OPTIMIZING LOW-PRESSURE DIE CASTING OF A356 ALUMINUM ALLOY WHEEL RIMS: A NOVEL SIDE CORE WITH INTEGRATED COOLING SYSTEM

Roni Kusnowo[1], Hanif Azis Budiarto[2*], Cecep Ruskandi[3], Sophiadi Gunara[4], Ery Hidayat[5], Muhammad Nahrowi[6], Emma Dwi Ariyani[7]
Department of Foundry Engineering, Politeknik Manufaktur Bandung, Bandung, Indonesia[13456]
Department of Design Engineering, Politeknik Manufaktur Bandung, Bandung, Indonesia[2]
Department of Manufacturing Engineering Technology, Politeknik Manufaktur Bandung, Bandung, Indonesia[7]
hanif@de.polman-bandung.ac.id

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**Corresponding Author*

ABSTRACT
This study explores the development of a novel side core design with an integrated cooling system for the low-pressure die casting (LPDC) of A356 aluminum alloy wheel rims in Indonesia. The objective is to reduce cycle time and minimize casting defects. The methodology involves 3D modeling using SolidWorks and simulations performed with MAGMAsoft to evaluate filling and solidification behavior, air pressure, and air entrapment. Notably, this is the first application of a cooling system in Side cores within the Indonesian automotive industry, motivated by the need to improve production efficiency and product quality, as current manufacturing processes suffer from long cycle times and high defect rates. Simulation results show a significant reduction in cycle time by 72 seconds, improving both efficiency and product quality. This study demonstrates the effectiveness of integrating cooling systems into side cores to enhance the LPDC process.
Keywords : *Side core, LPDC, cooling system, A356, Wheel, Magmasoft.*

1. Introduction

The automotive industry is a rapidly growing economic sector worldwide. Throughout its development, various innovations and technologies have been implemented to enhance the quality, efficiency, and competitiveness of automotive products. One crucial component in the automotive realm is the wheel rims (Figure 1), which significantly impacts both vehicle performance and aesthetics. Wheel rims are typically composed of various materials, with steel, aluminum alloy, and magnesium alloy being the primary types. The aluminum alloy wheel hub, constituting approximately 54% of the global wheel rims market, is particularly favored due to its lightweight nature, effective heat dissipation, high safety factor, and versatile design (Dong et al., 2023a). Also, the economic attractiveness of utilizing aluminum alloys for producing wheel rim also stems from their properties, including recyclability, strength, corrosion and wear resistance, and their processing and machining capabilities (Yağcı et al., 2021a).

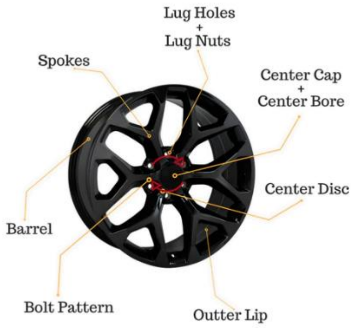


Fig. 1. Part of wheel rim (Jenny Estrada, 2018)

Low Pressure Die Casting (LPDC) is the primary method for manufacturing aluminum alloy wheel rims, with approximately 80% of aluminum alloy rims produced using this process. The LPDC method is known for its simplicity, automation, and ability to meet stringent performance and cost requirements, making it ideal for manufacturing complex structures like wheel rims (Fang et al., 2024). The Low Pressure Die Casting (LPDC) process operates cyclically, starting with the furnace pressurization. The heightened pressure within the furnace compels the upward movement of the aluminum melt, guiding it into the die cavity where it solidifies by transferring heat from the metal to the die. In the LPDC process, the melt is discharged from the bottom of the mold, ensuring a smooth and easily regulated mold-filling course. Simultaneously, castings undergo solidification under external pressure, resulting in compact components with a 10% enhancement in their mechanical properties compared to those produced using conventional foundry techniques (Kusnowo et al., 2021).

Dies/Molds represent the second largest investment after machinery. In the context of wheel rim manufacturing, the Side Core is a crucial component of the mold for forming the barrel, as depicted in Figure 1. The barrel encompasses the entire outer surface of the wheel where the rubber tire sits. Due to its complex geometry, the side core cannot be produced through machining processes but rather through sand casting.

In Indonesia, manufacturers face significant challenges in optimizing wheel rim production due to recurring defects like porosity and cracking, which are largely caused by insufficient mold cooling. These defects are particularly common in areas such as the spoke junction, where hotspots form due to uneven cooling rates in the mold (Guofa et al., 2009a; Kusnowo & Hidayat, 2021). Production capacity is often hampered by these failures, which not only increase rejection rates but also slow down manufacturing cycles. The X-ray image below depicts a rejected product attributed to a hotspot.

Fig. 2 Hot spot in rims

As seen in figure 3, it is evident that the product cycle time remains high. The company's production capacity for wheel rims is targeted at 180,205 units per month, with an average operational cycle time of 390 seconds per rim. Furthermore, research has shown that integrating cooling systems into molds can significantly reduce mold temperatures, product defects and increase productivity (Chavan & Kulkarni, 2020; Guofa et al., n.d.; Jadhav et al., 2021a; Kırmızıgöl S. Fatih et al., 2019a; Samuel et al., 2023a).

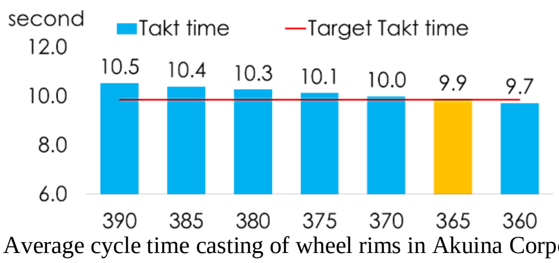


Fig. 3. Average cycle time casting of wheel rims in Akuina Corporation.

However, the application of cooling systems on side cores has not been widely adopted in Indonesia. This may be due to several technological, economic, and logistical challenges. For instance, materials like SKD 6, commonly used in mold production, are only available in block form and require extensive machining, all of which must be imported, significantly driving up costs. Addressing this gap could help manufacturers in Indonesia enhance production efficiency, reduce defect rates, and improve overall product quality, aligning with the industry's increasing demand for high-performance, defect-free wheel rims.

Therefore, this study aims to evaluate the effects of incorporating a cooling system on side cores in the LPDC process for wheel rim manufacturing. By using simulation-based analysis, the research seeks to optimize the production process, reducing defects, improving cycle times, and increasing the durability and performance of the final products.

