregarded [22,23].

The simulation system included a combination of temperature, flow, and electromagnetic fields. Consequently, solving the subsequent governing equations became imperative:

The electromagnetic field is described by Maxwell's equations and Ohm's law, which are formulated as follows [24,25]:

$$\nabla \times H = J \quad (1)$$

$$\nabla \times B = 0 \quad (2)$$

$$\nabla \times E = \frac{\partial B}{\partial t} \quad (3)$$

$$J = \sigma E \quad (4)$$

where H , J , B , E , and σ are the magnetic field intensity, induced current density, magnetic induction intensity, electric field intensity, and electrical conductivity, respectively.

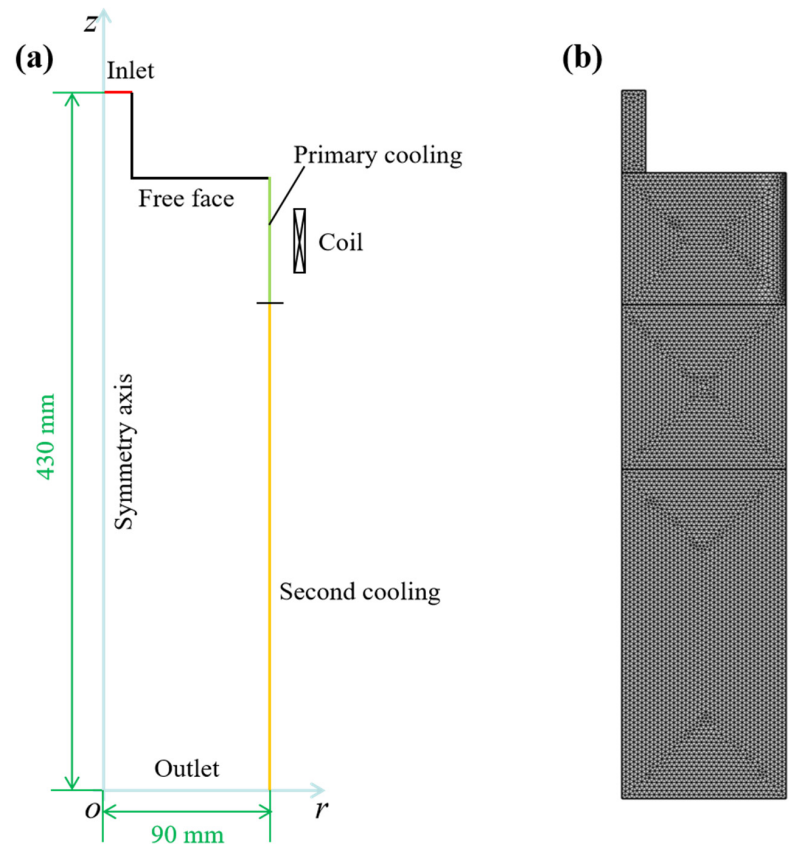


Figure 3. (a) Geometric model and (b) meshing of simulation process.

The Lorentz force can be calculated by the following relationship:

$$F = J \times B \quad (5)$$

In this research, the utilization of the “Continuum modeling” technique was implemented to solve the equations of the model [26]. The focus of this study was on employing a comprehensive collection of continuum equations, aiming to conserve mass, momentum, and energy within a system undergoing a solid–liquid phase transition. By adopting this methodology, the requirement to explicitly partition the region into distinct solid, liquid, and mushy zones was eliminated. As a result, the conservation equations can be expressed in the following manner:

Continuity equation [23]:

$$\nabla \cdot (\rho U) = 0 \quad (6)$$

Momentum equation:

$$\rho(U \cdot \nabla)U = \nabla \cdot (\mu_{eff} \nabla U) + \rho g + F + S - \nabla P \quad (7)$$

where ρ , U , μ_{eff} , g , F , S , and P represent the density, velocity, effective viscosity coefficient, gravitational acceleration, Lorentz force, source term generated by dendritic flow in the mushy zone, and pressure, respectively. Specifically, S is defined as follows [27]:

$$S = \frac{(1-f_L)^2}{(f_L^3 + \chi)^3} A_{mush} (U - U_{cast}) \quad (8)$$

$$f_L = \begin{cases} 0 & (T < T_S) \\ 1 - \frac{1}{1-k_p} \frac{T_L - T}{T_m - T} & (T_S < T < T_L) \\ 1 & (T > T_L) \end{cases} \quad (9)$$

$$f_S = 1 - f_L \quad (10)$$

where χ represents a minuscule value (making sure the denominator is not zero). A_{mush} , U_{cast} , f_L , and f_S denote the constants related to the mushy zone, casting velocity, liquid-phase fraction, and solid-phase fraction, respectively. k_p , T_S , T_L , and T_m represent the solute partition coefficient, solidus line, liquidus line, and melting point, respectively [18].

Energy equation:

$$\frac{\partial(\rho T)}{\partial t} + \rho C_p U \cdot T = \nabla \cdot (k \nabla T) + Q_h \quad (11)$$

where T , k , Q_h , and C_p represent the temperature, thermal conductivity, latent heat of solidification, and specific heat, respectively.

2.3. Boundary Conditions

Figure 3a illustrates the prescribed boundary conditions applied during the simulation process, where the secondary cooling, top, and mold surfaces were treated as immovable walls. To accommodate heat transfer conditions, the Cauchy boundary conditions were employed in the following manner:

$$k_{thermal} \frac{\partial T}{\partial n} = h(T - T_{ext}) \quad (12)$$

$$h = h_{mold} \times f_L + h_{air} \times f_S \quad (13)$$

where T_{ext} represents the ambient air temperature. The heat transfer coefficient, h , depends on the contact conditions and the solid-phase fraction. h_{mold} and h_{air} represent the heat transfer coefficients for contact and gas, respectively. The wall surface, in this case, functions as a moving boundary, progressing at the same speed as the withdrawal. The system employs a water curtain for cooling purposes, and the convective heat transfer coefficient is derived from the rate of the water flow used for cooling. This coefficient can be calculated using the equation provided [28]:

$$h_c = [-1.67 \times 10^5 + 357(T + T_{water})] Q^{\frac{1}{3}} \quad (14)$$

In this simulation, the axis of symmetry is represented by the central part. The physical parameters and initial conditions are presented in Table 2, considering the adiabatic boundary condition.

Table 2. Physical parameters used in this modeling.

