

Research Progress on Giga-cast Technology of Aluminum Alloys

Zhongyao Li¹, Yisheng Miao², Shihao Wang¹, Qinghuai Hou², Ye Tian²,
*Junsheng Wang^{2,3}

1. School of Mechanical Engineering, Beijing Institute of Technology, Beijing, 100081, China;
2. School of Materials Science and Engineering, Beijing Institute of Technology, Beijing, 100081, China;
3. School of Multidisciplinary Science, Beijing Institute of Technology, Beijing, 100081, China.

*Corresponding author. Tel.: +86 010 68915043. E-mail: junsheng.wang@bit.edu.cn (J.S. Wang)

Copyright ©2025 17th Asian Foundry Congress, Foundry Institution of Chinese Mechanical Engineering Society

Abstract: With the growing demand for automotive light-weighting and the development of new energy vehicles, Giga-cast technology for aluminum alloys has become a research hotspot in the field of lightweight manufacturing due to its advantages of integrated forming, simplified process flow, and significantly reduced production cost. This paper provides a systematic review of the development of high-pressure die casting (HPDC) technology, outlines the evolution from HPDC to large-scale giga-cast technology, and focuses on the analysis of key process parameters involved in giga-casting—such as injection velocity, die casting pressure, pouring temperature, mold temperature and vacuum level as well as their effects on casting quality. Additionally, the formation mechanisms and optimization strategies of common casting defects, including porosity-related, fusion-related, thermal contraction related, and inclusion-related defects are comprehensively summarized.

Keywords: aluminum alloy; HPDC; giga-casting; defect control

1 Introduction

In recent years, the automotive and aerospace industries have increasingly pursued lightweight manufacturing of components to reduce energy consumption and enhance mobility performance. For conventional internal combustion engine vehicles, every 100 kg reduction in curb weight can lower fuel consumption by approximately 0.3–0.5 L/100 km and reduce CO₂ emissions by 8–11 g/km. For new energy electric vehicles, a 10% reduction in curb weight can lead to a 13.7% increase in average driving range^[1]. Giga-cast technology for aluminum alloys offers significant advantages in reducing component weight and thus plays a vital role in lightweight manufacturing. Since its inception, this technology has greatly accelerated the application of aluminum alloys in high-end equipment manufacturing and has become a prominent research direction in the field of lightweight design^[2-4].

The Tesla Model Y was the first mass-produced vehicle to adopt a giga-cast aluminum rear underbody. In 2019, Tesla published patents related to giga-casting technology^[5], and in 2020, Tesla began collaborating

with the Italian die casting equipment manufacturer IDRA to utilize its 6000-ton large-scale integrated die casting machine. This enabled the giga-casting of the entire rear underbody assembly of the Tesla Model Y, consolidating more than 70 individual parts into a single large component, as shown in Figure 1. The process eliminated stamping and welding operations, reduced over 1,600 weld joints, achieved a 10% weight reduction of the rear body, and lowered manufacturing costs by 40%^[6].

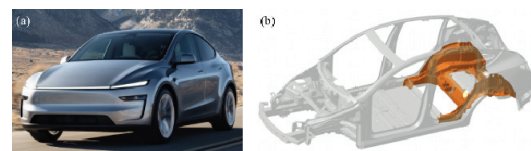


Fig. 1 (a) Tesla Model Y, (b) Rear underbody assembly of the Tesla Model Y

2 Development of Giga-cast technology

Giga-cast technology has evolved from high-pressure die casting (HPDC) technology. HPDC is a casting method that uses high pressure to fill molten or semi-solid metal

into a mold cavity and solidify the metal under pressure. Its origins can be traced back to the early 19th century^[7], when the demand for cast lead type in typesetting and printing equipment surged with the booming printing industry, prompting efforts to improve the production efficiency of lead type casting. In 1822, William Church^[7-9] developed the first typecasting machine that used a piston to inject molten lead, based on which J.J.Sturgiss^[10] introduced more precise molds and a piston mechanism with improved pressure stability, producing the first commercially viable, semi-automated typecasting machine capable of continuous production. Molten lead was injected into molds via the piston mechanism, rapidly solidified, and then the mold was opened to eject the type. The typecasting technology proposed by Sturgiss is regarded as the prototype of modern high-pressure die casting technology and laid the foundation for its subsequent development.

During the fifty years of the latter half of the 19th century, alongside innovations in high-pressure die casting processes and equipment, the use of HPDC technology expanded beyond the printing industry to mass-produce small industrial components such as gears, racks, cams, and connecting rods. However, due to the limitations of mold alloy performance, the materials used for high-pressure die castings during this period were low-melting-point metals such as lead and tin, and production was conducted primarily via the hot-chamber die casting method. The earliest hot-chamber die casting machine was invented by Dusenbury in 1877^[11], featuring both the original injection mechanism and mold opening and closing system. Hot-chamber die casting is suitable only for casting low-melting-point materials^[12], because during automated production, the shot sleeve is submerged in molten metal within the furnace. Continuous contact between the shot sleeve and high-temperature molten metals with high melting points causes rapid corrosion of the shot sleeve and injection mechanism, as well as severe thermal fatigue and corrosion^[13].

In 1885, German engineer Karl Benz manufactured the world's first automobile powered by an internal combustion engine and equipped with steering control and braking systems, marking the rise of the automotive industry. In 1904, the American company H. H. Franklin^[14] began producing zinc alloy automotive components using die casting. However, as the automotive industry developed, low-liquidus-temperature alloys die cast parts increasingly failed to meet the

high-performance requirements of automotive components. In 1920, Carl Roehe^[15] invented the cold-chamber die casting machine, which separates the furnace from the shot sleeve. Before production, molten metal at high temperature from the furnace is transferred into the shot sleeve, and then forced into the mold cavity by the injection mechanism to complete solidification. This design avoids prolonged contact between the shot sleeve and molten metal, thereby enabling the production of castings from alloys with high liquidus temperatures, such as aluminum alloys, magnesium alloys, and copper alloys. Figure 2 illustrates the process schematics of hot-chamber and cold-chamber die casting machines.

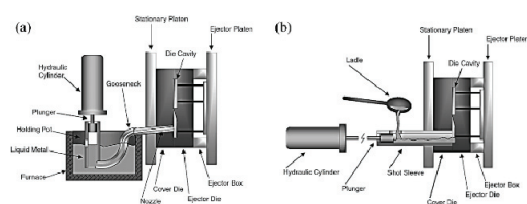


Fig. 2 Schematic diagram of: (a) Hot-chamber die casting machine, (b) Cold-chamber die casting machine^[16]

In the 1940s, the United States Steel Industry Consortium developed and promoted H13 tool steel, which exhibited excellent resistance to thermal fatigue. It was capable of withstanding cyclic thermal loads at temperatures ranging from 600 °C to 650 °C, and possessed outstanding hardenability, making it well-suited for manufacturing large-scale dies. Owing to its superior properties, H13 tool steel became an indispensable material for cold-chamber die casting molds and injection systems, significantly advancing their development. It remains one of the most widely used tool steels to this day^[17]. Since the latter half of the 20th century, the injection systems of cold chamber die casting (HPDC) machines have undergone continuous advancements, with injection speeds increasing from the initial 1–2 m/s to 8–10 m/s^[18]. The injection process evolved from a single-stage injection—where molten metal is driven into the mold cavity at a constant speed—to a three-stage process consisting of slow injection, fast injection, and pressurization^[19]. During the pressurization stage, the pressure exerted on the molten metal within the cavity can reach 120 MPa or even higher^[20]. The advancement of die materials, the implementation of high-speed injection systems, and the adoption of the three-stage injection process marked the transition of traditional high-pressure die casting (HPDC) into a mature application stage. Through successive

innovations in materials, processes, and die casting machines, traditional HPDC has eventually evolved into large-scale giga-casting technology.

2.1 Conventional HPDC

The conventional HPDC process consists of six steps^[21], as illustrated in Figure 3: (1) die preparation, during which a release agent is sprayed onto the cavity surface; (2) die closing; (3) dosing of molten metal into the shot sleeve; (4) performing three-stage injection (slow injection–fast injection–pressurization); (5) initiating localized die cooling at critical areas; and (6) opening the die and ejecting the casting after solidification. Compared to other casting methods, conventional HPDC exhibits several significant advantages: (1) It facilitates near-net-shape manufacturing, thereby minimizing or entirely eliminating the need for subsequent machining operations, which substantially reduces production costs; (2) The combination of high-speed injection and solidification under elevated pressure enables the fabrication of thin-walled castings, components with complex geometries, and intricate surface details; (3) It offers exceptionally high production efficiency, with cycle times for small parts produced in multi-cavity molds reduced to mere seconds, while large components typically require casting cycles of approximately one minute; (4) The process accommodates low-cost secondary alloys, often derived from recycled scrap, leading to considerable cost savings in material usage.