2. Literature Review

Low Pressure Die Casting (LPDC)

Low pressure die casting is a metal casting process conducted under low pressure, typically used to produce complex metal parts with high precision and surface finish, especially in aluminum alloys (Kridli et al., 2020a). This method offers significant advantages, such as minimized gas entrapment and reduced porosity, leading to superior product quality. Additionally, the controlled filling of the mold cavity allows for intricate geometries and less post-production machining, making LPDC a versatile and efficient manufacturing process for automotive components like wheel hubs This method offers significant advantages, such as minimized gas entrapment and reduced porosity, leading to superior product quality. Additionally, the controlled filling of the mold cavity allows for intricate geometries and less post-production machining, making LPDC a versatile and efficient manufacturing process for automotive components like wheel hubs (Cleary, 2010; Jadhav, Hujare, & Hujare, 2021; G. G. Wang & Weiler, 2023). The LPDC process involves a crucible, stoke body, and die-casting device equipped with heating furnaces and cooling systems, which are critical for ensuring proper solidification and casting quality (Kırmızıgöl S. Fatih et al., 2019).

In wheel hub production, LPDC is preferred due to its simplicity, automation, and capability to produce complex shapes under controlled conditions. Figure 4 outlines the flow process of LPDC for wheel hubs, illustrating how the method minimizes defects through careful management of mold filling and solidification stages.

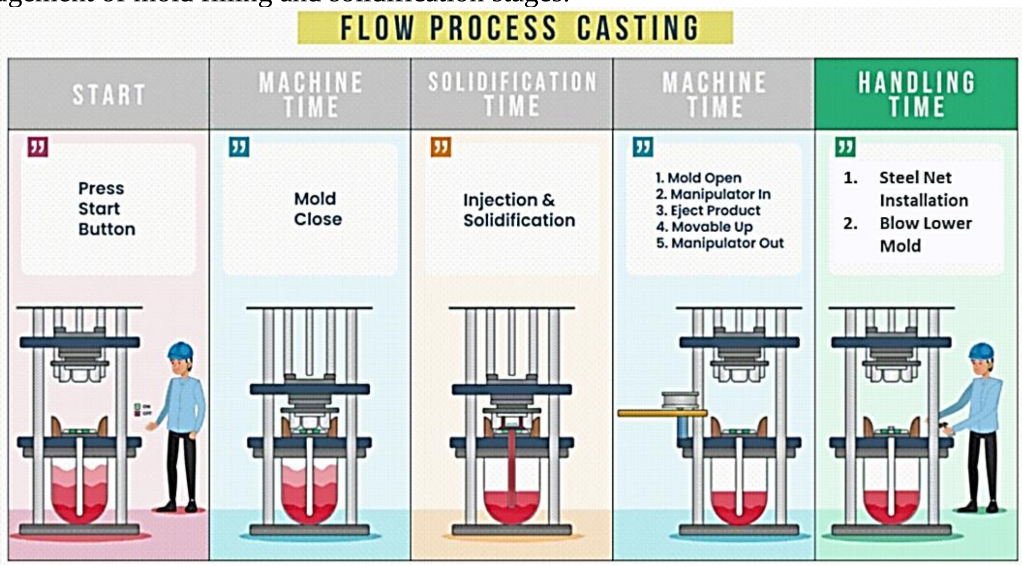


Fig. 4. Flow process LPDC

While advantageous for producing wheel aluminum alloys, exhibit several weaknesses that can impact product quality and manufacturing efficiency.

Common Defects

- *Casting Defects*: LPDC is prone to defects such as shrinkage, un-filling, blowholes, and porosity, which can compromise the integrity of the castings ((Waghmare & Bhatia, 2019)).
- Macro-Porosity: The formation of macro-porosity remains a significant challenge, often linked to process variability and inadequate control of operational parameters (Fan et al., 2019; Uyan et al., 2023a).

Process Limitations

- Turbulence Issues: The turbulence during metal filling can lead to defects, necessitating advanced control methods to mitigate these effects (Gursoy et al., 2021; Uyan et al., 2023b).
- Temperature Sensitivity: The casting temperature must be meticulously controlled; deviations can exacerbate defect rates, as seen in studies where optimal temperatures were critical for reducing defects (Fan et al., 2019; Waghmare & Bhatia, 2019).

Wheel Hub Material: A356

A356 is an aluminum-silicon-magnesium alloy widely used in the automotive industry, particularly in casting wheel hubs due to its excellent mechanical properties, lightweight nature, and corrosion resistance. The alloy is part of the 3xx.x series, classified by the Aluminum Association (AA) and offers a balance of strength, recyclability, and cost-efficiency for automotive applications (Dong et al., 2023c).

Table 1 - Material composition and properties of A356 (Dong et al., 2023c).

Specification			Units
Chemical	Al	Bal	%
Composition	Si	6.74	%
	Mg	0.35	%
	Fe	0.08	%
Physical parameters	Density	2.7 x 103	$kg\cdot m^{-3}$
	Specific Heat	0.963	$kJ\cdot kg^{-1}\cdot K^{-1}$
	Conductivity	42.2	$W\cdot m^{-1}\cdot K^{-1}$
	Solid-Liquidus	548-613	^oC
	Viscosity	1.17-1.83	centipoise

The composition of A356, which includes aluminum, silicon, and magnesium, makes it suitable for producing structural components such as control arms, wheels, and engine cradles (Kridli et al., 2020b) . Its relatively low viscosity, typically ranging between 1.17-1.83 centipoise, enhances the alloy’s ability to flow smoothly into molds during the casting process. This characteristic is particularly advantageous in the production of wheel rims, where the material must fill intricate mold designs while maintaining uniformity. The low viscosity also helps to minimize the formation of voids and other casting defects, contributing to the high dimensional accuracy and structural integrity required for wheel applications. Additionally, these properties lead to reduced vehicle weight and improved fuel efficiency (Dong et al., 2023b; Y. He et al., 2023a; Waghmare & Bhatia, 2019). Furthermore, its casting properties enable mass production of complex components with relatively low processing times and costs, making it ideal for high-volume manufacturing in the automotive sector (Berlanga-Labari et al., 2020; J. Gilbert Kaufman; & Elwin L. Rooy, 2004).

Die Material: SKD 6

SKD 6, a medium carbon alloy steel, is frequently employed in the production of dies for casting nonferrous materials due to its creep resistance and ability to handle complex geometries (X. He et al., 2020; Xue et al., 2021). The production of SKD 6 steel often involves rolling and forging techniques, but due to the cost and complexity of machining the material, sand casting is a preferred method for producing dies in automotive applications (Kusnowo et al., 2023a). Furthermore, certain studies have explored innovative methods, including recrystallization and partial melting (RAP) process, to fabricate SKD 6 (Meng et al., 2012).

With the current research, using SKD 6 in Side core design is critical due to its ability to withstand high-pressure and high-temperature conditions during the low-pressure die casting (LPDC) of aluminum wheels. Its creep resistance ensures dimensional stability and durability over prolonged cycles, which aligns with the research's objective to reduce cycle time and enhance production efficiency while maintaining product quality. The material’s toughness also helps minimize wear and tear on the dies, thus prolonging the life of the molds and reducing operational costs. Therefore, due to the intricacy of the geometry and the consideration of cost-effectiveness, sand casting has emerged as the most efficient approach for generating aluminum dies, including side cores, in automotive applications (Kusnowo et al., 2023b).