Items	Value (unit)
Casting speed, U_{cast}	60 (mm/min)
Melting point of alloy, T_m	818 (K)
Environment temperature, T_{ext}	293 (K)
Cooling water temperature, T_{water}	293 (K)
Solidus temperature, T_S	787 (K)
Liquid temperature, T_L	916 (K)
Latent heat, dH	360 (KJ/kg)
Mushy zone constant, A_{mush}	105
χ	0.001
Heat transfer coefficient (primary cooling zone), h_{mold}	1500 (W/m ² ·K)
Heat transfer coefficient(air), h_{air}	50 (W/m ² ·K)

3. Results

3.1. Microstructure

Figure 4a–d present the polarized light micrographs of the 2219 aluminum alloy ingots produced by using different electromagnetic powers. It can be observed that the α -Al grain produced by direct chill casting was coarse petaloid. The coarseness was more pronounced at the center and 1/2r positions, while the α -Al grains at the edge had some equiaxial crystals present. Upon applying an electromagnetic power of 10.6 kW, there was more uniform grain distribution in three positions of the ingot, the coarse petaloid grains became smaller, and the equiaxed crystals at the edge increased. As the electromagnetic power increased, the petaloid grains in the ingot center and 1/2r position became finer and the quantity of equiaxed crystals at the edges increased. Figure 5 illustrates the average grain size at different positions. Overall, α -Al was refined after applying the electromagnetic field compared to direct cooling casting. Furthermore, as the electromagnetic power increased, the refinement effect on the ingot center and 1/2r position improved significantly. The center of the ingot was refined from 300.6 μm (without EM) to 194.2 μm (10.6 kW), 132.4 μm (14.5 kW), and 85.2 μm (20.0 kW). However, the tissue refinement effect on the edge region remained relatively unchanged. Table 3 presents the refinement rates for representative positions at different powers. The overall refinement rate exceeded 12%, with the best overall refinement effect observed at 20.0 kW, reaching 71.7% in the center.

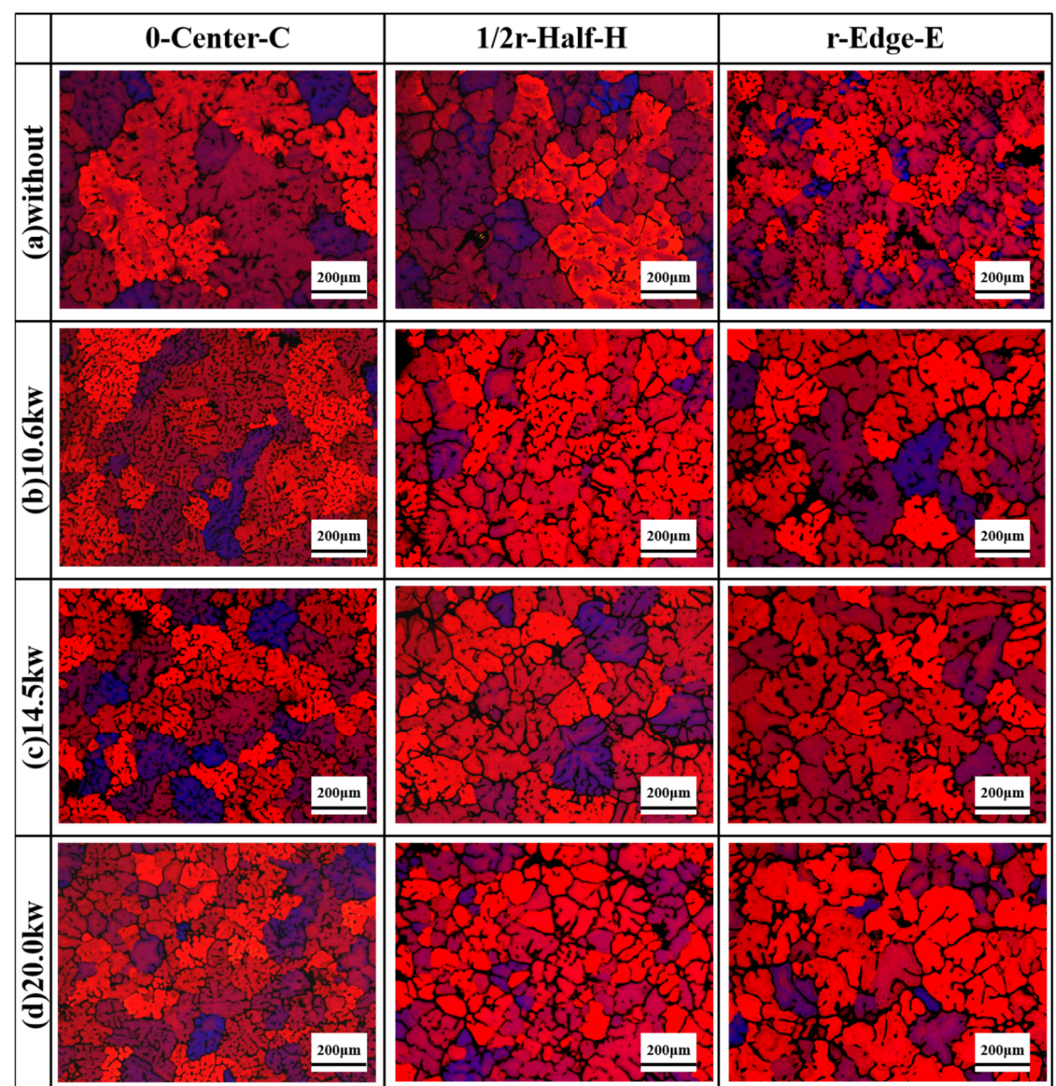


Figure 4. Polarized light metallograph images of 2219 aluminum alloy under different process.

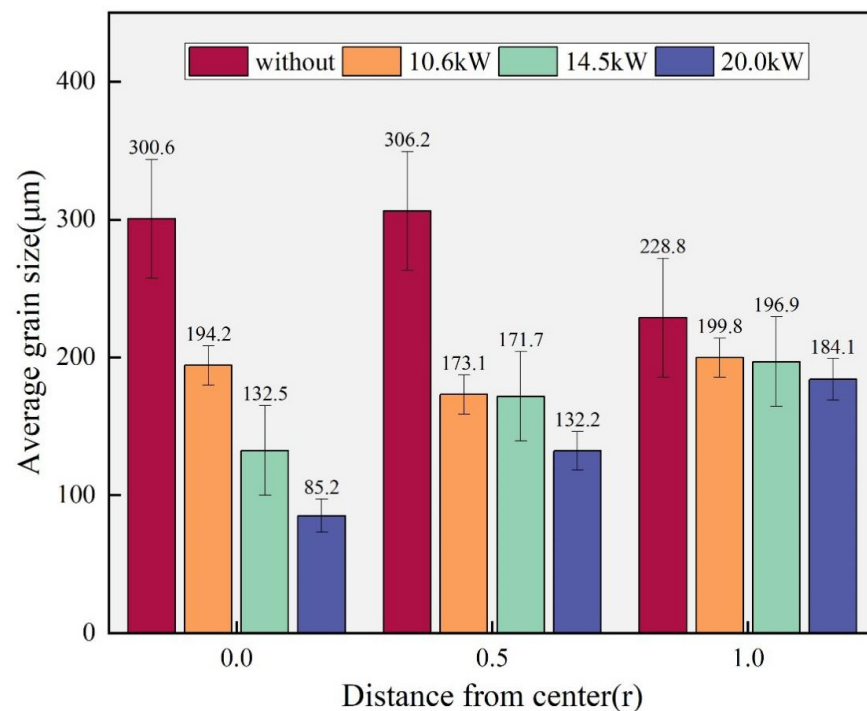


Figure 5. Average size of α -Al grain at specific sampling positions in 2219 ingots.

