

Research and Application of Grain Refining Technology in Casting Processes

Li Ma*

Xi'an Aeronautical Polytechnic Institute, Xi'an, 710089, China

*Corresponding author: mary830805@163.com

Abstract: Grain refining technology plays a significant role in enhancing the mechanical properties, improving material quality, and increasing the durability of castings during the casting process. This paper mainly discusses the theoretical foundation of grain refining, influencing factors, and its application in the casting process. The core mechanism of grain refining is to promote the formation of crystal nuclei and suppress excessive grain growth, thereby achieving precise control of grain size. Studies indicate that refining agents (such as rare earth elements, titanium, boron, etc.), cooling rate, and alloy composition are key factors that affect the grain refining effect. With the control of cooling rate, optimization of alloy composition, and the use of external refining agents, grain refining technology has been widely applied in the casting of materials such as aluminum alloys and steel alloys. In the future, with the development of new materials and intelligent manufacturing technologies, grain refining technology will play an even more crucial role in the production of high-performance castings.

Keywords: Grain refining; Casting process; Refining agents; Cooling rate; Alloy composition; Aluminum alloys; Steel alloys

Introduction

As one of the core technologies in casting processes, grain refining technology is crucial for improving the mechanical properties, fatigue resistance, and corrosion resistance of castings. By optimizing the grain size, it is possible to significantly enhance the strength and ductility of the castings, as well as improve their durability in harsh working environments. The study of grain refining has both important academic value and practical application prospects, especially in industries such as aerospace, automotive, and shipbuilding, where materials require superior comprehensive performance. Therefore, researching and optimizing grain refining technology is not only key to advancing casting processes and improving product quality but also provides strong technological support for the application of high-performance materials in the casting industry.

1. Theoretical Foundation and Development of Grain Refining

1.1 Physical Principles and Mechanisms of Grain Refining

The physical principles of grain refining are mainly related to the crystallization process of metals. In the casting process, when the liquid metal begins to solidify, the formation and growth of crystal nuclei determine the final grain size. The core mechanism of grain refining technology is to promote the generation of crystal nuclei and prevent excessive grain growth. In general, the more crystal nuclei present, the smaller the grain size. To achieve refining effects, it is necessary to introduce external refining agents, control the cooling rate, or optimize alloy composition during the casting process to precisely regulate the formation and growth of grains^[1].

From a physical perspective, grain refining mainly relies on the "nucleation" mechanism. Nucleation refers to the formation of crystal nuclei from small impurities, gas bubbles, or added substances in the liquid metal. When cooling conditions are appropriate, crystal nuclei proliferate, eventually forming a large number of small grains. Moreover, grain growth is influenced by factors such as temperature gradient, fluidity, and surface tension of the liquid metal. By controlling these factors, precise regulation of grain size can be achieved, thereby improving the mechanical properties of castings, especially enhancing their strength, plasticity, and fatigue life.

1.2 The Role and Influencing Factors of Grain Refining in the Casting Process

Grain refining significantly improves the performance of cast products. Smaller grains can enhance the material's strength, hardness, wear resistance, and ductility. According to the Hall-Petch relationship, refined grains can effectively hinder dislocation slip, thereby increasing tensile strength and yield strength. At the same time, fine grains improve the material's toughness and fatigue resistance, increasing the casting's crack resistance under dynamic loads.

The effect of grain refining is influenced not only by process parameters but also by the chemical composition of the alloy. The types and contents of alloying elements play an important role in the formation of crystal nuclei. For example, elements such as titanium, niobium, and boron can promote the formation of crystal nuclei, thus achieving refinement. Cooling rate is another key factor: a faster cooling rate is beneficial for nucleation, but care must be taken to avoid the formation of hot cracks. The addition of refining agents, such as rare earth elements, can further promote the nucleation process and improve the refinement effect.

In addition, the casting's geometric shape, pouring method, and the materials and temperature of the molds also affect the grain refining effect. Therefore, in practical production, it is necessary to optimize the process parameters and material ratios comprehensively to achieve the best grain refinement effect.

1.3 Current Research Status of Grain Refining Technology

Research on grain refining technology has evolved from empirical exploration to a more theoretical and systematic approach. Currently, the addition of rare earth elements and other trace elements has made significant progress in grain refining, being widely applied to materials such as aluminum alloys, magnesium alloys, and iron alloys. Rare earth elements, through the formation of powerful nucleating agents, significantly enhance the grain refining effect of casting alloys, thus improving the mechanical properties of castings. Furthermore, the use of composite refining agents is more advantageous than single refining agents, as their synergistic effects further optimize the refining process. Control of cooling rate is also an important method for refining technology. Researchers, by optimizing pouring temperature, mold design, and cooling medium selection, can effectively adjust the cooling rate and avoid casting defects such as cracks caused by excessively fast cooling^[2].