Table 2 - Material composition and properties of SKD 6 (ASM International, 1998).

Specification			Units
Chemical	C	0.32 – 0.42	%
Composition	Si	0.8 – 1,2	%
	Mn	0.5 max	%
	Cr	4.5 – 5.5	%
	V	0.3-0.5	%
	Mo	1 – 1.5	%
	S	< 0.02	%
	P	< 0.03	%
Physical parameters	Density	7.67	$kg\cdot m^{-3}$
	Specific Heat	0.46	$kJ\cdot kg^{-1}\cdot K^{-1}$
	Conductivity	25	$W\cdot m^{-1}\cdot K^{-1}$

Interfacial Heat transfer Coefficient

The interfacial heat transfer coefficient (IHTC) is crucial in understanding the heat exchange between the casting and the mold during solidification. Accurate measurement of IHTC can help optimize the cooling rates in the LPDC process, preventing defects like porosity and incomplete filling (Su et al., 2012).

There are two approaches for determining the interfacial heat transfer coefficients: one involves measuring the air gap size and correlating it to the appropriate coefficients, while the other, a more precise method, entails measuring temperatures at various points in the casting and the chill and using inverse techniques to calculate the IHTC (Liu et al., 2020).

The assumption was made that the movement of liquid metal was that of an incompressible Newtonian fluid. The equations that govern the filling and solidification stages in LPDC are as described below (Mi et al., 2009):

Navier-stokes equation.

$$\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\rho g_x+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (1)$$

$$\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\rho g_y+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (2)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\rho g_z+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (3)$$

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z} \quad (4)$$

Heat transfer equation.

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+L\frac{\partial f_s}{\partial t} \quad (5)$$

Where ρ represents the density, u, v, and w denote the velocity vectors, t represents the time, μ signifies the dynamic viscosity of the liquid metal, g_x, g_v, and g_z represent the gravitational acceleration vectors, p represents the pressure, C_p represents the specific heat of molten metal, λ represents the thermal conductivity, T represents the temperature, L represents the latent heat, and f_s represents the solid phase fraction at the solidification stage.

Beck et al.'s method for calculating IHTC is widely regarded as reliable, as it considers both the mold and casting temperatures simultaneously, improving the accuracy of the heat transfer analysis (Mi et al., 2009). The ability to manage heat transfer through careful calculation of IHTC is crucial in high-performance applications such as automotive wheel hub manufacturing, where precise thermal control is essential for ensuring product quality.

3. Research Methods

The research approach adopted in this study aims to reduce cycle time and production costs by improving the design of the side core in low-pressure die casting (LPDC) for wheel rim manufacturing. The methodology follows a systematic analysis of the existing condition, 3D modelling, simulation, and validation, all of which are closely tied to the research objectives. By analyzing the performance of the current condition and incorporating a cooling system, this study seeks to enhance both efficiency and product quality. Therefore, the new research method is outlined in figure 5.

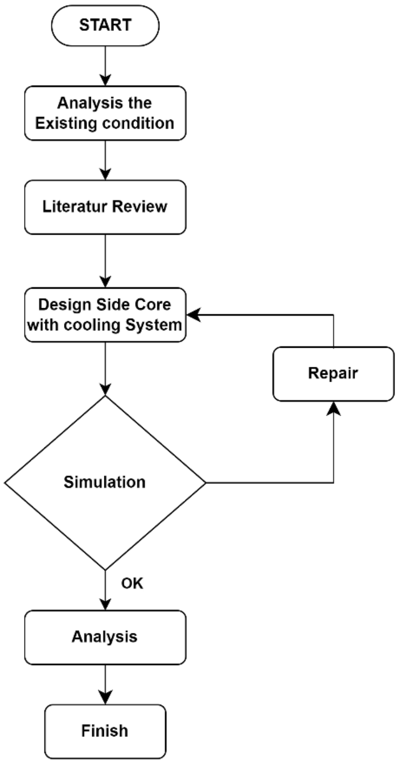


Fig. 5. Research Methodology

Existing Condition

The first phase of the research involved an analysis of the existing conditions, focusing on the actual performance of the current side core design during LPDC operations. A genba approach was utilized, where direct observations of the manufacturing process were conducted at the production site (Romansyah et al., 2023). This included monitoring key performance metrics such as cycle time solidification time and existing design. The data was then analyzed to identify potential areas of improvement. Design changes were made based on the findings and implemented at the production site. Finally, the performance of the modified side core design was evaluated and compared to the original design.

3D Modelling and Simulation

A new side core model was created using SolidWorks, to address the inefficiencies identified, incorporating a cooling system aimed at improving heat dissipation. A comprehensive list of requirements was compiled to streamline the allocation of operators and machines, as delineated in Table 3.

Table 3 - Design Parameter

Design Parameter	
Demands	Qualification
Product	
Product Dimension	According to 3D Model
Material	A356
Side Core	
Material	SKD 6

Foundry Process	Easy to foundry
Machining Process	Easy to machine
Assy Process	Easy to installation and maintenance
Cycle time	< 365 second

The use of MAGMAsoft for advanced simulation had a significant impact on subsequent design decisions. The filling simulation provided valuable insights into the behavior of molten metal during mold filling, leading to adjustments that minimized turbulence and ensured smooth flow. Similarly, the solidification simulation highlighted the importance of the cooling system in reducing thermal gradients and preventing defects such as porosity (Seydani et al., 2024). These findings directly influenced design decisions, resulting in modifications aimed at improving cycle time, temperature uniformity within the mold, and overall defect rates

The precise outcomes achieved through the use of a tetrahedron mesh with good adaptability and a designated mesh size of 6 mm in critical areas further contributed to informed design adjustments (Dong et al., 2023c). Furthermore, to enhance the accuracy of efficiency, the grid ruler of position surface of Side core was set to 10 mm. Consequently, the minimum side length of surface gride quality becomes less than 0.25.

Boundary condition

After the meshing process, it is imperative to establish a specific boundary condition for the flow of molten metal into the die and for the intensification phase. This step is crucial as it encompasses both fluid flow and heat transfer considerations.

Based on empirical production data, the optimal casting temperature is determined to be 700 °C and the mold temperature at 450 °C. While the LPDC pressure curve is shown in figure 6. Deviation from this temperature range can lead to various casting defects. Insufficient temperature contributes to defects such as cold shuts, misruns, and underfilling (Iwata et al., 2014). Conversely, excessively high temperatures pose their own set of challenges. Elevated temperatures promote the absorption of hydrogen gas by the molten metal from the surrounding atmosphere, exacerbating the risk of hydrogen-related porosity. Furthermore, heightened temperatures accelerate thermal erosion and cracking of the mold, significantly reducing its longevity and operational effectiveness. Accordingly, maintaining precise control within the specified temperature range is imperative to ensure quality casting outcomes, prolong the lifespan of the mold, and prevent issues such as poor metal flow and underfilling (Y. He et al., 2023b; Vossel et al., 2020).