Table 3. Average size of the α -Al grains and refinement efficiency (RE).

Samples	Position					
	0	RE (%)	1/2r	RE (%)	r	RE (%)
Without (μm)	300.6	-	306.2	-	228.8	-
10.6 kW (μm)	194.2	35.4	173.1	43.5	199.8	12.7
14.5 kW (μm)	132.4	55.7	171.7	43.9	196.9	14.0
20.0 kW (μm)	85.2	71.7	132.2	56.8	184.1	19.5

3.2. Distribution Characteristic of Eutectic Phase

The phase diagram of the Al-Cu binary alloy exported from the Jmatpro software (Jmatpro-v13) is shown in Figure 6. It can be shown that the eutectic mainly comprised α -Al and θ -Al₂Cu [29]. Hence, an analysis of the copper distribution in the ingots becomes crucial. The parameter ΔP quantifies the copper's macroscopic segregation [30], and it is represented by the equation as follows:

$$\Delta P = \frac{C - \bar{C}}{\bar{C}} \quad (15)$$

The copper content at a specific testing location is represented by C , while the average copper content of the ingot is denoted by $\bar{C}$. This research defines ΔP as the representation of copper's macroscopic segregation along the radial ingot direction, as illustrated in Table 4. In conventional direct chill casting, positive segregation was observed at both the center and 1/2r positions, while negative segregation occurred at the edge. The Cu content was highest in the central region, with a significant ΔP value of 0.068, whereas it was lowest at the edge position, exhibiting a ΔP value of -0.128 . After applying the electromagnetic field, the degree of segregation decreased at each position. The reduction in segregation became more pronounced as the electromagnetic power increased. At 20.0 kW, the ΔP at the center was only 0.014, and a negative deviation of -0.007 occurred at the 1/2r position.

Figure 7 illustrates the microstructure of a cast 2219 aluminum alloy. According to the analysis of elemental distribution (Figure 7a), it can be determined that the precipitate phase was mainly composed of aluminum (Al) and copper (Cu). The results of point scanning

(Figure 7b) indicated that the ratio of Al to Cu was approximately 2:1. Furthermore, an XRD analysis of the 2219 aluminum alloy sample (as shown in Figure 7c) confirmed the presence of the Al₂Cu phase, which is consistent with the EDS results.

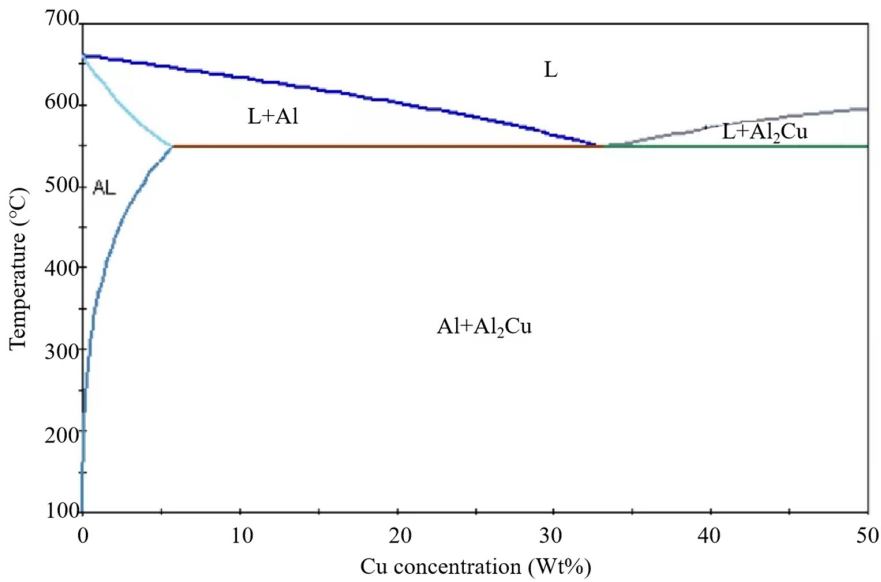


Figure 6. The phase diagram of the Al-Cu binary alloy.