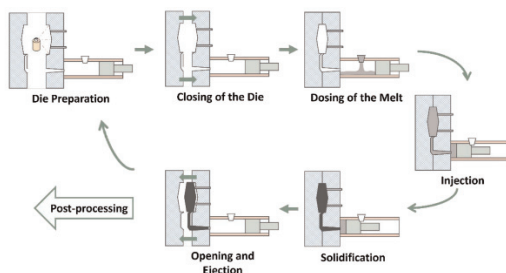


Fig. 3 General schematic diagram of conventional HPDC process cycle^[22]

Although conventional HPDC offers significant advantages over other casting methods in terms of cost reduction and production efficiency, its application in high-performance structural components remains highly constrained. During the conventional HPDC process, molten metal is injected into the mold cavity at extremely high speeds, generating turbulent flow that entraps gases within the cavity and leads to porosity formation during solidification. While the high pressure applied during

solidification can compress these pores to smaller sizes, the overall porosity volume fraction remains relatively high. Such elevated porosity levels cause internal pores to expand during T6 heat treatment of castings produced by traditional HPDC, resulting in swelling or even cracking of the parts. Since conventional aluminum alloys like A356 require T6 heat treatment to achieve satisfactory strength, this issue substantially limits the engineering applications of conventional HPDC.

2.2 Vacuum HPDC

In recent years, vacuum high-pressure die casting has been increasingly employed in the production of high-performance castings to reduce or even eliminate the abundant porosity defects caused by gas entrainment during the casting process. The core concept of vacuum high-pressure die casting is to create a vacuum environment inside the mold cavity using vacuum valves prior to injection. As a result, when molten metal is injected into the cavity at high speed, the generated turbulence does not entrain gas, fundamentally reducing or even eliminating porosity defects caused by gas entrapment^[23,24]. Additionally, the surface tension of molten metal decreases under vacuum conditions, significantly enhancing its fluidity and making it more suitable for the production of thin-walled components. The resulting castings exhibit improved tensile strength, elongation, hardness, and density^[25]. Moreover, due to the reduction of porosity defects, castings produced by vacuum high-pressure die casting can undergo heat treatment and welding processes.

Based on the achievable cavity vacuum level of die casting machines, vacuum high-pressure die casting can be classified into vacuum-assisted die casting (VADC)^[26] and high vacuum die casting (HVDC)^[27]. VADC can maintain the cavity vacuum level within 60 to 300 mbar, whereas HVDC can achieve cavity vacuum levels below 60 mbar^[28,29]. However, HVDC requires higher standards for mold sealing, vacuum systems, and die casting machine control systems, resulting in increased costs. Currently, HVDC is primarily employed for producing structural components and thin-walled parts that demand superior weldability and heat treatability, such as automotive chassis and body structural parts. Although VADC achieves relatively lower vacuum levels, its equipment cost and operational requirements are lower, making it suitable for products with lower sensitivity to porosity and for traditional aluminum alloy components that do not require heat treatment.

2.3 Giga-casting

Giga-casting essentially involves the application of high vacuum die casting (HVDC) technology to the integrated forming of large, complex structural components^[30]. The successful implementation of giga-casting technology benefits from advancements in tool steel performance, large-scale die casting machines, and heat-treatment-free casting aluminum alloys. The mold, die casting machine, and casting materials—collectively referred to as the "three elements of die casting"^[31], which jointly determine the quality, efficiency, and performance of die cast components.

Giga-cast components are characterized by large dimensions, complex geometries, and uneven wall thicknesses, which lead to increased mold size and structural complexity. Compared to molds for smaller parts, giga-casting molds are subjected to greater molten metal impact forces and longer impact durations. To meet the demands of large-scale production of complex giga-cast components, mold steels used in giga-casting must possess excellent comprehensive properties, primarily including high hardenability, thermal fatigue resistance, and thermal conductivity. Currently, commonly used hot-work tool steels for giga-casting molds include 5CrMnMo, 5CrNiMo, 4CrNi4Mo, 4Cr3Mo3SiV, and 3CrW8V^[32].

Both the injection filling and pressurization solidification of large giga-cast components require higher injection pressures. The clamping force provided by large die casting machines prevents mold separation caused by high pressure during the casting process, which is critical to ensuring the efficient operation of the giga-casting process and producing denser castings. Since IDRA produced the OL6100CS large die casting machine with a clamping force of 6000 t for Tesla in 2020, manufacturers capable of producing large die casting machines have continued to develop machines with higher clamping forces. By 2022, LK Technology, in collaboration with Guangdong Hongtu Technology Co., Ltd., increased the clamping force to 12,000 t^[33].

Although giga-cast components are filled under high vacuum conditions, effectively minimizing gas-entrained porosity defects, their oversized dimensions and thin-walled structures still make them prone to warping deformation and dimensional deviations during heat treatment. These issues increase the difficulty of subsequent shaping and reduce the yield of finished products. Heat-treatment-free aluminum alloys exhibit excellent mechanical properties in the as-cast state that

meet the mechanical performance requirements of giga-cast components, eliminating the need for heat treatment. The omission of the heat treatment step significantly optimizes the manufacturing workflow of giga-cast components, enhancing production efficiency while effectively reducing overall manufacturing costs without compromising mechanical performance.

3 Giga-casting process

The process flow of giga-casting is fundamentally consistent with that of high vacuum die casting (HVDC), with mass production of a single casting involving a continuous cycle of eight steps: cavity spraying, mold closing, pouring, slow injection, vacuum evacuation, fast injection, pressurization and solidification, demolding, and post-processing. Specifically, in each cycle, a release agent is first sprayed onto the die cavity surfaces, followed by mold closing. A precise amount of molten metal is then poured into the shot sleeve. Slow injection is performed via the injection mechanism until the plunger seals the pouring gate, at which point vacuum evacuation of the cavity is rapidly initiated. Fast injection is then carried out to fill the cavity completely, followed by pressurization that is maintained until the molten metal solidifies. Finally, the mold is opened and the casting is ejected by the ejection mechanism. The casting then undergoes subsequent finishing operations such as deburring and surface polishing.

The various stages of the giga-casting process involve numerous process parameters that govern the flow and solidification behavior of the molten metal during die casting. Appropriate process parameters can effectively reduce casting defects, enhance the mechanical properties of castings, and improve the stability of the production cycle. Conversely, inappropriate parameters may lead to various defects, degrade mechanical performance, and potentially shorten the service life of giga-casting molds. Given the complexity of different casting geometries, extensive debugging and optimization of process parameters are required. Therefore, a thorough understanding of these parameters is of critical importance for successful giga-casting production.

3.1 Injection speed

Injection speed refers to the velocity of the plunger as it drives the molten metal within the shot sleeve. In the three-stage injection process, the plunger moves at a relatively low speed during the first stage to seal the pouring gate and gradually push the molten metal

upward, filling the shot sleeve and runner system. In the second stage, the plunger accelerates to a high speed and pressure to overcome flow resistance and inject the molten metal into the mold cavity. After the cavity is filled, the process enters the third stage, during which pressurization is maintained to ensure solidification of the metal under high pressure. Therefore, injection speed can be divided into slow injection speed and fast injection speed, corresponding to the plunger velocities during the first and second stages of the three-stage injection, respectively. In the third stage, the plunger continues to apply pressure on the molten metal but experiences counterforce from the metal in the cavity, resulting in minimal movement with a very low velocity that ultimately approaches zero.

During the injection process, the flow of molten metal can be divided into three stages: shot sleeve filling, runner system filling, and casting cavity filling. In the shot sleeve filling stage, the molten metal surface rises slowly to fill the shot sleeve, forcing the air inside the shot sleeve to flow through the runner into the cavity. Meanwhile, the plunger seals the pouring gate, isolating the cavity from external gases. The runner filling stage typically causes the molten metal to rise to the front edge of the inner gate or the runner itself. This stage allows sufficient time for the vacuum valves to evacuate air from the cavity, ensuring that the subsequent casting cavity filling occurs under a high vacuum environment^[34]. The flow stages of the molten metal during injection, along with the velocity profile of the three-stage injection process, are illustrated in Figure 4.