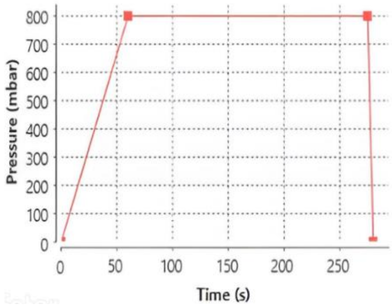


Fig. 6. The LPDC pressure curve

Analysis

This section compares the simulation results between the existing side core design without a cooling system (V01) and the new side core equipped with a cooling system (V02). The analysis aims to evaluate the performance of both designs in terms of production cycle time, heat distribution, and casting quality. The simulation results will demonstrate the effectiveness of the cooling system in reducing solidification time, lowering thermal gradients, and minimizing defects such as porosity compared to the side core without a cooling system.

4. Results and Discussions

Analysis the Exisiting Condition

The genba results indicate that the cycle time for the existing side core is 447 seconds, while the target cycle time is set at 410 seconds (as shown in Table X). It is also observed that solidification time is the most dominant factor in the overall production process. Therefore, reducing cycle time by shortening solidification time is considered the optimal solution.

Table 4 - Cycle Time from Genba

Item	Standard (s)	Nth Observation					The Mode (s)
		1	2	3	4	20	
Machine time	40	50	48	50	50	50	50
Solidification Time	365	250	261	390	388	390	390
Handling Time	5	7	7	6	7	7	7
Cycle Time	410						447

In Figure 7, the solidification time for the side core is presented. The results show that if the solidification time for the existing side core is accelerated, defects such as those shown in Figure 8 will occur. Porosity is present in the product hub region. This is caused by the process being forced before the metal has fully solidified, resulting in incomplete solidification at the end of the process. This, in turn, decreases the product's strength due to the porosity. The relationship between solidification time and product quality is crucial. Faster solidification can lead to defects like porosity, which compromises the product's structural integrity. Therefore, optimizing solidification time is essential to ensure a high-quality, defect-free final product. Consequently, a new solution is required, which involves designing a new side core equipped with a cooling system.

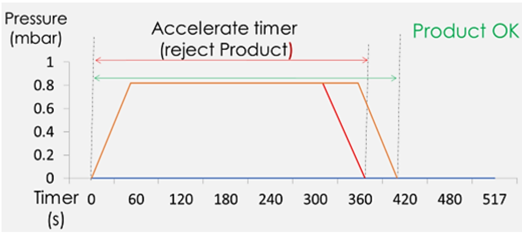
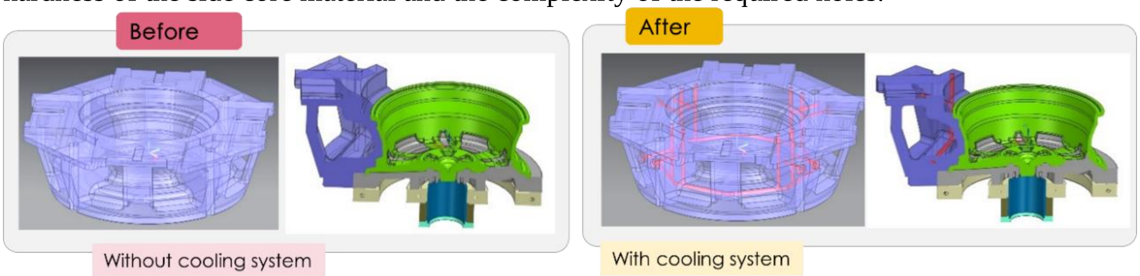


Fig. 7. The LPDC pressure curve

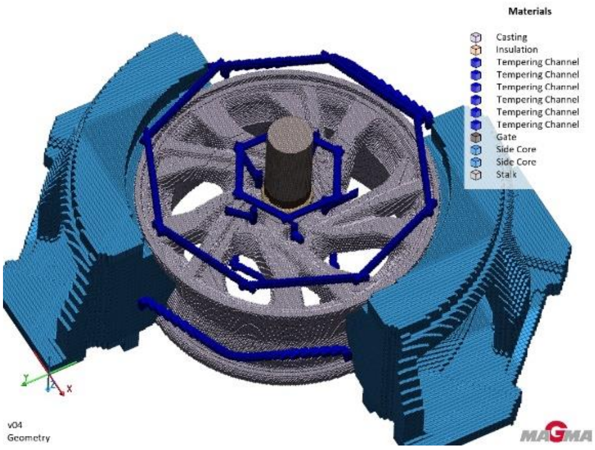
Fig. 8 Porosity in hub area

4.1 3D modelling

Figure 4 shows a comparison of the side core design before and after the implementation of a cooling system. This cooling system is separately designed using steel pipe channels, enabling the installation process of the cooling pipes during the mold manufacturing stage. With this approach, the need for drilling cooling channels can be eliminated. The benefits are significant as this post-production process is time-consuming and challenging, considering the hardness of the side core material and the complexity of the required holes.



(a) (b)



(c)

Fig. 9. 3D modelling of side core (a) without cooling system (b) with cooling system. (c) Mesh of the rims and Side core

4.2 Filling simulation

The evaluation of casting issues during the cavity filling process, especially those arising from decreased molten metal temperature, mold temperature, and trapped air, is essential. These factors can lead to various defects in the final product (Dong et al., 2023a), ultimately compromising its quality and structural integrity (Dybowski et al., 2023; Uyan et al., 2023a).