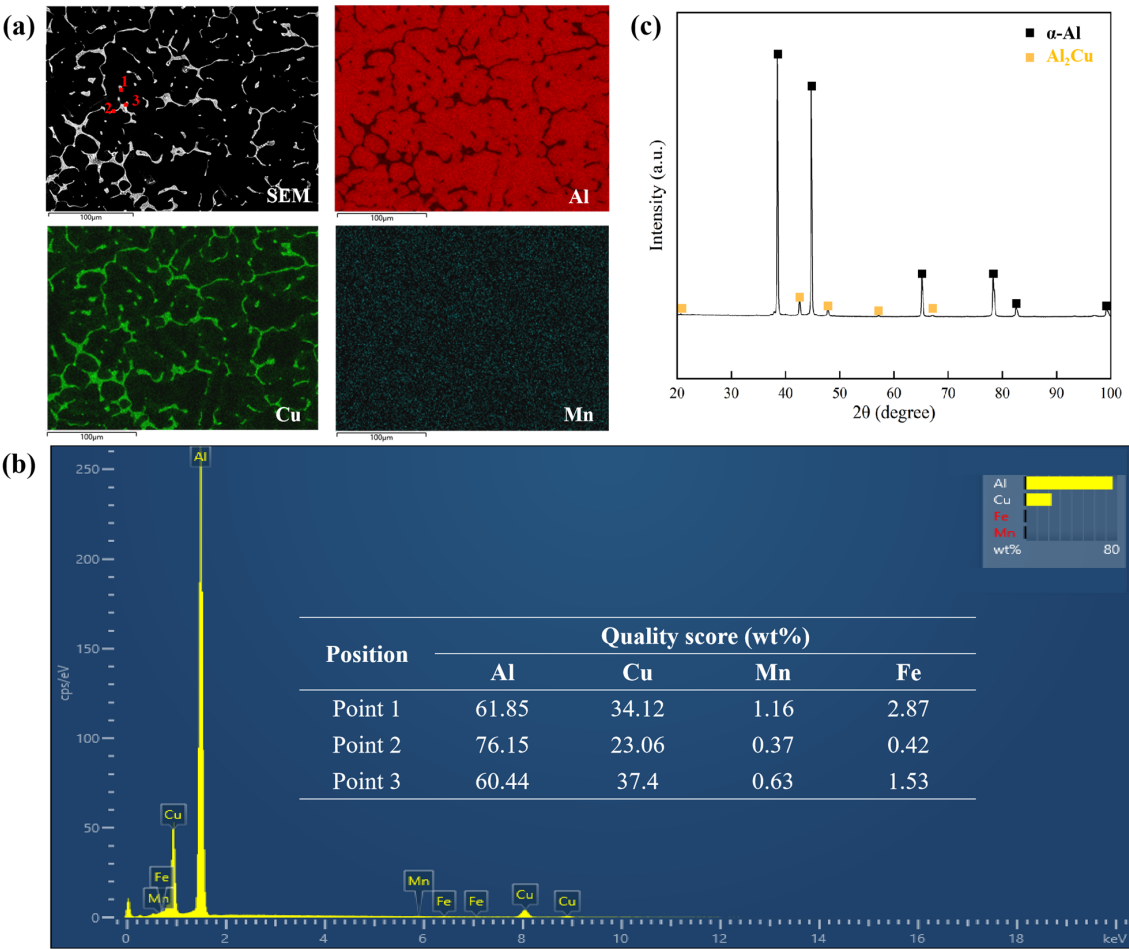
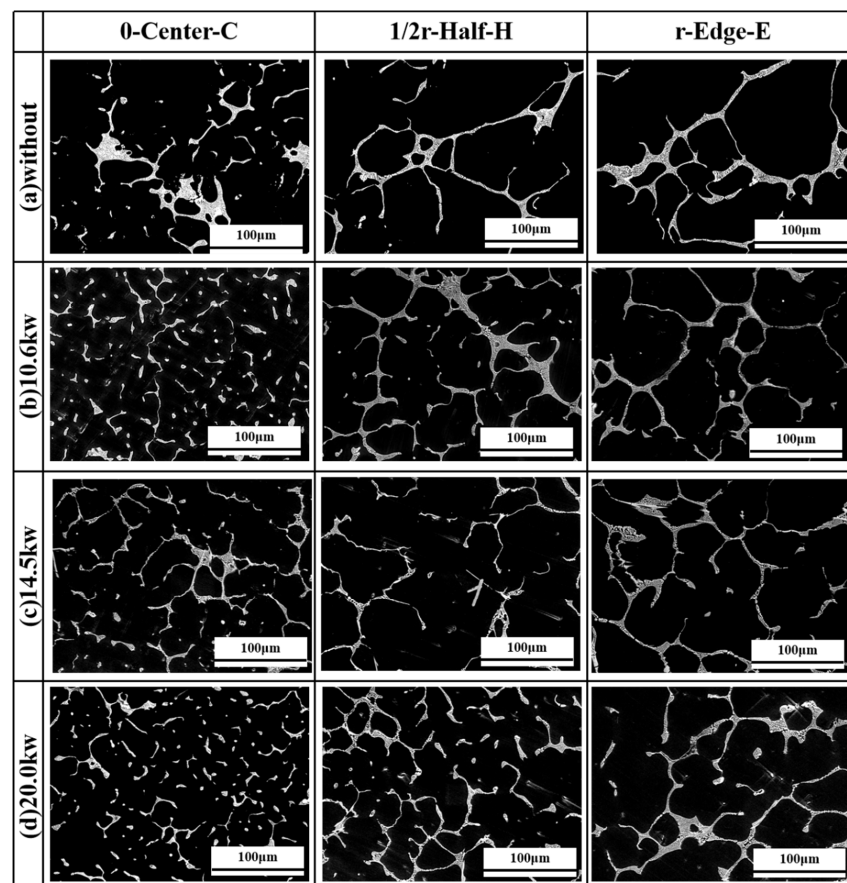


Figure 7. Microstructure of as-cast 2219 Al alloys: (a) grain size distribution map (Red dots 1, 2, 3 indicate the spot scan location), (b) XRD patterns, and (c) point scan.

Table 4. The macro-segregation indicator (ΔP) of Cu element at three specific positions.

	Position		
	0	1/2r	r
Without	0.068	0.059	−0.128
10.6 kW	0.024	0.022	−0.047
14.5 kW	0.017	0.010	−0.027
20.0 kW	0.014	−0.007	−0.008

In Figure 8a–d, the distribution and morphology of the eutectic phases in four types of ingots of α -Al and θ -Al₂Cu, as well as the θ -Al₂Cu particles, are illustrated in four ingots. It is apparent that the eutectic phase tended to aggregate along the grain boundaries of the α -Al. Additionally, the fine spherical θ -Al₂Cu precipitates were dispersed within the α -Al grains in the ingot. In the case of conventional direct chill casting, a coarse eutectic skeleton was observed at all three positions, with noticeable agglomerations. At the edges of the ingot, the second phase formed a finer continuous lattice. In the center, the grain was coarse and the secondary dendritic arms were well-developed. Upon applying the electromagnetic field, second-phase structural agglomeration was significantly reduced at each position, particularly at the center, where the continuity of the second-phase network was weakened. As the electromagnetic power increased, the thickness of the second-phase dendrites became finer and more uniformly distributed. It is important to note that the distribution of the second phase at the 1/2r position in the 10.6 kW ingot still exhibited a coarse network.