With the development of computer simulation technology, the simulation of thermal fields, stress fields, and microstructural evolution during the casting process has gradually become an important research direction. Numerical simulation technology can predict the formation and development of grains under different process conditions, providing theoretical guidance to optimize casting processes. Although significant progress has been made in grain refining technology, how to balance refining effects with factors such as casting fluidity, integrity, and cost remains a subject that requires further research. With the development of new materials and technologies, grain refining technology will play an increasingly important role in the casting industry.

2. Grain Refining Methods and Technologies in the Casting Process

2.1 Types of Refining Agents and Their Mechanisms of Action

Refining agents are widely used in casting processes to promote the generation of crystal nuclei and inhibit excessive grain growth, thereby enhancing the performance of castings. Common refining agents include rare earth elements, titanium, niobium, and boron. Rare earth elements (such as lanthanum, cerium, and yttrium) react with alloy elements to form fine compounds, which act as nucleation sites, increasing the number of crystal nuclei and refining the grain size, ultimately improving the mechanical properties of the alloy, especially its tensile strength and ductility. Titanium and niobium help regulate the fluidity of liquid metal, with titanium being particularly effective at suppressing the formation of large grains, thereby enhancing the material's toughness. Boron has a significant refining effect in some alloys, helping to homogenize the microstructure and improve crack resistance and fatigue life of castings.

The mechanism of action of refining agents primarily involves the chemical reaction that generates small nucleation particles, increasing the density of crystal nuclei and shortening the grain growth period. Additionally, refining agents form stable secondary phases in the liquid metal, which prevent further grain growth, ensuring that the casting has a high density and fine-grain structure. These actions

collectively improve the mechanical properties and service life of castings.

2.2 The Relationship Between Cooling Rate and Grain Refining, and Its Regulation

The cooling rate is one of the key factors influencing grain refinement. The cooling rate during the casting process directly determines the number of crystal nuclei and the size of the grains as the metal solidifies. By precisely controlling the cooling rate, grain refinement can be achieved, and the mechanical properties of the castings can be improved. A cooling rate that is too fast may cause excessive thermal stress in the casting, while a rate that is too slow may result in the formation of coarse grains.

2.2.1 The Effect of Cooling Rate on Nucleation of Grains

During casting, a faster cooling rate can effectively increase the number of crystal nuclei and limit grain growth. Specifically, a larger temperature gradient promotes the formation of more crystal nuclei in the liquid metal, thereby enhancing the refining effect. Rapid cooling also allows the grains to reach a stable state quickly, preventing excessive grain growth and improving the strength and hardness of the material. However, excessively fast cooling may lead to the formation of cracks, so it should be combined with other refining methods.

2.2.2 Optimization and Control of Cooling Rate

To achieve the optimal grain refinement effect, the cooling rate needs to be adjusted based on the shape, thickness, and characteristics of the casting alloy. By properly designing the mold structure and materials, adjusting the pouring temperature during the casting process, and using different cooling media (such as water or air cooling), the cooling rate can be effectively controlled. Particularly for thick-walled castings, optimizing the flow and temperature of the cooling medium can effectively prevent the occurrence of coarse grains due to uneven cooling^[3].

2.2.3 Factors Affecting Cooling Rate

The cooling rate is influenced not only by the casting environment but also by the casting's geometry, mold materials, and pouring temperature. For example, the thicker the casting, the slower the cooling rate, so adjustments to the pouring temperature or the use of molds with higher thermal conductivity may be needed to accelerate the cooling process. The control and optimization of the cooling rate are critical methods for achieving grain refinement, and must be flexibly adjusted according to the specific casting process.

2.3 The Relationship Between Alloy Composition and Grain Refining Effect

Alloy composition is one of the fundamental factors determining the effectiveness of grain refinement. Different alloy elements not only affect the solidification behavior of the metal but also directly impact the size and distribution of the grains by altering the alloy's solubility, interface energy, and crystal growth mechanisms. Optimizing the alloy composition is an essential approach to enhancing the performance of castings and achieving ideal grain refinement effects.

2.3.1 The Effect of Alloy Elements on Nucleation of Grains

In the casting process, alloy elements regulate grain size by affecting nucleation temperature, interface energy, and crystal growth rate. For instance, adding refining elements like titanium, niobium, and boron to aluminum alloys increases the nucleation density and promotes grain refinement. These elements typically react with the base metal to form stable compounds or particles, which provide additional nucleation sites and reduce excessive grain growth.