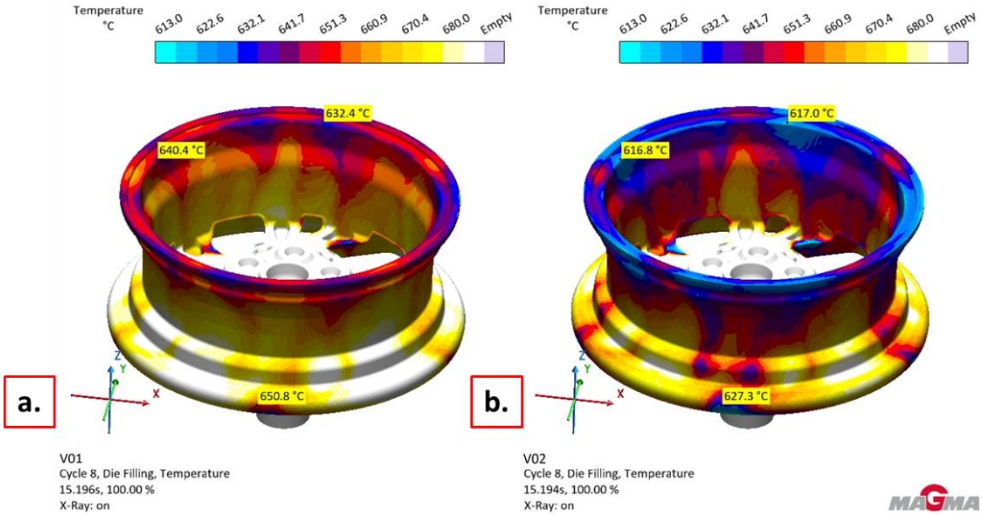


Fig. 10. Temperature distribution (a) V01: without cooling system (b) V02: with cooling system

Figure 9 illustrates the temperature distribution during the filling process in two configurations:**(**a) V01: without cooling system and (b) V02: with cooling system. In the continuous casting process, the water-cooling system along the sides effectively reduced the mold temperature. This reduction in mold temperature is crucial as it directly impacts the solidification rate of the material, leading to a more uniform grain structure. Consequently, the final product exhibits enhanced mechanical properties and reduced internal stresses. Consistent temperature management ensures higher quality and fewer defects in the cast material (Guerra et al., 2023; Huang et al., 2019). However, a significant temperature drop in the molten metal was observed, resulting in defects such as cold shuts (Iwata et al., 2013; Seydani et al., 2024).

Notably, Design V02 exhibits a lower molten metal temperature compared to Design V01 when the cavity is 100% filled (as seen in Figure 5). Despite this reduction, the temperature remains above the standard liquidus temperature threshold of $T \leq 613°C$. Therefore, while the simulation-driven addition of cooling channels on the side core affects overall mold temperature, it does not appear to introduce defects like cold shuts in the final product.

In terms of microstructure, the cooling rate during solidification leads to notable variations across the casting. Regions that experience slower cooling rates tend to develop coarser microstructures, whereas areas with faster cooling rates exhibit finer grain structures. This variance in cooling not only affects grain refinement but also contributes to the formation of shrinkage porosity. Such defects are typically more prevalent in areas with thicker walls and junctions due to uneven cooling (Huang et al., 2019; Y. Li et al., 2022).

The mechanical properties of the castings, including tensile strength and hardness, are closely tied to these microstructural changes. Studies have demonstrated that optimizing temperature control during the LPDC process can significantly enhance these mechanical properties. For example, various thermal treatments applied to LPDC 319 Al alloy have shown improvements in both strength and hardness (Vandersluis et al., 2020). However, it is important to note that mechanical performance can vary by up to 12% across different regions of a casting, further underscoring the importance of maintaining uniform temperature distribution throughout the process (Y. Li et al., 2022).

Nevertheless, while uniform temperature control is crucial to minimizing defects and ensuring consistent quality, there are scenarios where localized variations in temperature can be beneficial. Targeted temperature adjustments can enhance specific mechanical properties in certain areas of the casting, thus offering potential advantages depending on the intended application of the final product.

Max air pressure

The simulations revealed that peak air pressure levels between Design V01 and V02 vary, with V01 exceeding 1100 mbar and V02 below it. This suggests a low likelihood of blow hole defects in Design V02, as these defects typically occur when air pressure exceeds 1100 mbar. Elevated air pressure shortens takt time and accelerates metal movement. However, for commercial viability, maintaining 850-1100 mbar is recommended. However, for commercial viability, maintaining air pressure within the range of 850-1100 mbar is recommended (Ou et al., 2020).

Blow holes, a casting defect, are caused by high air pressure levels during the metal casting process. This phenomenon typically arises when gas is released from the mold or the metal itself, and if the pressure is too high, it can create pockets of gas that become encapsulated as the metal solidifies. These voids can compromise the final product's structure and lead to failure (Latte & Chougule, 2017; Nagasankar P et al., 2018).

On the other hand, excessively low air pressure can lead to cold shuts, which occur when the metal solidifies before fully filling the cavity (Iwata et al., 2014). These defects are particularly problematic in casting, where flow dynamics and cooling rates are critical. Studies have shown that poor mold design and converging metal flow significantly contribute to cold shut formation (Kumar et al., 2023a). Advanced simulation techniques, such as the Volume-of-Fluid (VOF) method, have proven effective in predicting cold shuts and helping manufacturers optimize casting parameters before production reducing defects (Jabbari et al., 2014; Kumar et al., 2023a).

Therefore, the balance of air pressure is critical in ensuring high-quality casting results, and this simulation helps determine the appropriate air pressure range to mitigate both blow holes and cold shuts during the molten metal filling process (Iwata et al., 2014).

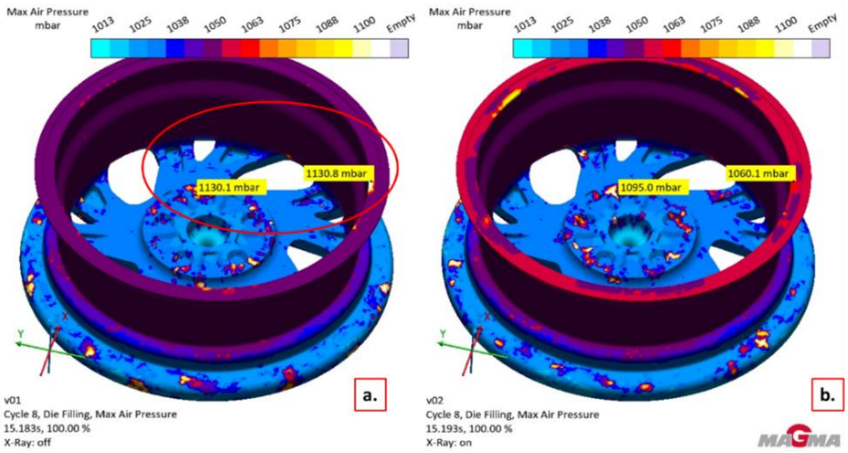


Fig. 11. Max air pressure (a) V01: without cooling system (b) V02: with cooling system

Air entrapment

In the analysis of air entrapment within casting cavities, which can lead to gas porosity, it is imperative to address potential issues arising from the design of non-side water cooling, denoted as V02 (S. Li et al., 2010; Majerník & Podaril, 2019). Specifically, in commercial purposes, a considerable risk of gas porosity occurrence due to inadequate air entrapment accounting for less than 30% of the total volume. As shown in figure 11, the V01 has more than 30% air entrapment. In contrast, V02 demonstrates significantly lower air entrapment, accounting for less than 30% of the total volume. This distinction highlights the importance of design considerations in minimizing gas porosity. The comparative analysis indicates that V02 is more efficient at reducing air entrapment than V01. V02’s design incorporates optimized cooling channels and improved venting mechanisms that facilitate better airflow and reduce the likelihood of air pockets forming. Additionally, the strategic placement of cooling system enhances the uniformity of the cooling process, thereby minimizing areas where air can become trapped. These design improvements collectively contribute to the lower air entrapment observed in V02, making it a more effective solution in commercial casting applications.