**Figure 8.** Distribution and morphology of eutectic phases in four types ingots.

3.3. Mechanical Properties

Figure 9a–c show the tensile strength, yield strength, and elongation measured by sampling from four ingots at three special positions. In the ingots without electromagnetic treatment, the tensile strength decreased from the center to the edge. The yield strength did

not vary significantly across the three positions. However, the elongation was highest in the center and only slightly different between the 1/2r and edge positions. When a 10.6 kW electromagnetic field was applied, both the tensile and yield strengths improved at all three positions. The elongation increased in the central and edge regions, with the highest enhancement observed in the central region (14.49%), but there was a slight decrease at the 1/2r position. The sample treated with a power of 14.5 kW exhibited a slightly higher tensile strength compared to the 10.6 kW sample. The yield strength increased significantly in the central and 1/2r positions, while the difference in the edge region was minimal compared to the 10.6 kW sample. It is worth noting that the elongation decreased at all three positions compared to the direct chilled ingot. Under a power of 20.0 kW, the ingot demonstrated a noteworthy enhancement in tensile strength at the central region. However, there was no significant variation in the yield strength among the three positions when compared to the 14.5 kW power level. On the other hand, the elongation improved at all three positions in comparison to the regular direct chilled ingot. Consequently, the tensile and yield strengths were enhanced by the electromagnetic field. With an increase in the electromagnetic power, the tensile strength in the center of the ingot rose from 189.6 MPa (without electromagnetic field) to 247.9 MPa (20.0 kW), marking a notable enhancement of 30.8%. Furthermore, the yield strength increased from 112.1 MPa (without electromagnetic field) to 164.4 MPa (20.0 kW), representing a significant improvement of 46.7%.

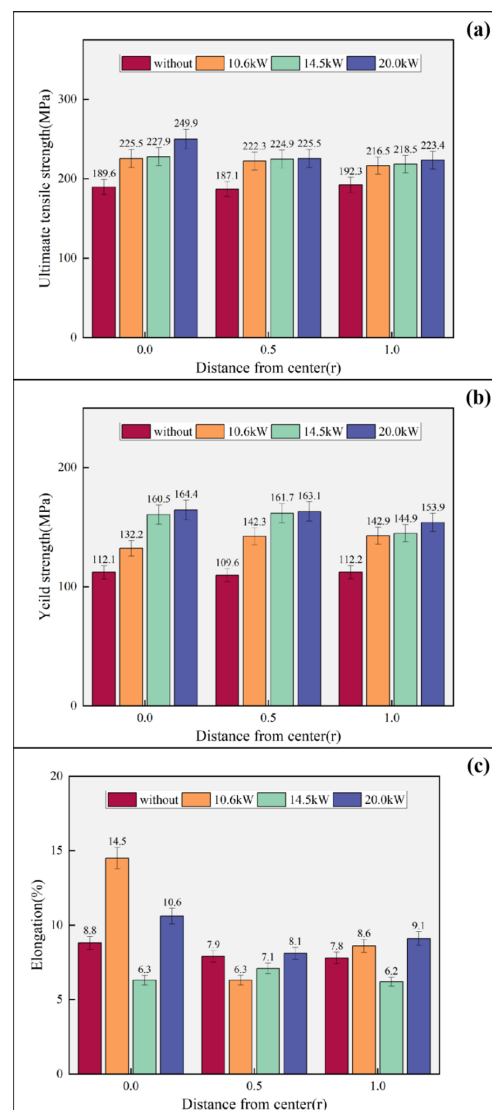


Figure 9. Mechanical properties of four ingots: (a) tensile strength, (b) yield strength, and (c) elongation.

4. Discussion

4.1. Effect of Physical Field on Grains

The strengthening mechanism of the electromagnetic continuous casting process has been studied extensively and widely [31,32]. A schematic diagram of the melt and mushy zone during electromagnetic continuous casting, demonstrating the strengthening mechanism of the electromagnetic field on the ingot structure, is shown in Figure 10. Firstly, the electromagnetic continuous casting process involves applying electromagnetic pressure to the melt, increasing the melting point and the supercooling. This leads to an increase in the solidification driving force and facilitates nucleation in the melt, leading to a more refined grain structure. Additionally, the interaction between the applied electromagnetic field and the melt causes Lorentz force stirring, which alters the trajectory of solute elements and leads to the phenomenon of a ‘magnetically dispersive’ distribution of the second phase [33]. This leads to the precipitation of the secondary phase on the grain boundary being reduced, leading to less thinning of the grain boundary. The solute element content within the grain increases while decreasing at the grain boundary [34]. Overall, as depicted in the lower right of Figure 10, the primary strengthening mechanisms of EMC can be attributed to dendrite breakage, heat exchange, outgassing, and enhanced mixing and stirring. This process leads to the elevation of energy, composition, and structure fluctuation, which aids in nucleation and homogenization, ultimately achieving the goals of grain refinement, the enhancement of mechanical properties, and a reduction in segregation.

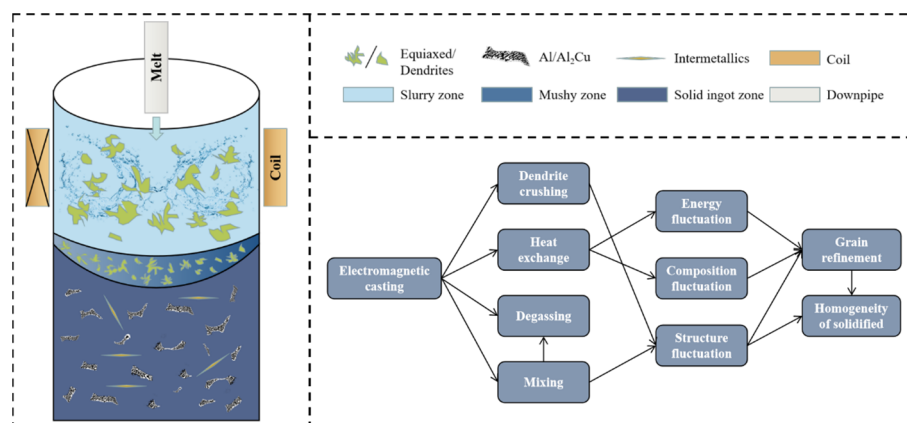


Figure 10. Schematic illustration of possible strengthening mechanisms during the 2219 aluminum alloy electromagnetic continuous casting process.

The simulation results presented in Figure 11 depict the temperature fields in four different ingots. Figure 11a shows that the temperature distribution is non-uniform, with a large temperature gradient from the center to the radius. At the edge, heat can rapidly transfer to the crystallizer and cooling water, leading to the rapid crystallization of α -Al grains and a higher nucleation rate due to significant undercooling. Consequently, partial equiaxed grains appear on the surface (at the edge position), while the core region exhibits higher temperatures. During the final solidification stage, due to the overlap of the dendrite network, the liquid phase between the dendrite arms struggles to flow. This leads to the accumulation of solute elements at the solid–liquid interface, causing supercooling of the composition, which leads to the rapid growth of dendritic crystals, the formation of well-developed dendritic crystals, and a significant increase in the grain size. The temperature distribution is more uniform, as evidenced by Figure 11b–d. The electromagnetic field accelerates the flow of the melt, leading to the production of a shear stirring vortex between the crystallizer and the melt in the liquid cavity. This vortex drives the high-temperature melt from the heart to the low-temperature region, enhancing convection heat transfer and creating a uniform temperature field. Thus, the temperature gradient is reduced and the non-uniform nucleation of the melt can continuously exist, leading to an improvement in the nucleation rate and the refinement of the microstructure.