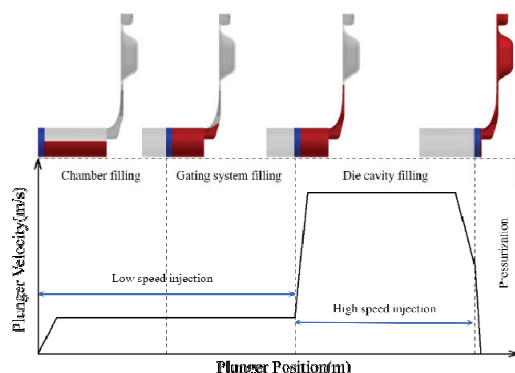


Fig. 4 The three stages of molten metal flow during injection and the velocity profile of the three-stage injection process

A considerable number of studies have revealed that both the slow injection speed and the fast injection speed should fall within a reasonable range^[35-39]. For instance,

Lopez^[40] demonstrated that when the slow injection speed is below a certain threshold, the molten metal fills the shot sleeve smoothly during the filling phase. Otherwise, the melt surface becomes turbulent and entraps air in the shot sleeve, resulting in gas porosity defects in the casting, which deteriorates the density and mechanical properties of the part. This mechanism was also experimentally validated by Zamora^[41]. However, an excessively low slow injection speed can reduce the production pace, adversely affecting manufacturing efficiency and even causing a drop in the melt temperature, thereby diminishing fluidity. Choi and Jiao conducted studies on the injection process of die casting. Choi^[42] found that increasing the fast injection speed, along with higher mold temperatures, improved the mechanical performance of the castings. In contrast, Jiao^[43] observed that moderately lowering the fast injection speed could help reduce internal casting defects. If the fast injection speed is too low, the molten metal may encounter difficulties in cavity filling, leading to defects such as incompleteness, cold lap, lamination, and flow mark. Conversely, an excessively high fast injection speed may cause the melt to violently impact the mold surface. Conversely, an excessively high fast injection speed may cause the melt to violently impact the mold surface^[44], resulting in droplet splashing and cold shot defects, which in turn deteriorate the mechanical properties of the casting.

3.2 Die casting pressure

Die casting pressure refers to the force per unit area exerted by the plunger on the molten metal, and can be divided into injection pressure and pressurization pressure. Injection pressure refers to the force per unit area applied by the plunger to the molten metal inside the shot sleeve during the fast injection stage. This pressure drives the molten metal to overcome viscous resistance and local solidification contraction, thereby completing the cavity filling. In contrast, pressurization pressure refers to the pressure applied after the cavity is completely filled. During the pressurization stage, the plunger further compresses the molten metal to reduce porosity defects and enhance the density of the casting^[45].

In the giga-casting process, the relationship between injection speed and die casting pressure varies across different stages. At the initial stage of fast injection, a higher injection pressure can correspondingly increase the injection speed. As the mold cavity gradually fills, the resistance exerted by the molten metal on the

plunger increases, leading to a certain degree of decline in injection speed. During the pressurization stage, since the cavity is fully filled, the plunger experiences a significantly greater counterforce from the molten metal, resulting in a rapid drop of the injection speed to zero.

The selection of injection pressure in die casting is typically influenced by multiple factors, including the geometry, size, and complexity of the die, the properties of the alloy, and the pouring temperature. A relatively high injection pressure can help the molten metal fill the cavity more smoothly; otherwise, insufficient filling may occur, particularly in large, complex, and thin-walled castings with high filling resistance. However, excessively high injection pressure may cause the molten metal to impact the die violently, shortening the die's service life. In addition, excessive pressurization pressure places extra mechanical burden on the injection system, die, and die casting machine^[46].

3.3 Pouring temperature and mold temperature

The pouring temperature refers to the temperature of the molten metal at the time it enters the shot sleeve at the beginning of the die casting process. A higher pouring temperature can reduce the Newtonian viscosity of the molten metal, thereby decreasing the resistance during cavity filling^[47,48]. However, an excessively high pouring temperature can intensify solidification shrinkage and increase the tendency for hot cracking in the casting. Conversely, if the pouring temperature is too low, the molten metal may have difficulty filling the cavity, which can lead to defects such as cold lap, incompleteness, and surface flow marks.

Before the die casting process cycle begins, the die must be preheated to a specified temperature, known as die preheating^[49]. In the subsequent production cycles, the die absorbs heat from the molten metal on one hand, and dissipates it through the cooling system and air convection on its surface on the other. Eventually, the die reaches a state of thermal equilibrium, where the die temperature at the same moment in each process cycle tends to become consistent^[50]. Some studies have indicated that the steady-state die temperature after reaching thermal equilibrium is independent of the initial preheating temperature. However, die preheating remains a critical step. Without preheating, more production cycles are required for the die to reach thermal equilibrium and produce castings with stable quality. Additionally, before thermal equilibrium is achieved,

repeated impacts of high-temperature molten metal on the cold die cavity surface can lead to significant temperature fluctuations, which reduce the die's service life. It is important to note that die preheating merely provides a basic thermal condition for the mold filling process; maintaining an appropriate thermal balance during production is also essential. If the equilibrium die temperature is too low, casting defects such as incomplete filling, cold shut, and flow marks may occur^[51,52]. Conversely, an excessively high equilibrium die temperature may result in slow solidification and coarse grain formation, leading to a decline in the mechanical properties of the casting. The equilibrium die temperature can be adjusted through cooling processes, such as regulating the flow rate of the cooling medium (typically compressed air or water) within the cooling channels, or by adding localized insulation materials.

3.4 Vacuum level

The application of vacuum technology to enable molten metal to fill and solidify under a high-vacuum environment represents a significant breakthrough in the high-pressure die casting process. This technique markedly reduces casting defects and enhances the mechanical properties of the castings^[53-56]. Cao^[57] found that a high vacuum level can reduce the flow resistance of the molten metal and suppress turbulence generation to a certain extent. Lagiewaka^[58] investigated the effect of cavity vacuum degree on the surface quality of castings and observed that castings formed under high vacuum conditions exhibited the smoothest surfaces. Szalva^[59] reported that compared to conventional high-pressure die casting, the porosity rate inside castings decreased from 1.10% to 0.47% under a 70 mbar vacuum environment, representing a reduction of 57%, with smaller pore sizes. Yalçin^[47] conducted process optimization on pouring temperature, casting pressure, injection speed, and vacuum level, revealing that a vacuum environment in the mold cavity significantly improves the mechanical properties of the material and promotes the formation of a fine-grained microstructure.

The high vacuum level inside the mold cavity is primarily achieved through vacuum valves. After the vacuum pump creates a vacuum environment within the cavity, there are two main methods to close the spool: one is the mechanical valve, which is closed by the flow of molten metal pushing against it; the other is the trigger valve, which closes the spool upon receiving specific signals such as the impact of molten metal, elapsed time, or temperature. Besides the vacuum valve, the sealing

performance of the mold, the sealing between the plunger and the shot sleeve, as well as the control accuracy of the vacuum system, are also important influencing factors.

4 Defects in giga-casting

Due to fluctuations in process parameters or errors in the control system, various defects are inevitably generated in die castings during production. Jian^[60] categorized common defects into four types based on their formation mechanisms and locations as internal defects, surface defects, geometrical defects, and material defects. However, defects originating from the same mechanism may occur at different locations within the casting. Therefore, Elena^[61] and colleagues proposed a two-level classification for defects in die castings. The 1st level categorizes defects based on their location into internal defects, surface defects, and geometrical defects. The 2nd level classifies them according to their formation mechanisms, as illustrated in Tables 1 to 3.

Tab. 1 Classification of internal defects^[61]

1 st Level	2 nd Level	Defect
Internal defects	Shrinkage defects	Macro shrinkage
		Interdendritic shrinkage
	Gas-related defects	Hydrogen pore
		Gas entrainment
	Filling-related defects	Cold shut lamination
	Undesired phases	inclusion
	Thermal contraction defects	Cold crack
		Hot crack

Tab. 2 Classification of surface defects^[61]

1 st Level	2 nd Level	Defect
Surface defects	Shrinkage defects	Sink
	Gas-related defects	Blister
	Filling-related defects	Cold shut lamination
	Undesired phases	Contamination
	Thermal contraction defects	Cold crack
		Hot crack

Tab. 3 Classification of geometrical defects^[61]

1 st Level	2 nd Level	Defect
Geometrical defects	Lack of material	Incompleteness
	Excess material	Flash
	Out of tolerance	Deformation

4.1 Porosity defects

According to the defect classification proposed by Elena et al., macro shrinkage pore, interdendritic shrinkage, hydrogen pore, gas entrainment pore, gas-shrinkage pore within internal defects, as well as blister and sink among surface defects, can be categorized as porosity defects. Their morphologies are shown in Figure 5.

4.1.1 Macro shrinkage pore and interdendritic shrinkage
Shrinkage pores and interdendritic shrinkage are common defects across various casting processes, often exhibiting complex and irregular morphologies. These defects originate from similar mechanisms but manifest at different scales^[64]. At the macroscopic level, the geometric design of the casting and the thermal control of the mold can result in regions of heat concentration within the cavity, known as hot spots^[65]. In such regions, the molten metal solidifies later than the surrounding areas, and the contraction during solidification is not compensated by additional feed metal, leading to the formation of large shrinkage pores, as illustrated in Figure 6(a). In complex thin-walled components, early solidification of the thin sections can block the feeding paths, creating isolated liquid zones and ultimately resulting in shrinkage defects.