2.3.2 Optimization of Alloy Composition Design

Different alloy systems require specific composition designs to optimize the grain refinement effect. For example, adding appropriate amounts of titanium and boron to aluminum-silicon alloys significantly improves grain refinement and enhances the mechanical properties of the casting. In magnesium alloys, the addition of elements like calcium and zinc helps improve the fluidity of the alloy and its grain refinement effect. The optimization of alloy composition involves not only increasing the content of refining elements but also balancing other performance parameters such as corrosion resistance, strength, and plasticity.

2.3.3 Synergistic Effect of Alloy Composition and Cooling Rate

The alloy composition and cooling rate often work synergistically to achieve the best grain refinement effect. For example, in some aluminum alloys, the adjustment of cooling rate is closely related to the addition of refining agents. A properly matched alloy composition can promote nucleation, and when combined with rapid cooling, it can further suppress grain growth, optimizing the microstructure of the casting^[4].

3. Application of Grain Refinement Technology in Casting Production

3.1 Application of Grain Refinement Technology in Aluminum Alloy Casting

Aluminum alloy casting, as a typical example of lightweight alloy casting, is widely applied in fields such as automotive, aerospace, and construction. Grain refinement plays a key role in improving the mechanical properties of castings, enhancing surface quality, and increasing corrosion resistance. By reasonably controlling the alloy composition, cooling rate, and adding refining agents, the microstructure of aluminum alloys can be significantly optimized, thus enhancing the overall performance of the castings.

3.1.1 Application of Rare Earth Elements in Grain Refinement of Aluminum Alloys

Rare earth elements (such as lanthanum, cerium, yttrium, etc.) are widely used in aluminum alloys for grain refinement. Rare earth elements react with other elements in aluminum alloys to form fine compounds, which act as nucleation sites, promoting grain refinement. The addition of rare earth elements not only improves the corrosion resistance of aluminum alloys but also enhances the fatigue strength and high-temperature performance of castings. In aluminum alloy casting, especially in high-performance aluminum alloys like Al-Si alloys, rare earth elements effectively improve the grain structure and inhibit the formation of macro defects^[5].

3.1.2 Influence of Cooling Rate on Grain Refinement of Aluminum Alloys

The cooling rate significantly affects the degree of grain refinement in aluminum alloy casting. A faster cooling rate increases the number of nucleation sites and reduces grain growth, achieving grain refinement. However, excessively fast cooling rates may cause surface cracks or porosity in the castings. Therefore, in aluminum alloy casting, the cooling rate should be precisely controlled based on the specific size and complexity of the casting, through careful mold design, use of high thermal conductivity materials, and optimization of the cooling medium flow to achieve the desired grain structure.

3.1.3 Promoting Effect of Alloy Composition Optimization on Grain Refinement of Aluminum Alloys

The grain refinement effect of aluminum alloys is closely related to the alloy composition. By adding appropriate refining elements (such as boron, titanium, etc.), the degree of grain refinement in aluminum alloys can be significantly improved. Titanium, as a grain refining agent, plays a role in suppressing excessive grain growth and improving casting performance. Optimizing the ratio of alloy elements and selecting suitable refining elements can not only improve the strength and hardness of castings but also enhance their corrosion resistance and ductility.

3.2 Refinement Technology and Performance Optimization in Steel Alloy Casting

Steel alloys are widely used in industrial manufacturing, construction, and heavy machinery due to their high strength and good toughness. Grain refinement technology plays an extremely important role in steel alloy casting, significantly improving the mechanical properties, wear resistance, and fatigue resistance of steel castings.

3.2.1 Refining Effect of Titanium, Boron, and Rare Earth Elements in Steel Alloys

The application of titanium, boron, and rare earth elements in steel alloys can effectively improve the grain refinement degree of castings. Titanium reacts with nitrogen and carbon to form titanium compounds, which help suppress excessive grain growth and enhance the strength and heat resistance of the castings. Boron lowers the solidification temperature range of molten steel, improves fluidity, and promotes nucleation, reducing the occurrence of coarse grains. Rare earth elements can react with impurity elements in steel alloys, improving the stability of molten steel, reducing the formation of pores and inclusions, and thereby improving the overall mechanical properties of castings^[6].

3.2.2 Synergistic Effect of Cooling Rate and Grain Refinement in Steel Alloys

The cooling rate is crucial for grain refinement during the casting of steel alloys. Since the solidification temperature of steel alloys is relatively high, cooling rates are slower. Therefore, controlling the temperature gradient during the casting process is necessary to optimize the grain refinement effect. By using appropriate cooling media (such as water or air cooling) and mold materials, the solidification process of molten steel can be precisely controlled to achieve uniform grain refinement. In high-alloy steel casting, proper control of the cooling rate can effectively prevent casting defects caused by coarse grains, improving wear resistance and fatigue performance.