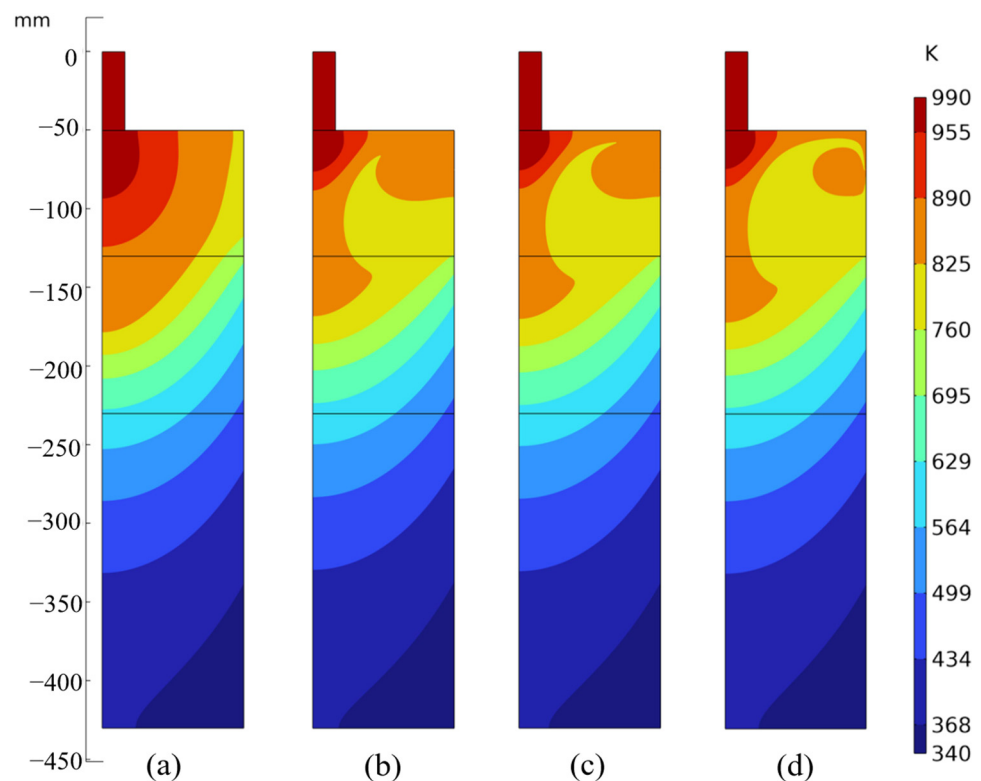


Figure 11. Temperature field results at the different electromagnetic power: (a) without, (b) 10.6 kW, (c) 14.5 kW, and (d) 20.0 kW.

The simulation results of the temperature distribution along the radial direction at the center position of the electromagnetic coil are shown in Figure 12. It can be seen that, without an electromagnetic field, the temperature decreased from 962 K at the center to 806 K at the edge, with a significant temperature gradient and a temperature difference of 156 K. After applying the electromagnetic field, it is evident that the temperature at the center significantly decreased, most notably at a 20.0 kW power, dropping to 871 K, with a decrease of 9.5%. The decrease in temperature at the center position improved the cooling rate. This increased cooling rate provided more suitable conditions for nucleation, resulting in a significant refinement of the grain structure in the center. The temperature gradient in the 0–20 mm region from the center was not significantly different from that of a conventional direct chilled ingot, but it decreased with an increase in the electromagnetic power, as the electromagnetic force was smaller at the center and increasing the power could expand the range of electromagnetic stirring. In the 20 mm to the edge region, the temperature curve leveled off, with the melt in this region mainly being subjected to electromagnetic stirring, resulting in a very uniform temperature distribution. In the 80 mm to 90 mm range, the temperature of the ingot in the electromagnetic continuous casting process was around 824 K, slightly higher than that of a conventional direct chilled ingot, explaining why there was not a significant difference in grain size at the edge under the four different processes.

Figure 13 displays the simulated results of the liquid-phase fraction for four types of ingots. It is evident that the implementation of an electromagnetic field accelerated the stirring caused by the Lorentz force, facilitating the exchange of molten material between the center and the edges. This process reduced the temperature gradients and the depth of liquid pools, causing low-temperature molten material to migrate towards the center and high-temperature molten material to migrate towards the edges. As a result, a more uniform temperature field was achieved within the molten material. Moreover, this stirring promoted thorough mixing of the components, leading to an improvement in the phenomenon of segregation. The increased dissipation of heat along the front

of solidification heightened the inclination for liquid undercooling, thereby triggering a substantial amount of crystal nucleation.

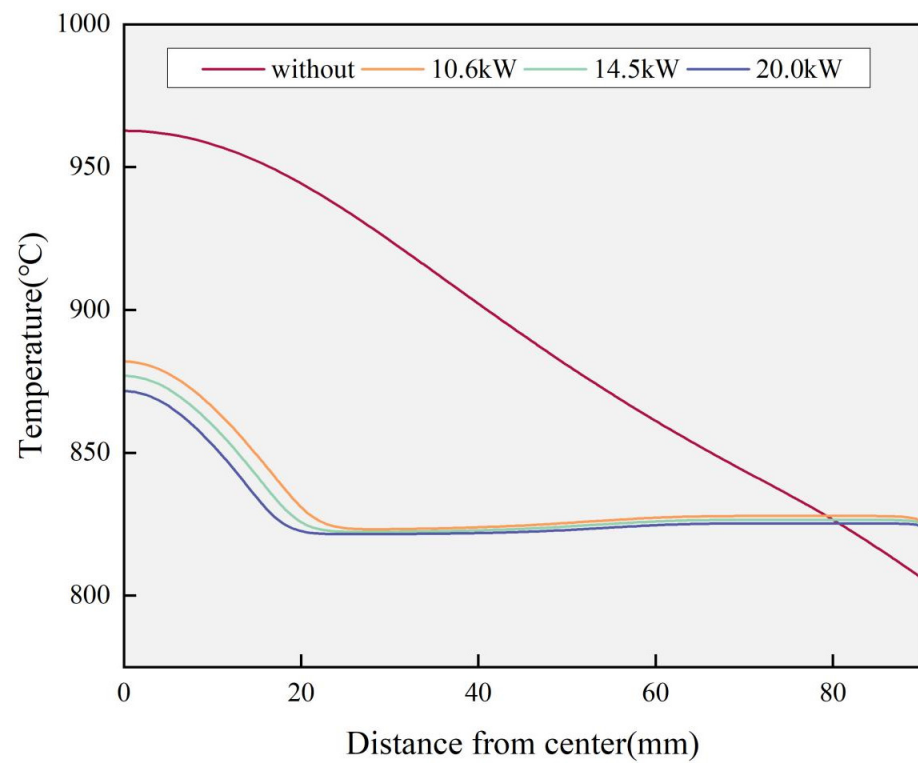


Figure 12. Simulation results of temperature distribution along the radial direction at the center of the coil.