At the microscopic scale, metal atoms transition from the random distribution of the liquid phase to the ordered structure of the solid phase, forming dendrites and resulting in volume shrinkage. Cavities form between dendrite arms, and the feeding metal flows in from the direction opposite to the growth direction of the dendrites. When the pressure of the molten metal continuously decreases and falls below the critical level required to overcome the resistance of the dendrite arms and reach the cavities, numerous irregularly shaped micro-shrinkage pores form^[66], as shown in Figure 6(b). These micro-pores are referred to as interdendritic shrinkage.

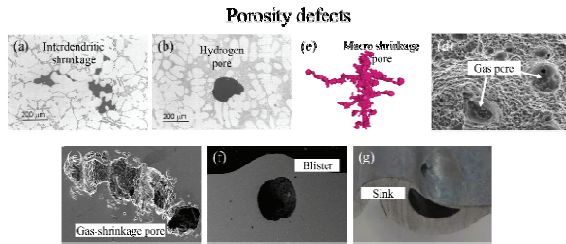


Fig. 5 Morphology of porosity defects[61-63]: (a) Interdendritic shrinkage, (b) Hydrogen pore, (c) Macro shrinkage pore, (d) Gas entrainment pore, (e) Gas-shrinkage pore, (f) Blister, (g) Sink

4.1.2 Hydrogen pore

Hydrogen has high solubility in liquid aluminum alloys. During solidification, the solubility of hydrogen decreases, leading to supersaturation of hydrogen in the interdendritic liquid metal. When the local hydrogen supersaturation reaches a level sufficient to sustain the critical volume of a hydrogen pore, hydrogen atoms tend to aggregate into hydrogen molecules, forming bubbles that diffuse and escape from the melt. If these bubbles are not expelled before solidification completes, they will remain in the casting as hydrogen pore defects^[67,68]. Hydrogen pores are typically spherical or ellipsoidal in shape, with smooth surfaces free of oxide films, and are distributed throughout the casting^[69]. The nucleation and growth process of hydrogen pores is illustrated in Figure. 6(c).

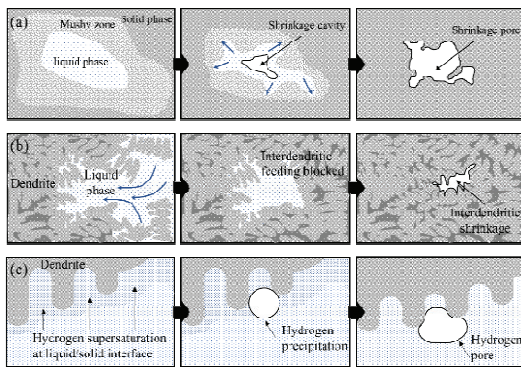


Fig. 6 Formation mechanism of (a) Macro shrinkage pore, (b) Interdendritic shrinkage, (c) Hydrogen pore^[70,71]

4.1.4 Gas entrainment and gas pore

The formation of gas entrainment is closely related to the injection process and vacuum system, with two primary causes. The first is that the slow injection speed exceeds the critical threshold, causing air in the shot sleeve to be entrained into molten metal, which is then injected into the mold cavity. The second cause is insufficient vacuum in the cavity, leading to gas entrainment during injection, as shown in Figure 7. The entrained gas becomes enclosed by the high-temperature molten metal and, due to internal pressure, typically forms smooth, rounded

pores. An oxide film often forms on their surfaces, and as the molten metal solidifies, entrapped gas pores are eventually formed^[72]. In addition to the air present in the shot sleeve and die cavity, gases generated from the decomposition of lubricate or die release agent may also become entrained in the molten metal, leading to the formation of gas porosity.

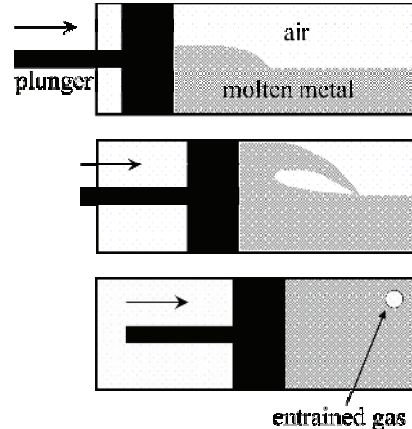


Fig. 7 Process of gas entrainment in shot sleeve

4.1.3 Gas-shrinkage pore

During solidification, when interdendritic shrinkage forms between dendrite arms and hydrogen pores simultaneously precipitate, they may encounter each other and form gas-shrinkage pores^[73,74]. The morphology of gas-shrinkage pores reflects the coexistence of shrinkage gaps and gas bubbles, with irregular tortuous cracks extending around the spherical or ellipsoidal cavities.

4.1.5 Blister and sink

When gas porosity defects occur near the casting surface, the internal gas pressure may cause localized plastic deformation, leading to blisters^[75]. In another way, if shrinkage pore occurs near the surface of the casting, the external atmospheric pressure may cause the surface layer to undergo plastic deformation and collapse inward, forming sink defects^[61]. The formation mechanism of blister and sink is illustrated in Figure 8.

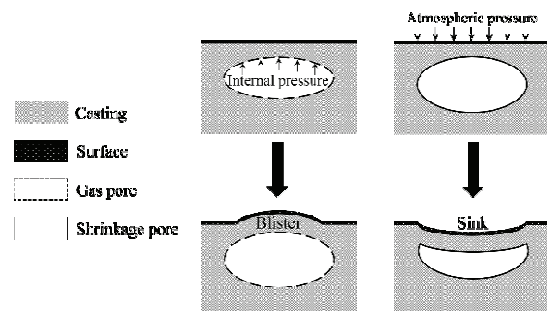


Fig. 8 Formation mechanism of blister and sink defects

4.2 Fusion-related defects

During the injection process, the molten metal is forced into the die cavity, and in areas with complex geometries, multiple metal streams may form. When these streams converge, the presence of oxide films or temperature differences may prevent them from fully fusing, resulting in internal or surface fusion defects such as cold lap, cold shot, lamination, or flow mark, whose morphologies are shown in Figure 9.

Fusion-related defects

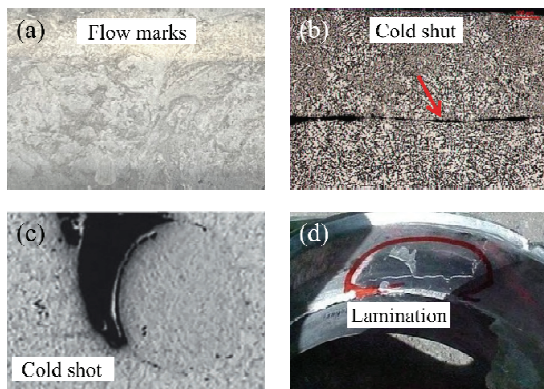


Fig. 9 Morphology of fusion-related defects[61]: (a) Flow marks, (b) Cold shut, (c) Cold shot, (d) Lamination

4.2.1 Cold lap

In complex, large-scale castings, the molten metal undergoes extended flow paths, making the convergence of two metal streams common. At the point of intersection, at least one of the streams often experiences a significant temperature drop and may be covered by an oxide film, preventing the two streams from fusing into one. This results in a distinct boundary or crack in the solidified casting, known as a cold lap defect^[61,76], as demonstrated in Figure 10(a).

4.2.2 Cold shot

The formation mechanism of cold shots is illustrated in Figure 10(b). If the injection speed is excessively high or the mold cavity structure is complex and tortuous, molten metal droplets may splash and rapidly solidify upon contacting the mold surface. These solidified droplets fail to fuse with the subsequent molten metal flow, ultimately resulting in cold shots, which manifest as spherical metal particles or pits within the casting^[61,77].

4.2.3 Lamination

As illustrated in Figure 10(c), when one stream of molten metal contacts the metal liquid first and rapidly solidifies, forming an oxide film on its surface, the subsequent molten metal covers it and solidifies slowly, resulting in lamination defects. The microstructures of the surface

metal layer and the internal metal differ significantly and are separated by the oxide film.

4.2.4 Flow mark

When the molten metal flows along the mold surface within the cavity, the temperature at the leading edge of the liquid front decreases and solidifies, or multiple molten streams stack and fold back due to the complexity of the casting structure, resulting in non-directional textures that are not the same color as the metal substrate on the casting surface, known as flow marks. The main causes of flow marks include low pouring temperature, low mold temperature, or insufficient injection speed, which lead to rapid cooling and solidification of the leading molten metal during cavity filling. Subsequent molten metal then flows over and replaces it as the new front, leaving wave-like or strip-like marks at their junction^[60,61], as illustrated in Figure 10(d).