Air entrapment within casting cavities is primarily caused by the interaction between air and liquid metal during the mold filling stage (S. Li et al., 2010; Majerník & Podaril, 2019). Water cooling systems efficiently dissipate heat from the die, reducing the temperature gradient between the molten metal and the die surface. This minimizes thermal expansion differences that can lead to air pockets forming between the molten metal and the die surface (Q. He et al., 2017). Further, by maintaining optimal die temperature, water cooling systems facilitate smoother metal flow during the casting process. This reduces turbulence and eddies that can trap air bubbles within the molten metal, leading to fewer instances of air entrapment (Bate et al., 2023; X. Wang et al., 2023).

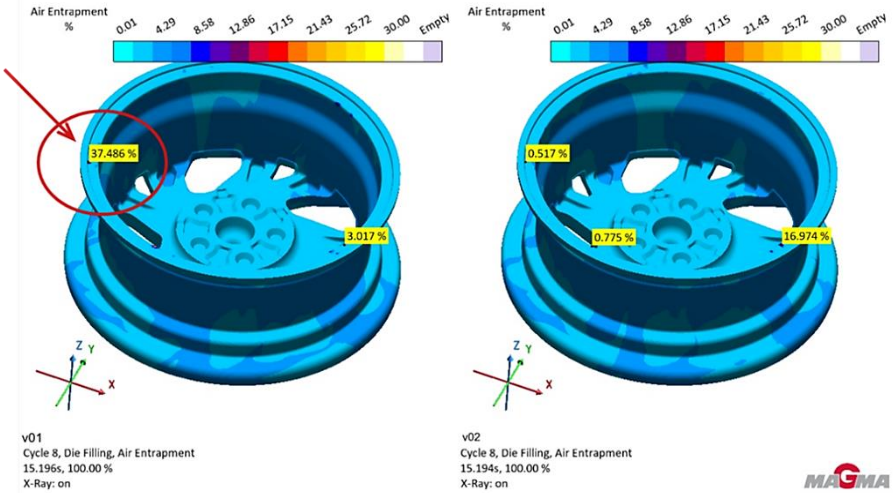


Fig. 12. Air entrapment (a) V01: without cooling system (b) V02: with cooling system

4.3 Solidification Simulation

Based on the analysis of solidification rates, it is evident that the solidification rate within the cavity of the side water cooling design (Figure 12.b) is generally faster on a point-by-point comparison basis. For instance, data shows that the solidification rate at the Hub area is 0.247 mm/s, compared to 0.324 mm/s in the traditional design. Similarly, at the outer lip, the solidification rate is 1.365 mm/s, while the conventional method only achieves 1.576 mm/s. These measurements clearly illustrate the enhanced efficiency of the side water cooling design.

Figure 13 illustrates the solidification temperature in areas equipped with a cooling system. The temperature in these areas drops significantly, reducing solidification and cooling time by half. A similar trend is observed in the solidification time simulation (Figure 14). The simulation results suggest a potential cycle time reduction of 72 seconds. This reduction is noted exclusively in the filling and solidification phases, without considering cycle time related to handling and machine movements.

The solidification rate refers to how quickly the metal cools and solidifies during the casting process, typically expressed in units of time per distance or volume. On the other hand, solidification time represents the total duration required for the liquid metal to transform into a solid within the mold completely.

The implementation of a cooling system plays a crucial role in optimizing the solidification process in casting. By efficiently dissipating heat from the mold, cooling systems such as side water cooling enhance the thermal management of the casting process (Y. He et al., 2023b). This not only accelerates the solidification rate but also helps maintain uniform cooling throughout the casting, reducing the likelihood of defects such as shrinkage cavities or porosity (Guofa et al., 2009b). Moreover, the controlled cooling provided by such systems also minimizes thermal stresses within the casting, contributing to improved dimensional accuracy and overall quality of the final product (Zhang et al., 2023) This can help to reduce the need for postprocessing, such as machining, and can also reduce energy costs. Furthermore, the use of controlled cooling can also reduce the amount of waste generated during casting. Minimizing postprocessing can lead to substantial economic benefits for manufacturers. By reducing the need for additional machining and finishing tasks, companies can save on labor costs and decrease production time. Additionally, lowering energy consumption during these stages further cuts operational expenses, ultimately enhancing overall profitability.

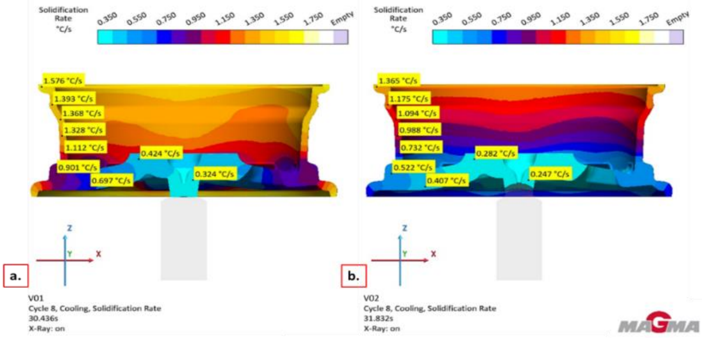


Fig. 13. Solidification rate (a) V01: without cooling system (b) V02: with cooling system

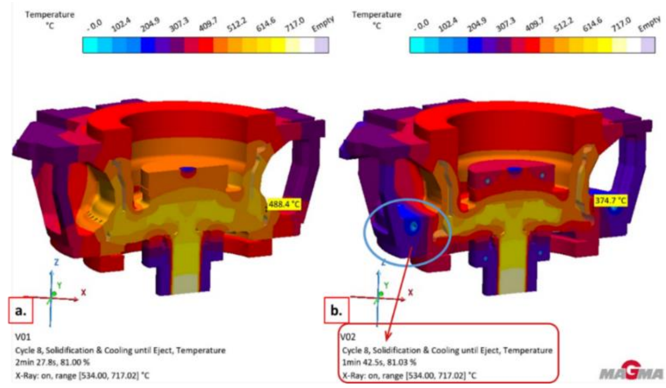


Fig. 14. Solidification temperature in the mold (a) V01: without cooling system (b) V02: with cooling system