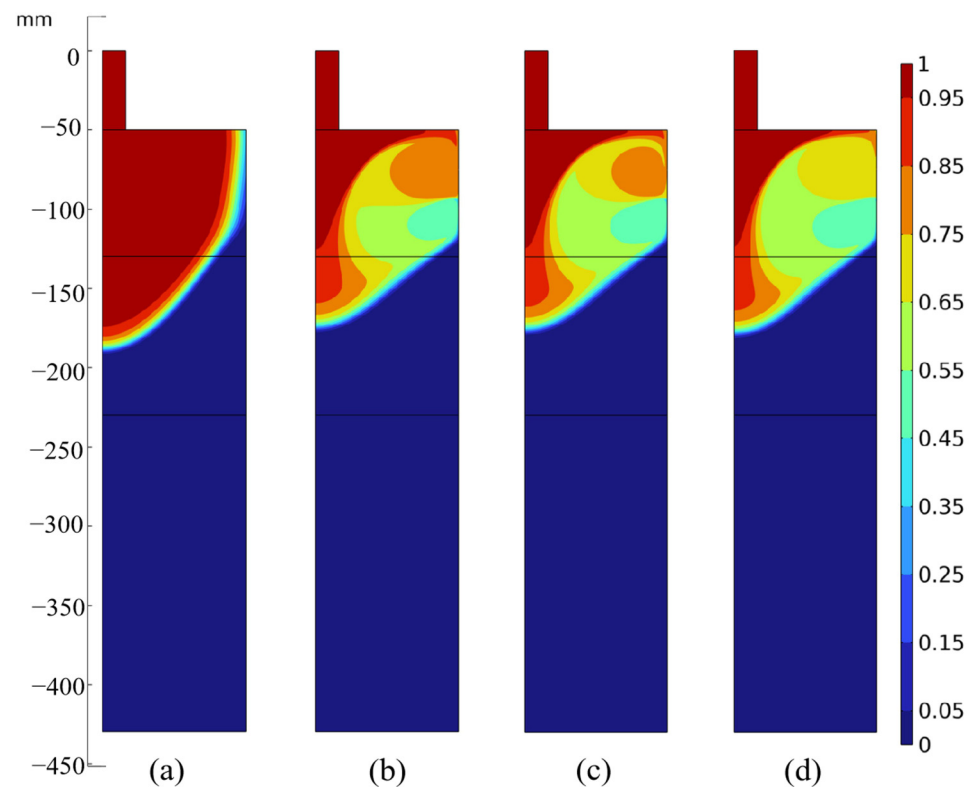


Figure 13. Liquid fraction at different electromagnetic power: (a) without, (b) 10.6 kW, (c) 14.5 kW, and (d) 20.0 kW.

Furthermore, the electromagnetic field helped to expel gases [15], reduce their interference in grain growth, and improve the fluidity of the liquid. At the same time, the fast flow of molten material along the solidification front prevented the growth of dendrites. Agitation can break up dendrites, and the dendrite fragments separate from the solidification front and enter the mushy zone with the flowing melt, forming crystal nuclei. The collision and friction of these nuclei promote the formation of equiaxed crystals. In sum, treatment with an electromagnetic field produced a fine and uniform microstructure in the cast ingots.

4.2. Effect of Physical Field on Eutectic Phase

In the solidification process of the 2219 Al-alloy, with the temperature decrease, an α -Al matrix was gradually formed, the solubility of Cu elements in the matrix decreased from the α -Al phase diffusion enriched outside the grain boundaries, and precipitated Al_2Cu and α -Al formed eutectic tissues after reaching the composition of Al_2Cu . Figure 14 displays the outcomes of the flow field simulation conducted on four various ingots. The liquid phase line is the red line, while the solid phase line is the green line. During the direct cooling casting process, solidification occurred first at the edge, and a deal of Cu elements were discharged at the liquid–solid front in the region of first solidification, resulting in solute enrichment in the post-solidified region of the heart, which explains the positive segregation in the heart, negative segregation phenomenon at the edge, and the formation of the coarsened second phase at the center.

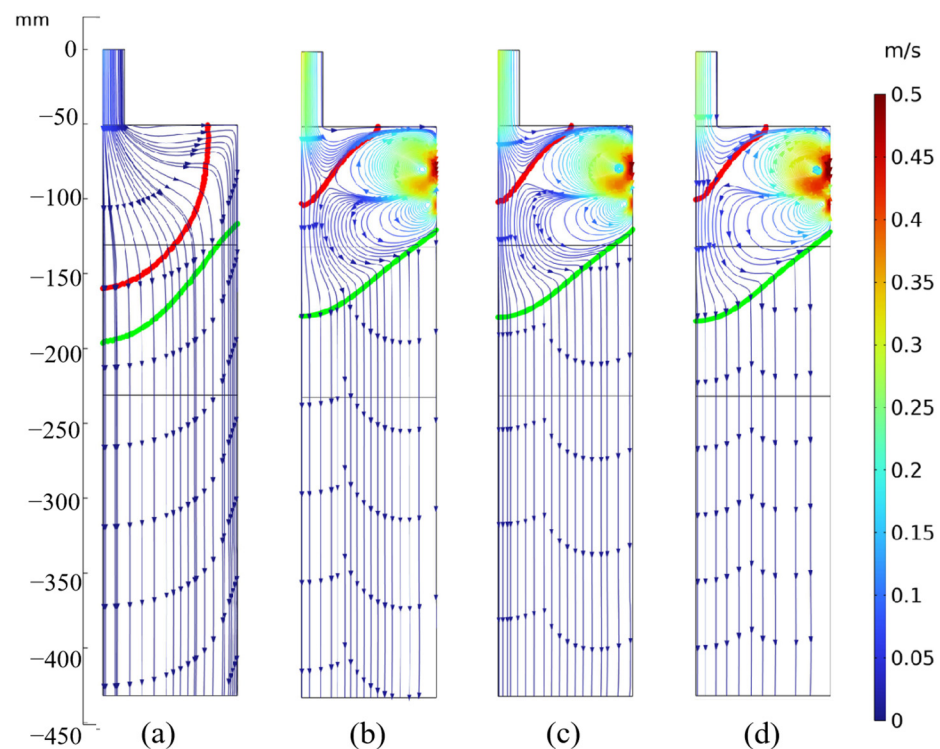


Figure 14. Flow field results at different electromagnetic power: (a) without, (b) 10.6 kW, (c) 14.5 kW, and (d) 20.0 kW. The solidus is represented by the green line and the liquidus is represented by the red line.