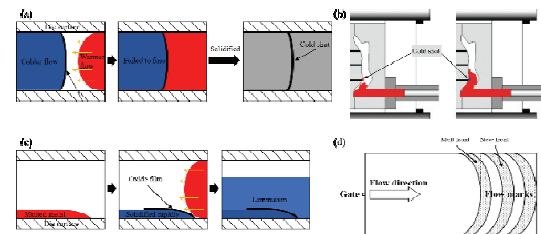


Fig. 10 Formation mechanism of fusion-related defects: (a) Cold shut, (b) Cold shot, (c) Lamination

4.3 Geometrical defects

Geometrical defects refer to deviations of the casting's geometry from the intended shape, including incompleteness, flash, and deformation, as shown in Figure 11.

Geometrical defects

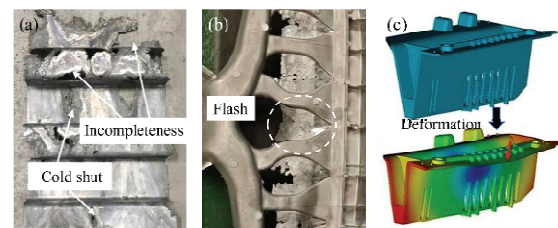


Fig. 11 Morphology of geometrical defects^[76]: (a) Incompleteness, (b) Flash, (c) Deformation

4.3.1 Incompleteness

Incompleteness refers to castings that solidify without fully filling the mold cavity, resulting in geometrical deficiencies in the final product. This defect primarily arises from two causes: insufficient molten metal supply in the shot sleeve and improper pouring temperature, mold temperature, or injection parameters that prevent

the molten metal from completely filling the mold cavity^[78,79].

4.3.2 Flash

During the die casting process, the volume of molten metal added into the shot sleeve is generally sufficient to fill the entire mold cavity, as well as the venting channels and gating system. When the plunger applies high pressure to the molten metal, the metal inside the cavity may be forced into the assembly gaps between mold parts. After solidification, the metal in these mold part gaps solidifies into thin, sheet-like residuals known as flash. The primary causes of flash formation include excessively large mold assembly clearances, insufficient clamping force, and excessively high injection pressure. Once the casting has solidified, additional machining is required to remove the flash defects, which increases the difficulty and cost of the machining process.

4.3.3 Deformation

After the casting solidifies in the mold, it undergoes a cooling process before the removal of the vacuum and gating systems attached to the casting. During solidification, uneven cooling rates, large temperature gradients, and asynchronous shrinkage at different locations within the casting induce thermal and shrinkage stresses. Subsequent rapid cooling treatments, such as water quenching, after demolding can significantly amplify residual stresses, leading to deformation of the casting, such as warping. Moreover, the deformation may become more pronounced after the vacuum and gating systems are removed^[80,81].

4.4 Thermal contraction defects

Thermal contraction defects include hot crack and cold crack, as shown in Figure 12. Both hot and cold cracks are caused by internal stress. Hot cracks occur in the late solidification stage, with cracks propagating along grain boundaries. On the contrary, cold cracks occur after the casting has fully solidified and cooled to a lower temperature, with cracks developing through the grains.

Thermal contraction defects

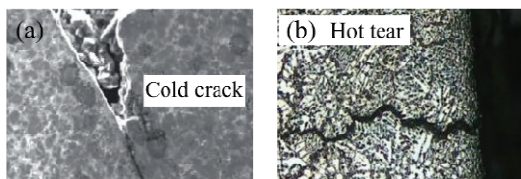


Fig. 12 Morphology of geometrical defects^[61,82]: (a) Cold crack, (b) Hot crack

4.4.1 Hot crack

Hot cracking is a typical crack defect that occurs during the solidification process or immediately after solidification while the metal is still at a high temperature. The formation mechanism of hot cracks is described by the solidification shrinkage-compensation theory: during the late solidification stage, when a region within the mushy zone is subjected to tensile stresses from multiple directions, the intergranular liquid film lacks sufficient plastic strength, leading to the formation of micropores. If the liquid phase cannot timely compensate and heal these micropores, they will expand along grain boundaries under shrinkage tensile stress, resulting in hot cracks characterized by irregular, branched fissures, as shown in Figure 13. Such defects severely compromise the mechanical properties and service reliability of castings^[66].

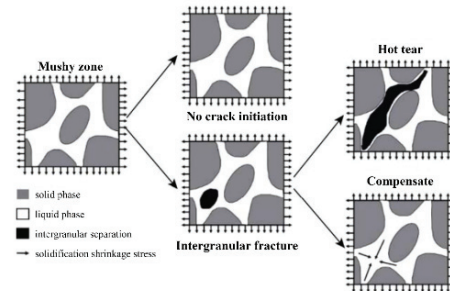


Fig. 13 Formation mechanism of hot cracking (solidification shrinkage-compensation theory)^[83]

4.4.2 Cold crack

Cold cracking is a common defect in castings, typically occurring when the material has solidified and cooled to relatively low temperatures. Its primary causes include the combined effects of shrinkage stress, thermal stress from uneven cooling, and embrittlement of segregation-prone regions, which together initiate and propagate cracks within the metal interior or on its surface, as illustrated in Figure 14. Cold cracks often propagate as fracture of grains, spreading rapidly with a distinct audible snap, forming continuous fractures almost instantaneously and leading to casting failure^[82].

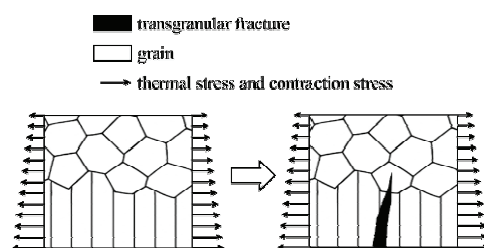


Fig. 14 Formation mechanism of cold crack

4.5 Inclusion and contamination

4.5.1 Inclusion

Inclusions refer to foreign metallic or non-metallic substances with distinct boundaries present within the metal matrix, as shown in Figure 15(a). Metallic inclusions mainly consist of primary crystals of various metal compounds that are insoluble in the matrix and high-melting-point pure metal particles that have not fully melted. Non-metallic inclusions include oxides, sulfides, carbides, fluxes, slag, coatings, and silicates^[84]. During the aluminum alloy die casting process, Al_2O_3 oxide film inclusions are the most common type of inclusion defects. When high-temperature molten metal is added into the shot sleeve, the molten metal is exposed to air, forming oxide films that break and become entrapped within the metal liquid when entering the shot sleeve. During the metal filling stage, the initially formed solidified layer may also be fractured by impact, dispersing into the melt and forming inclusions. Inclusions can also originate from metallurgical slag residues, mold scale, and decomposition products of mold release agents. These inclusions reduce the fluidity of the molten metal, act as initiation sites for shrinkage cavities or gas pores, promote crack initiation and propagation^[85], and adversely affect the mechanical properties of the casting.

4.5.2 Contamination

Contamination defects are the result of interaction between metal and environment. When a contamination defect occurs, part of the casting surface has a different color than other regions, as shown in Figure 15. (b).

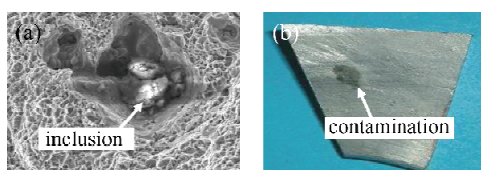


Fig. 15 Morphology of (a) inclusion and (b) contamination

4.5 Defect control

Casting defects, to varying degrees, undermine the microstructural continuity and mechanical properties of cast components, becoming critical factors that limit their service safety and fatigue life. Porosity defects such as gas entrainment and shrinkage cavities reduce material density and often serve as initiation sites for fatigue cracks. Metallic compound inclusions and non-metallic inclusions disrupt the metallurgical bonding interfaces, significantly compromising the strength and ductility of the casting. Severe fusion-related defects and thermal

contraction defects, such as cold laps and cold cracks—may even cause structural failure directly. Therefore, systematic investigation into the mechanisms of defect formation, along with the implementation of effective control strategies through alloy design, process parameter optimization, and mold structure improvement, is essential for enhancing casting quality and ensuring consistent product performance. Table 4 summarizes the potential causes of various defects and the corresponding directions for process optimization.