3.2.3 Coordinated Control of Alloy Composition and Cooling Rate

The grain refinement effect in steel alloys depends not only on the addition of refining agents but also on the synergistic effect of cooling rate and alloy composition. By optimizing the alloy element ratios, such as increasing the content of nickel, molybdenum, and chromium, the strength and corrosion resistance of steel can be improved. At the same time, controlling the cooling rate can further refine the grains and improve the overall performance of the casting. Rational alloy design combined with cooling rate control can meet the high-performance requirements of steel alloy castings.

3.3 Prospects of Grain Refinement Technology in High-Performance Casting Production

With the increasing demand for high-performance materials, the application of grain refinement technology in high-performance casting production has become more promising. Particularly in industries such as aerospace, automotive, shipbuilding, and high-end machinery manufacturing, grain refinement technology is a key method for enhancing the strength, toughness, wear resistance, and other properties of castings.

3.3.1 Application of Grain Refinement in High-Performance Aluminum and Magnesium Alloys

High-performance aluminum and magnesium alloys have broad application prospects in aerospace and automotive industries. Grain refinement technology can significantly improve the overall performance of aluminum and magnesium alloys, enhancing their strength, fatigue resistance, high-temperature performance, and corrosion resistance. By adding refining agents such as rare earth elements, titanium, and boron, grain refinement can be effectively achieved, reducing casting defects and enhancing the reliability and safety of high-performance aluminum and magnesium alloys.

3.3.2 Application of Grain Refinement Technology in Additive Manufacturing

The rise of additive manufacturing technology has opened new directions for the application of grain refinement technology. During the additive manufacturing process, grain formation often exhibits unevenness due to changes in the cooling rate between layers. Grain refinement technology can reduce the mechanical property unevenness caused by coarse grains in additive manufacturing by controlling the cooling rate and alloy composition during the printing process. As additive manufacturing technology continues to develop, grain refinement technology will play an increasingly important role in the production of high-performance castings.

3.3.3 Integration of Grain Refinement with Smart Manufacturing Technology

The integration of smart manufacturing and big data technologies offers new possibilities for optimizing grain refinement technology. By monitoring temperature, pressure, cooling rate, and other parameters in real-time during the casting process, and using big data analysis and artificial intelligence algorithms for optimization and control, precise adjustments can be made to grain refinement technology. In high-end manufacturing industries, the application of smart manufacturing technology will further enhance the effects of grain refinement, enabling high-precision and high-performance casting production.

Conclusion

This paper explores the application of grain refinement technology in casting, discusses the role of refinement in improving casting performance, and examines the mechanisms behind its implementation. Grain refinement improves the mechanical properties, wear resistance, and corrosion resistance of castings by promoting nucleation and suppressing excessive grain growth. The use of refining agents such as rare earth elements, titanium, and boron, combined with the optimization of alloy composition and cooling rate, has provided significant support for the advancement of casting technology. Despite

certain progress, challenges remain in balancing refinement effects with casting flowability, cost, and other factors. Future research should focus on the environmental and cost-effectiveness of refining agents, integrating numerical simulation and artificial intelligence to optimize the refining process, and exploring the enhancement of refinement effects through additive and smart manufacturing technologies. Additionally, further study is needed on the coordinated control of alloy composition and cooling rate to achieve the precise production of high-performance castings. The prospects for grain refinement technology in high-performance casting production are broad, especially in aerospace, automotive, and other high-end manufacturing sectors, where it plays a significant role in improving casting performance.

References

- [1] Zhang Keren, Li Jingguang, An Juntaing, et al. *Research Progress on Grain Refinement Methods for Casting γ -TiAl Alloys* [J]. *Foundry Technology*, 2024, 45(03): 249-258.
- [2] Li Xikuo, Cheng Guangkui, Sun Ming, et al. *Research Progress on Grain Refinement Behavior in Magnesium Alloy Casting with External Energy Fields* [J]. *Casting*, 2023, 72(06): 629-640.
- [3] Hu Wenxin. *Preparation and Key Technology Development of Nano Rare Earth Magnesium-Zirconium Alloy Grain Refining Agents* [R]. Baotou Rare Earth Research Institute, Inner Mongolia Autonomous Region, 2023-10-11.
- [4] Ren Simiao. *Study on Grain Refinement and Deformation Behavior of 316L Austenitic Stainless Steel by Asynchronous Rolling* [D]. Harbin Institute of Technology, 2023.
- [5] Dong Zhihai, Li Yiwen, Aleksandr Babkin, et al. *Research Status of Grain Refinement Technology in Ferritic Stainless Steel Welds* [J]. *Materials Review*, 2022, 36(21): 188-197.
- [6] Wang Mengfei, Liu Jie, Peng Yong, et al. *Effect of TiN on Phase Transformation Texture and Grain Refinement in Laser Welded TiAl-based Alloys* [J]. *Chinese Journal of Lasers*, 2022, 49(16): 143-151.