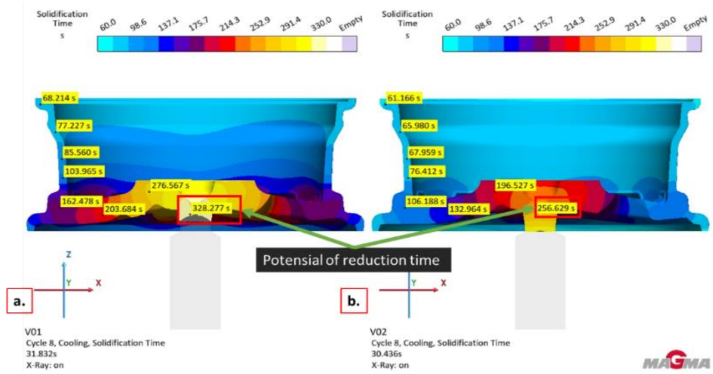


Fig. 15. Solidification time (a) V01: without cooling system (b) V02: with cooling system

4.4 Porosity

The solidification simulation indicates a risk of Shrinkage Porosity both in designs V01 and V02, as shown by the simulation results (Figure 15): Porosity in the root area. However, the design with Side Water (figure 15.b.) exhibits lower porosity values compared to the non-side water cooling design. The design likely incorporates better cooling channel placement and optimized cooling rates, allowing for more uniform solidification and less localized shrinkage compared to V01.

Shrinkage porosity refers to voids or cavities formed within a casting due to the shrinkage of the metal as it transitions from a liquid to a solid-state during solidification. This type of porosity typically occurs in areas of the casting where the metal undergoes the greatest volume reduction as it cools and solidifies (Uyan et al., 2023a). Porosity can have significant adverse effects on the final product's performance, reliability, and lifespan. Voids and cavities caused by shrinkage porosity reduce the material's overall strength and structural integrity, making the component more susceptible to fatigue, cracking, and failure under stress.

Water cooling systems also help to mitigate shrinkage porosity by controlling the rate of cooling and solidification of the casting. By maintaining a uniform temperature distribution and promoting rapid and consistent cooling, water cooling systems minimize the volume changes that occur during solidification, reducing the likelihood of void formation (Dybowski et al., 2023).

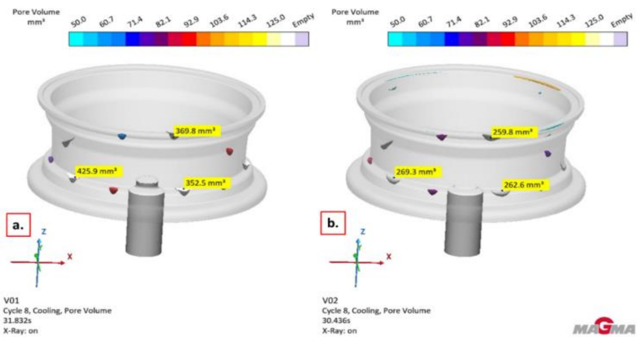


Fig. 16. Shrinkage Porosity (a) V01: without cooling system (b) V02: with cooling system

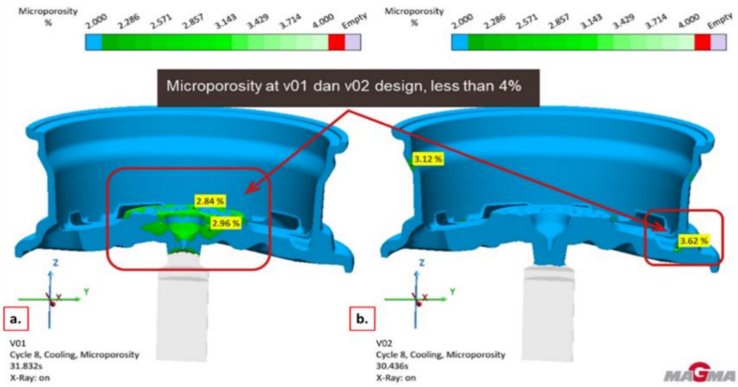


Fig. 17. Microporosity (a) V01: without cooling system (b) V02: with cooling system

Microporosity or micro shrinkage indicates locations that are at risk of leakage issues and potential cracking during testing. The occurrence potential of microporosity is evaluated by failure, where microporosity values ≥ 4%.

Microporosity refers to tiny voids or pores within a solidified material, typically found in castings. These micropores are often not visible to the naked eye but can significantly compromise the structural integrity and mechanical properties of the material (Adeleke et al., 2022). In the context of casting processes, microporosity can occur due to various factors such as insufficient cooling rates, improper gating and riser design, or inadequate venting systems (Samuel et al., 2023b).

4.5 Summary

The simulation results demonstrated improvements in shrinkage porosity and solidification time with the implementation of the cooling system, but there are several limitations and unexpected findings that warrant critical analysis. First, the cooling system, while effective at reducing porosity and enhancing solidification, also caused a noticeable drop in molten metal temperature (Figure 10), leading to potential defects like cold shuts, which were unexpected given the intended uniformity of cooling. Although the overall temperature remained above the liquidus threshold, such temperature variations could introduce risks if not carefully controlled.

Additionally, the simulation indicated that Design V02 had a lower air entrapment percentage compared to V01, which was beneficial. However, air entrapment remained a persistent issue, especially in areas with complex geometries where even the optimized cooling system could not fully eliminate void formation. This suggests that further adjustments to venting mechanisms or casting parameters may be needed to fully resolve gas porosity issues.

Finally, the cooling system successfully accelerated solidification, reducing the cycle time by 72 seconds. However, the faster cooling in some areas also led to increased thermal stresses, which might affect the overall structural integrity of the cast parts over time. These thermal stresses could reduce the lifespan of the components, particularly in areas with complex junctions that experience uneven cooling.

Future studies should focus on refining the cooling system design, particularly to address temperature drops and air entrapment, as well as investigating the long-term effects of increased thermal stresses on product durability.

5. Conclusion

This study successfully employed CAE simulation to optimize the low-pressure die casting (LPDC) process for producing aluminum wheels. The integration of a cooling system into the side core design showed significant improvements in production efficiency. The key findings reveal that the modified side core with a cooling system achieved a solidification time reduction of 72 seconds, alongside enhanced performance in terms of air pressure control, reduced air entrapment, and minimized porosity. These results demonstrate the effectiveness of incorporating cooling systems into LPDC molds to not only increase productivity but also to ensure better product quality.