Among porosity defects, hydrogen porosity cannot be completely eliminated through process control alone, but its quantity and size can be significantly reduced by various means. For example, degassing the molten aluminum prior to casting to lower the hydrogen content can markedly decrease the size of hydrogen pores in the casting. In addition, appropriately increasing the cooling rate of the casting can shorten the growth period of hydrogen pores, thereby reducing their overall volume. As for shrinkage pores, it can be completely eliminated as long as sufficient feeding is ensured during the solidification of the molten metal in all regions of the casting. This can be achieved by optimizing the casting geometry to eliminate hot spots or by locally cooling or insulating the mold to alter the solidification sequence and ensure feeding paths for regions with concentrated heat. Moreover, inclusions may block compensating paths or induce discontinuous solidification, resulting in isolated liquid zones that cause shrinkage pores. Therefore, controlling inclusion defects can also reduce the possibility of shrinkage pores. Interdendritic shrinkage originates from the blockage of compensating paths between dendrite arms at the microscopic scale, making it difficult to eliminate completely. It can only be mitigated by increasing the pressurization pressure to help the molten metal overcome the flow resistance between dendrites, thereby minimizing the occurrence of interdendritic shrinkage.

High flow resistance of the molten metal and locally low mold temperatures are key factors contributing to fusion-related defects and incompleteness in castings. Therefore, in the die casting process, it is essential to design an appropriate mold heating and cooling scheme to maintain a stable and reasonable mold temperature. On the other hand, injection speed should be increased within an optimal range to prevent defects such as incompleteness, cold lap, lamination, and flow marks. However, the injection speed should not be too high to avoid droplet splashing, which leads to cold shot defects.

Prevention of hot cracking involves two main approaches. First, optimizing the alloy composition to reduce the solidification range facilitates effective feeding of shrinkage during the late solidification stage, thus mitigating crack initiation. Second, appropriately increasing the mold temperature lowers the cooling rate of the casting, allowing sufficient time for accumulated strains to be released during solidification, thereby

reducing the tendency for hot cracking. Prevention of cold cracking focuses on managing internal thermal stresses and brittle phases within the casting. This includes controlling mold temperature uniformity to avoid uneven cooling, incorporating fillets in the design to relieve internal stresses, and optimizing alloy composition to minimize the formation of brittle phases.

Tab. 4 Potential causes of casting defects and corresponding process optimization strategies.

Defects	Potential causes	Process optimization strategies
Shrinkage pore	Macro shrinkage cavities left uncompensated at isolated liquid zones	Optimize die structure, decrease mold temperature locally at hot spots ^[65,86-88]
Interdendritic shrinkage	Compensating between dendrite arms are obstructed	Increase pressurization pressure ^[89,90]
Hydrogen pore	Hydrogen supersaturation	Hydrogen degassing, pressurization and increase cooling rate ^[70,91-94]
Gas entrainment	Gas entrainment during the injection process	Reduce slow injection speed and increase cavity vacuum level ^[55,72,95]
Cold lap	Two metal flows collide with each other but fail to fuse	Increase mold temperature and optimize gating system ^[61,76]
Cold shot	Metal splashing onto the mold surface and rapidly solidifying	Increase mold temperature and reduce injection speed ^[61,76]
Lamination	Large temperature gradient between metal flows leads to poor fusion	Appropriately increase mold temperature
Flow mark	Rapid cooling of the molten metal front	Appropriately increase mold temperature and injection speed
Incompleteness	Incomplete cavity filling	Appropriately increase mold temperature and injection speed
Flash	Molten metal forced into molds assembly clearance	Increase clamping force, improve mold assembly accuracy, and reduce injection pressure
Hot crack	Intergranular cracking under shrinkage tensile stress	Optimize alloy composition, increase pouring temperature and mold temperature ^[83]
Cold crack	Grain fracture under residual stress	Optimize alloy composition and optimize mold design to prevent uneven cooling
Inclusion	Metallic and non-metallic substances dispersed within the molten metal.	Optimize the gating system, mold structure and injection speed, clean the furnace, hopper, and shot sleeve ^[84,85]

Acknowledgement

This work was financially supported by the Key Research and Development Program of China (No. 2024YFB4607200). We are also grateful for the help from all members at the Integrated Computational Materials Engineering (ICME) lab, Beijing Institute of Technology, China.

5 Conclusions

As a crucial component of modern advanced manufacturing systems, aluminum alloy giga-cast technology has become a key enabler for achieving lightweight, high-performance, and cost-effective production of structural components.

(1) Conventional high-pressure die casting (HPDC) technology has matured through multiple stages of technical evolution, laying the foundation for giga-casting technology. Originating from movable type casting in the early 19th century, high-pressure casting evolved from hot-chamber to cold-chamber processes, overcoming challenges associated with casting high-liquidus alloys. In the mid-20th century, the introduction of H13 tool steel and the upgrade to multi-stage control of the injection system propelled the industrial application of HPDC. Notably, the establishment of the three-stage injection process enabled precise, phased control of injection speed and pressure, significantly improving mold filling efficiency and casting quality.

(2) Vacuum die casting significantly reduces gas entrainment by evacuating gases from the mold cavity prior to filling, thereby enhancing the density and mechanical properties of castings and addressing the challenges of heat treatment and welding faced by

conventional HPDC castings. Building upon this, the integration of large-scale die casting machines, high-performance mold materials, and heat-treatment-free aluminum alloys has enabled giga-casting technology to achieve high-precision integrate forming of ultra-large, complex structural components, substantially reducing the number of parts and manufacturing costs.

(3) Process parameters have a decisive impact on the quality of casting formation. Key parameters such as injection speed, casting pressure, pouring temperature, mold temperature, and vacuum level directly affect the molten metal's flow behavior, filling capability, and solidification process, ultimately determining the casting's density, mechanical properties, and surface quality. Proper control of these parameters not only prevents various casting defects but also extends mold life and stabilizes the production cycle.

(4) Giga-casting defects are diverse, requiring control strategies that integrate material selection, process optimization, and structural design. These defects can be categorized into internal defects, surface defects, geometric defects, and material defects, with their origins linked to metallurgical bonding, flow dynamics, and thermal fields. Conducting systematic analyses of defect formation mechanisms and implementing effective control measures in material formulation, process parameter optimization, and mold structure improvement are crucial for enhancing casting quality and stabilizing product performance.

Reference

- [1] Z
- [2] hang W B. Research on Multiobjective optimization technology of automobile manufacturing process[D]. Harbin: Harbin University of Science and Technology, 2023.
- [3] Amirkhanlou S, Ji S. Casting lightweight stiff aluminum alloys: a review[J]. Critical Reviews in Solid State and Materials Sciences, 2020, 45(3): 171-186.
- [4] Gupta M K, Singhal V. Review on materials for making lightweight vehicles[J]. Materials Today: Proceedings, 2022, 56: 868-872.
- [5] Hao Z Y, Ju Y, Chen L X. The use of aluminium and magnesium alloys in automotive lightweight technologies[J]. Journal of Mechanical Science and Technology, 2023, 37(9): 4615-4622.
- [6] Kallas M K. Multi-directional unibody casting machine for a vehicle frame and associated methods: US20190217380A1[P]. 2019-07-18.
- [7] Li X Z. Integrated Die Casting Technologies of Aluminum Alloy[J]. Automobile Technology & Material, 2023(7): 17-21.
- [8] Barton H K. Charles Babbage and the beginning of die casting[J]. Die Casting Engineer, 1976, 20(4): 12-22.
- [9] Kaye A, Street A. Chapter 1 - Early developments in die casting[M]. Kaye A, Street A. Die Casting Metallurgy. Butterworth-Heinemann, 1982: 1-9.
- [10] Bill T. The golden age of die casting[J]. Die Casting Engineer, 1976, 20(4): 24-26.
- [11] Nishi N. History of die casting[J]. Journal of Japan Foundry Engineering Society, 2013, 85: 293-298.
- [12] Nishi N. History of Machine and Alloy for Die Casting in Japan[J]. Journal of the Japan Foundrymen's Society, 2006, 78: 413-421.
- [13] Cross R. Passivating commercial grades of Aluminum alloy for use in hot chamber die casting[J]. Die Casting