At the center of the ingots, the depth of the liquid channel in a conventional direct-chilled ingot was approximately 145 mm. After applying the electromagnetic field, the depth of the liquid channel decreased to 130 mm, 128 mm, and 127 mm with an increasing electromagnetic power, with a decrease in depth of more than 10% in all cases. The reduction in the liquid channel depth shortened the metal flow path, thereby altering the solidification rate and temperature gradient of the aluminum alloy casting. This led to a more

uniform distribution of the second phase, reducing local concentration differences and segregation phenomena [35]. At the same time, in conventional continuous casting, the solidus line had a steep slope, with a difference of approximately 80 mm between the edge and the center in the longitudinal direction. After applying an electromagnetic field, the solidus line became flatter, and the difference decreased to around 55 mm. This phenomenon provided favorable conditions for the formation of a homogeneous solidification structure.

In the process of electromagnetic continuous casting, α -Al grain refinement led to a reduction in the eutectic network area. The refined α -Al phase enhanced the number of boundaries between grains, thereby increasing the interface area. This allowed the eutectic phase to precipitate at multiple locations, resulting in a decrease in its continuity. Furthermore, according to the findings presented in Figure 13, the electromagnetic field application led to a more uniform distribution of solid contents in the melt, which aligns with the distribution of Cu elements shown in Table 4. The uniform distribution of the solute discouraged the formation of enlarged eutectic networks.

It is worth noting that, in this study, it was observed that there were still coarse eutectic networks present at the 1/2r position when a power of 10.6 kW was applied. This can be attributed to the relatively low input power of the electromagnetic field, which led to minimal energy changes and a weakened stirring effect on the melt. The ability to break down dendrites was diminished, and it was observed that the eutectic networks were coarser at the edges in comparison to the central region across all three power levels. This phenomenon can be explained by non-equilibrium solidification caused by the rapid cooling of the mold.

4.3. Effect of Physical Field on Mechanical Properties

Grain refinement is advantageous in augmenting material strength, as shown by the Hall–Petch formula (Equation (16)):

$$\sigma_s = \sigma_0 + Kd^{-0.5} \quad (16)$$

where σ_s represents the yield strength, σ_0 denotes the material constant, K stands for the Hall–Petch slope, and d represents the average grain size [36]. The refinement of alloys involves not only the refinement of primary phases, but also the morphology of intermetallic compounds or eutectic structures. Additionally, the use of an electromagnetic field during the metal solidification process can aid in the elimination of gases, leading to enhancements in mechanical properties.

The improvement in mechanical properties can depend on the redistribution of the solute and the quantity of eutectic precipitates. Solute redistribution is a result of the superposition of solid back-diffusion and solute micro-segregation. During the ordinary solidification process in casting, the solute redistribution path can lie between the solidus and liquidus lines. When electromagnetic power is applied during the solidification process, the phenomenon of back-diffusion is affected. Based on discussions among scholars [37,38], solute redistribution is the only measurable concentration. On the other hand, solute micro-segregation can only be theoretically calculated. Therefore, according to the definition of ΔP mentioned earlier, as the electromagnetic power increases, the value of ΔP decreases, indicating an increase in the back-diffusion parameter. The increase in the back-diffusion parameter should lead to a decrease in the quantity of eutectic precipitates. The reduction in eutectic precipitates, along with the uniformity brought about by the redistribution, contributes to the enhancement of mechanical properties.

Typically, strength and ductility are considered to be conflicting properties, and an increase in strength leads to a decrease in elongation. However, the refinement of grain size can simultaneously enhance both strength and ductility [39]. Therefore, the use of an electromagnetic field results in improvements in both tensile strength and yield strength. When comparing elongation, it was observed that the elongation at the 10.6 kW and 20.0 kW power levels was slightly higher compared to that of traditional direct chill casting. On the other hand, the decrease in elongation at the 14.5 kW power level was due to the

combined effect of reduced plasticity caused by increased strength and the influence of precipitated intermetallic compounds. Notably, in the central region at the 10.6 kW power level, there was a substantial increase in elongation. Further investigation is warranted.

In industrial production, electromagnetic continuous casting technology has advantages over traditional direct chill casting, such as an optimized crystal structure, reduced defects, and improved production efficiency. However, it also faces challenges including high equipment costs, technical complexity, and time-consuming process adjustments.

5. Conclusions

This study investigated the effects of different electromagnetic powers in electromagnetic continuous casting technology on the microstructure and mechanical properties of 2219 Al-alloy. The influence of temperature fields and flow fields was investigated through computational modeling. To summarize the key findings of this investigation:

- (1) An electromagnetic field can lead to a reduction in grain size when compared to traditional ingots. At the core position with a power of 20.0 kW, the maximum efficiency of grain refinement for α -Al grains was from 300.6 μm to 85.2 μm . Furthermore, the segregation phenomenon of the ingot showed significant improvement, with the segregation index ΔC not exceeding 0.014 at a power of 20.0 kW.
- (2) The mechanical properties of 2219 Al-alloy were significantly enhanced by the electromagnetic field. The optimal comprehensive mechanical performance of the ingot was achieved at a power level of 20.0 kW. The tensile strength, yield strength, and elongation at the center increased from 189.6 MPa to 249.9 MPa, 112.1 MPa to 164.4 MPa, and from 6.25% to 10.62%, respectively.
- (3) The distribution of the temperature field in the casting process was significantly influenced by the electromagnetic field. The field accelerated the exchange of heat between the central position and the edge, resulting in a reduction in the temperature gradient. Additionally, it helped in making the liquid cavities shallower. Moreover, the electromagnetic field was capable of enhancing the flow rate and increasing the distance between the solid–liquid interface, which ultimately led to an expansion of the paste zone. The Lorentz force generated by the electromagnetic field could drive the stirring of the paste zone, which was effective in crushing dendrites, promoting composition mixing, and improving the segregation phenomenon.
- (4) With an increase in electromagnetic power, the stirring of the melt increased and the melt sped up. This led to more thorough stirring of the melt at the center, further increasing the system energy and enhancing the strengthening effect. As a result, better organization and mechanical properties were obtained at 20.0 kW, and the segregation phenomenon was further improved.

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