- Engineer, 2002, 46(1): 52-55.
- [14] Marshall P W. Hot chamber aluminum die casting-an evaluation[J]. Die Casting Engineer, 1971, 15(2): 12-24.
- [15] Huang X, Xie R, Tian Z, et al. The Development and The Outlook of The Die Casting Technology[J]. New Technology & New Process, 2008.
- [16] Dańko R, Kowalczyk W. New trends in cold-chamber die casting machine design[J]. China Foundry, 2015(4): 5.
- [17] Ibrahim H, Esfahani S N, Poorganji B, et al. Resorbable bone fixation alloys, forming, and post-fabrication treatments[J]. Materials Science and Engineering: C, 2017, 70: 870-888.
- [18] Bao Z J, Yang H Y, Dong B X, et al. Development trend in composition optimization, microstructure manipulation, and strengthening methods of die steels under lightweight and integrated die casting[J]. Materials, 2023, 16(18).
- [19] May S J. Recent developments in multiple-slide die casting technology[J]. Die Casting Engineer, 2002, 46(5): 24-27.
- [20] Cole B K. Hot chamber magnesium die casting in high-tech computer applications. SDCE 14th International Die Casting Congress and Exposition[C]. Toronto, 1987.
- [21] Frenette R J. High-Speed Multislide Die-Casting Machines. SDCE 12th International Die Casting Congress and Exposition[C]. Minneapolis, 1983.
- [22] Low- and High-Pressure Casting Aluminum Alloys: A Review[M]. Nunes H, Emadinia O, F. Vieira M, et al. Recent Advancements in Aluminum Alloys. IntechOpen, 2024.
- [23] Ferdyn M, Piątkowski J. Influence of vacuum on adjusting parameters of high pressure die casting parts from alloy AlSi9Cu3(Fe). 29th International Conference on Metallurgy and Materials[C]. Brno, 2020.
- [24] Jorstad J, Apelian D. Pressure Assisted Processes for High Integrity Aluminum Castings[J]. International Journal of Metalcasting, 2008, 2(1): 19-39.
- [25] Uchida M. Development of vacuum die-casting process[J]. China Foundry, 2009, 6(2): 137-144.
- [26] Budiarto B, Kurniawan T D. Effect of vacuum system on porous product defects and micro structures on the ADC-12 aluminum material with cold chamber die casting machines[J]. IOP Conference Series: Earth and Environmental Science, 2021, 878(1): 012072.
- [27] Niu X P, Hu B H, Pinwill I, et al. Vacuum assisted high pressure die casting of aluminium alloys[J]. Journal of Materials Processing Technology, 2000, 105(1): 119-127.
- [28] Lordan E, Zhang Y, Dou K, et al. High-Pressure Die Casting: A Review of Progress from the EPSRC Future LiME Hub[J]. Metals, 2022, 12(10): 1575.
- [29] Wang Q liang, Xiong S mei. Vacuum assisted high-pressure die casting of AZ91D magnesium alloy at different slow shot speeds[J]. Transactions of Nonferrous Metals Society of China, 2014, 24(10): 3051-3059.
- [30] Shi X Y, Li D J, Luo A A, et al. Microstructure and Mechanical Properties of Mg-7Al-2Sn Alloy Processed by Super Vacuum Die-Casting[J]. Metallurgical and Materials Transactions A, 2013, 44(10): 4788-4799.
- [31] Li T, Song J F, Zhang A, et al. Progress and prospects in Mg-alloy super-sized high pressure die casting for automotive structural components[J]. Journal of Magnesium and Alloys, 2023, 11(11): 4166-4180.
- [32] Tao Y L, Yang J J, Liu X T, et al. Large die-casting die is the key technology to realize integrated die-casting[J]. Die & Mould Manufacture, 2023, 23(4): 47-52.
- [33] Bao Z J, Yang H Y, Dong B X, et al. Development Trend in Composition Optimization, Microstructure Manipulation, and Strengthening Methods of Die Steels under Lightweight and Integrated Die Casting[J]. Materials, 2023, 16(18): 6235.
- [34] Tan Y X, Ma J H, Zhao H D, et al. Progress in integrated die casting of aluminum alloys[J]. Aeronautical Manufacturing Technology, 2024, 67(14): 66-75.
- [35] Liu B C, Xiong S M. High pressure die casting process of magnesium alloys and its modeling and simulation for automobile industry[J]. Automotive Safety and Energy, 2011, 2(1): 1-11.
- [36] Xie H C, Wang J, Li Y F, et al. Fast shot speed induced microstructure and mechanical property evolution of high pressure die casting Mg-Al-Zn-RE alloys[J]. Journal of Materials Processing Technology, 2024, 331: 118523.
- [37] Kang H jung, Jang H sung, Oh S H, et al. Effects of gate system design on pore defects and mechanical properties of pore-free die-cast Al-Si-Cu alloy[J]. Materials Today Communications, 2022, 31: 103673.
- [38] Kim H H, Lee S M, Kang C G. Reduction in Liquid Segregation and Microstructure Improvement in a Semisolid Die Casting Process by Varying Injection Velocity[J]. Metallurgical and Materials Transactions B, 2011, 42(1): 156-170.
- [39] Jiao X Y, Zhang W, Liu Y X, et al. The characterization of porosity and its relationship with externally solidified crystal in a high-pressure die-cast AlSi10MnMg alloy via a laboratory CT technique[J]. Materials Letters, 2023, 335: 133807.
- [40] Niu X P, Hu B H, Pinwill I, et al. Vacuum assisted high

- pressure die casting of aluminium alloys[J]. *Journal of Materials Processing Technology*, 2000, 105(1): 119-127.
- [41] Lo'pez J, Faura F, Herna'ndez J, et al. On the Critical Plunger Speed and Three-Dimensional Effects in High-Pressure Die Casting Injection Chambers[J]. *Journal of Manufacturing Science and Engineering*, 2003, 125(3): 529-537.
- [42] Zamora R, Hernandez-Ortega J J, Faura F, et al. Experimental Investigation of Porosity Formation During the Slow Injection Phase in High-Pressure Die-Casting Processes[J]. *Journal of Manufacturing Science and Engineering*, 2008, 130(051009).
- [43] Choi S W, Kim Y C, Cho J I, et al. Influence of die casting process parameters on castability and properties of thin walled aluminium housings[J]. *International Journal of Cast Metals Research*, 2008, 21(1-4): 330-333.
- [44] Jiao X Y, Zhang Y F, Wang J, et al. Characterization of externally solidified crystals in a high-pressure die-cast AlSi10MnMg alloy and their effect on porosities and mechanical properties[J]. *Journal of Materials Processing Technology*, 2021, 298: 117299.
- [45] Arisuda Y, Hasuno A, Yoshida J. Improvement of die life in high speed injection die casting[J]. *China Foundry*, 2008, 5(4): 280-285.
- [46] Zhang Y, Lordan E, Dou K, et al. Influence of porosity characteristics on the variability in mechanical properties of high pressure die casting (HPDC) AlSi7MgMn alloys[J]. *Journal of Manufacturing Processes*, 2020, 56: 500-509.
- [47] Liu W H, Liu Y A, Xiong S M, et al. Influences of Casting Pressure Conditions on the Quality and Properties of a Magnesium Cylinder Head Cover Die Casting[J]. *Journal of Materials Science & Technology*, 2005, 21: 170-174.
- [48] Yalçın B, Koru M, Ipek O, et al. Effect of Injection Parameters and Vacuum on the Strength and Porosity Amount of Die-Casted A380 Alloy[J]. *International Journal of Metalcasting*, 2017, 11(2): 195-206.
- [49] Ferreira A F, Chrisóstimo W B, Sales R C, et al. Effect of pouring temperature on microstructure and microsegregation of as-cast aluminum alloy[J]. *The International Journal of Advanced Manufacturing Technology*, 2019, 104(1): 957-965.
- [50] Liparoti S, Sorrentino A, Speranza V, et al. Fast mold surface temperature evolution: Challenges and opportunities[J]. *AIP Conference Proceedings*, 2019, 2139(1).
- [51] Han X W, Chen D P. Numerical Simulation Life Prediction of Alu- Alloy Die -Casting Dies[J]. *Advanced Materials Research*, 2012, 472-475: 2296-2303.
- [52] Koru M, Serçe O. The Effects of Thermal and Dynamical Parameters and Vacuum Application on Porosity in High-Pressure Die Casting of A383 Al-Alloy[J]. *International Journal of Metalcasting*, 2018, 12(4): 797-813.
- [53] Niu Z C, Liu G Y, Li T, et al. Effect of high pressure die casting on the castability, defects and mechanical properties of aluminium alloys in extra-large thin-wall castings[J]. *Journal of Materials Processing Technology*, 2022, 303: 117525.
- [54] Yang J, Liu B, Shu D W, et al. Effect of ultra vacuum assisted high pressure die casting on the mechanical properties of Al-Si-Mn-Mg alloy[J]. *Journal of Alloys and Compounds*, 2025, 1026: 180531.
- [55] Soares G, Neto R, Madureira R, et al. Characterization of Al Alloys Injected through Vacuum-Assisted HPDC and Influence of T6 Heat Treatment[J]. *Metals*, 2023, 13(2): 389.
- [56] Hu C, Zhao H D, Wang X L, et al. Microstructure and properties of AlSi12Fe alloy high pressure die-castings under different vacuum levels[J]. *Vacuum*, 2020, 180: 109561.
- [57] Yang H M, Yu W B, Cao Y Y, et al. Effect of different processing parameters on interfacial heat-transfer behavior in high-pressure die-casting process[J]. *Transactions of Nonferrous Metals Society of China*, 2018, 28(12): 2599-2606.
- [58] Cao H X, Wang C C, Shan Q Y, et al. Kinetic analysis of pore formation in die-cast metals and influence of absolute pressure on porosity[J]. *Vacuum*, 2019, 168: 108828.
- [59] Łagiewka M, Konopka Z, Nadolski M, et al. The Effect of Vacuum Assistance on the Quality of Castings Produced by High Pressure Die Casting Method[J]. *Archives of Foundry Engineering*, 2014, 14(2): 23-26.
- [60] Szalva P, Orbulov I N. The Effect of Vacuum on the Mechanical Properties of Die Cast Aluminum AlSi9Cu3(Fe) Alloy[J]. *International Journal of Metalcasting*, 2019, 13(4): 853-864.
- [61] Yang J, Liu B, Shu D W, et al. Vehicle giga-casting Al alloys technologies, applications, and beyond[J]. *Journal of Alloys and Compounds*, 2025, 1013: 178552.
- [62] Fiorese E, Bonollo F, Timelli G, et al. New Classification of Defects and Imperfections for Aluminum Alloy Castings[J]. *International Journal of Metalcasting*, 2015, 9(1): 55-66.
- [63] Liu R X, Zheng J, Godlewski L, et al. Influence of pore characteristics and eutectic particles on the tensile

- properties of Al - Si - Mn - Mg high pressure die casting alloy[J]. Materials Science and Engineering: A, 2020, 783: 139280.
- [64] Huang M J, Jiang J F, Wang Y, et al. Correlation between microstructures and mechanical properties of super-sized new-energy automobile structural component formed by vacuum HPDC process[J]. Journal of Materials Research and Technology, 2025, 36: 1146-1159.
- [65] Liu R X, Zheng J, Godlewski L, et al. Influence of pore characteristics and eutectic particles on the tensile properties of Al - Si - Mn - Mg high pressure die casting alloy[J]. Materials Science and Engineering: A, 2020, 783: 139280.
- [66] Marathe S, Quadros C. Thermal hot spot prediction in high pressure die casting by determination of Chvorinovs rule shape constant[J]. Materials Today: Proceedings, 2021, 47: 5607-5617.
- [67] Timelli G, Bonollo F. Microstructure, defects and properties in aluminium alloys casting: a review[M]. ITA, 2007.
- [68] Lee P D, Chirazi A, See D. Modeling microporosity in aluminum - silicon alloys: a review[J]. Journal of Light Metals, 2001, 1(1): 15-30.
- [69] Lee P D, Atwood R C, Dashwood R J, et al. Modeling of porosity formation in direct chill cast aluminum - magnesium alloys[J].
- [70] Zhang Q Y, Sun D K, Pan S Y, et al. Microporosity formation and dendrite growth during solidification of aluminum alloys: Modeling and experiment[J]. International Journal of Heat and Mass Transfer, 2020, 146: 118838.
- [71] Zhang Y X, Xue C P, Wang J S, et al. Quantifying the effects of hydrogen concentration and cooling rates on porosity formation in Al - Li alloys[J]. Journal of Materials Research and Technology, 2023, 26: 1938-1954.
- [72] Liu K, Wang J, Yang Y, et al. An integrated microporosity model of 3D X-ray micro-tomography and directional solidification simulations for Ni-based single crystal superalloys[J]. Computational Materials Science, 2021, 188: 110172.
- [73] Cao H X, Hao M Y, Shen C, et al. The influence of different vacuum degree on the porosity and mechanical properties of aluminum die casting[J]. Vacuum, 2017, 146: 278-281.
- [74] Wan Q, Zhao H D, Zhou C. THREE-DIMENSIONAL CHARACTERIZATION AND DISTRIBUTION OF MICROPORES IN ALUMINUM ALLOY HIGH PRESSURE DIE CASTINGS[J]. Acta Metall Sin, 2013, 49(3): 284-290.
- [75] Lee S G, Gokhale A M. Formation of gas induced shrinkage porosity in Mg-alloy high-pressure die-castings[J]. Scripta Materialia, 2006, 55(4): 387-390.
- [76] Dybowski B, Kielbus A, Poloczek Ł. Effects of die-casting defects on the blister formation in high-pressure die-casting aluminum structural components[J]. Engineering Failure Analysis, 2023, 150: 107223.
- [77] Niu Z C, Liu G Y, Li T, et al. Effect of high pressure die casting on the castability, defects and mechanical properties of aluminium alloys in extra-large thin-wall castings[J]. Journal of Materials Processing Technology, 2022, 303: 117525.
- [78] Richter R, DeYoung D. Control of rolling ingot surface quality[J]. Aluminum Cast House Technology, 2007.
- [79] Jeong S I, Jin C K, Seo H Y, et al. Mould design for clutch housing parts using a casting simulation of high pressure die casting[J]. International Journal of Precision Engineering and Manufacturing, 2016, 17(11): 1523-1531.
- [80] Verran G O, Mendes R P K, Rossi M A. Influence of injection parameters on defects formation in die casting Al12Si1,3Cu alloy: Experimental results and numeric simulation[J]. Journal of Materials Processing Technology, 2006, 179(1): 190-195.
- [81] Miyazaki T, Maruyama Y, Fujimoto Y, et al. Improvement of X-ray stress measurement from a Debye - Scherrer ring by oscillation of the X-ray incident angle[J]. Powder Diffraction, 2015, 30(3): 250-255.
- [82] Sasaki T, Maruyama Y, Ohba H, et al. Two-dimensional imaging of Debye-Scherrer ring for tri-axial stress analysis of industrial materials[J]. Journal of Instrumentation, 2014, 9(07): C07006.
- [83] Jolly M, Katgerman L. Modelling of defects in aluminium cast products[J]. Progress in Materials Science, 2022, 123: 100824.
- [84] Hu B, Li D J, Li Z X, et al. Research Progress on Hot Tearing Behavior of Cast Magnesium Alloys[J]. Journal of NetShape Forming Engineering, 2020, 12(5): 1-19.
- [85] Dai X, Yang X, Campbell J, et al. Influence of oxide film defects generated in filling on mechanical strength of aluminium alloy castings[J]. Materials Science and Technology, 2004.
- [86] Francis J A, Cantin G M D. The role of defects in the fracture of an Al - Si - Mg cast alloy[J]. Materials Science and Engineering: A, 2005, 407(1): 322-329.
- [87] Dhisale M, Vasavada J, Tewari A. An approach to optimize cooling channel parameters of Low pressure Die

- casting process for reducing shrinkage porosity in Aluminium alloy wheels[J]. *Materials Today: Proceedings*, 2022, 62: 3189-3196.
- [88] Dong G, Li S, Ma S, et al. Process optimization of A356 aluminum alloy wheel hub fabricated by low-pressure die casting with simulation and experimental coupling methods[J]. *Journal of Materials Research and Technology*, 2023, 24: 3118-3132.
- [89] Wang Z P, Su X P, Kang Z Y. Design and Optimization of Low Pressure Casting Process Parameters for A356 Aluminum Alloy Wheel Hub[J]. *Hot Working Technology*, 2023.
- [90] Sun J, Le Q, Fu L, et al. Gas entrainment behavior of aluminum alloy engine crankcases during the low-pressure-die-casting process[J]. *Journal of Materials Processing Technology*, 2019, 266: 274-282.
- [91] Timelli G, Caliarì D, Jovidi R. Influence of Process Parameters and Sr Addition on the Microstructure and Casting Defects of LPDC A356 Alloy for Engine Block[J]. *Journal of Materials Science & Technology*, 2016(32): 515-523.
- [92] Gu C, Lu Y, Luo A A. Three-dimensional visualization and quantification of microporosity in aluminum castings by X-ray micro-computed tomography[J]. *Journal of Materials Science & Technology*, 2021, 65: 99-107.
- [93] Zhang Y X, Xue C P, Yang X H, et al. Uncovering the effects of local pressure and cooling rates on porosity formation in AA2060 Al-Li alloy[J]. *Materials Today Communications*, 2023, 35: 106384.
- [94] Wang B, Zhang M S, Wang J S. Quantifying the effects of cooling rates and alloying additions on the microporosity formation in Al alloys[J]. *Materials Today Communications*, 2021, 28: 102524.
- [95] Li X X, Yang X H, Xue C P, et al. Predicting hydrogen microporosity in long solidification range ternary Al-Cu-Li alloys by coupling CALPHAD and cellular automata model[J]. *Computational Materials Science*, 2023, 222: 112120.
- [96] Kohlstädt S, Vynnycky M, Goeke S, et al. On Determining the Critical Velocity in the Shot Sleeve of a High-Pressure Die Casting Machine Using Open Source CFD[J]. *Fluids*, 2021, 6(11): 386.