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References

Adeleke, A. A., Oki, M., Anyim, I. K., Ikubanni, P. P., Adediran, A. A., Balogun, A. A., Orhadahwe, T. A., Omoniyi, P. O., Olabisi, A. S., & Akinlabi, E. T. (2022). Recent Development in Casting Technology: A Pragmatic Review. *Revue Des Composites et Des Matériaux Avancés*, *32*(2), 91–102. https://doi.org/10.18280/rcma.320206

ASM International. (1998). *Metals Handbook Desk Edition* (J. R. Davis, Ed.). ASM International. https://doi.org/10.31399/asm.hb.mhde2.9781627081993

Bate, C., King, P., Sim, J., & Manogharan, G. (2023). A Novel Approach to Visualize Liquid Aluminum Flow to Advance Casting Science. *Materials*, *16*(2), 756. https://doi.org/10.3390/ma16020756

Berlanga-Labari, C., Biezma-Moraleda, M. V., & Rivero, P. J. (2020). Corrosion of cast aluminum alloys: A review. *Metals*, *10*(10), 1–30. https://doi.org/10.3390/met10101384

Chavan, R., & Kulkarni, P. S. (2020). Die design and optimization of cooling channel position for cold chamber high pressure die casting machine. *IOP Conference Series: Materials Science and Engineering*, *810*(1). https://doi.org/10.1088/1757-899X/810/1/012017

Cleary, P. W. (2010). Extension of SPH to predict feeding, freezing and defect creation in low pressure die casting. *Applied Mathematical Modelling*, *34*(11), 3189–3201. https://doi.org/10.1016/j.apm.2010.02.012

Dong, G., Li, S., Ma, S., Zhang, D., Bi, J., Wang, J., Starostenkov, M. D., & Xu, Z. (2023a). Process optimization of A356 aluminum alloy wheel hub fabricated by low-pressure die casting with simulation and experimental coupling methods. *Journal of Materials Research and Technology*, *24*, 3118–3132. https://doi.org/10.1016/j.jmrt.2023.03.214

Dong, G., Li, S., Ma, S., Zhang, D., Bi, J., Wang, J., Starostenkov, M. D., & Xu, Z. (2023b). Process optimization of A356 aluminum alloy wheel hub fabricated by low-pressure die casting with simulation and experimental coupling methods. *Journal of Materials Research and Technology*, *24*, 3118–3132. https://doi.org/10.1016/j.jmrt.2023.03.214

Dong, G., Li, S., Ma, S., Zhang, D., Bi, J., Wang, J., Starostenkov, M. D., & Xu, Z. (2023c). Process optimization of A356 aluminum alloy wheel hub fabricated by low-pressure die casting with simulation and experimental coupling methods. *Journal of Materials Research and Technology*, *24*, 3118–3132. https://doi.org/10.1016/j.jmrt.2023.03.214

Dybowski, B., Kiełbus, A., & Poloczek, Ł. (2023). Effects of die-casting defects on the blister formation in high-pressure die-casting aluminum structural components. *Engineering Failure Analysis*, *150*, 107223. https://doi.org/10.1016/j.engfailanal.2023.107223

Fan, P., Cockcroft, S. L., Maijer, D. M., Yao, L., Reilly, C., & Phillion, A. B. (2019). Porosity Prediction in A356 Wheel Casting. *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science*, *50*(5), 2421–2435. https://doi.org/10.1007/s11663-019-01642-9

Fang, H., Liu, H., Mo, Z., Huang, C., Chen, Z., & Lu, Z. (2024). Defect prediction of large-size aluminum alloy wheel hub in low pressure die casting process. In W. Chen & X. Liu (Eds.), *Fourth International Conference on Mechanical Engineering, Intelligent Manufacturing, and Automation Technology (MEMAT 2023)* (p. 52). SPIE. https://doi.org/10.1117/12.3026157

Guerra, F. V., Bedolla-Jacuinde, A., Valdes-Vera, H., Quintero-Ortiz, J., Zarate-Rangel, A., & Pacheco-Cedeño, J. S. (2023). Measurement of Air Entrainment and its Effect on the Microstructure and Mechanical Properties of a A356 Aluminum Alloy. *International Journal of Metalcasting*, *17*(3), 2109–2127. https://doi.org/10.1007/s40962-022-00924-4

Guofa, M., Xiangyu, L., Kuangfei, W., & Hengzhi, F. (n.d.). Numerical simulation of low pressure die-casting aluminum wheel. In *CHINA FOUNDRY* (Vol. 48, Issue 1).

Guofa, M., Xiangyu, L., Kuangfei, W., & Hengzhi, F. (2009a). Numerical simulation of low pressure die-casting aluminum wheel. *CHINA FOUNDRY*, *48*(1). https://doaj.org/article/173bf1de795a466e997c0e50aff84824

Guofa, M., Xiangyu, L., Kuangfei, W., & Hengzhi, F. (2009b). Numerical simulation of low pressure die-casting aluminum wheel. *CHINA FOUNDRY*, *48*(1). https://doaj.org/article/173bf1de795a466e997c0e50aff84824

Gursoy, O., Nordmak, A., Syvertsen, F., Colak, M., Tur, K., & Dispinar, D. (2021). Role of metal quality and porosity formation in low pressure die casting of A356: Experimental observations. *Archives of Foundry Engineering*, *21*(1), 5–10. https://doi.org/10.24425/afe.2021.136071

He, Q., Su, Z., Xie, Z., Zhong, Z., & Yao, Q. (2017). A Novel Principle for Molten Steel Level Measurement in Tundish by Using Temperature Gradient. *IEEE Transactions on Instrumentation and Measurement*, *66*(7), 1809–1819. https://doi.org/10.1109/TIM.2017.2668598

He, X., Hu, C., Wang, Z., Zhao, H., Wei, X., & Dong, H. (2020). Carbide transformation behaviors of a Cr-Mo-V secondary hardening steel during over-ageing. *Materials Research Express*, *7*(3). https://doi.org/10.1088/2053-1591/ab7c86

He, Y., Lu, D., Li, Z., & Lu, D. (2023a). Multi-Objective Optimization of The Low-Pressure Casting of Large-Size Aluminum Alloy Wheels through a Systematic Optimization Idea. *Materials*, *16*(18). https://doi.org/10.3390/ma16186223

He, Y., Lu, D., Li, Z., & Lu, D. (2023b). Multi-Objective Optimization of The Low-Pressure Casting of Large-Size Aluminum Alloy Wheels through a Systematic Optimization Idea. *Materials*, *16*(18). https://doi.org/10.3390/ma16186223

Huang, J. M., Zhao, H. D., & Chen, Z. M. (2019). Microstructure and Properties of A356 Alloy Wheels Fabricated by Low-Pressure Die Casting with Local Squeeze. *Journal of Materials Engineering and Performance*, *28*(4), 2137–2146. https://doi.org/10.1007/s11665-019-03993-5

Iwata, Y., Dong, S., Sugiyama, Y., & Iwahori, H. (2013). Effects of solidification behavior during filling on surface defects of aluminum alloy die casting+. *Materials Transactions*, *54*(10), 1944–1950. https://doi.org/10.2320/matertrans.F-M2013819

Iwata, Y., Dong, S., Sugiyama, Y., & Iwahori, H. (2014). Change in molten metal pressure and its effect on defects of aluminum alloy die castings. *Materials Transactions*, *55*(2), 311–317. https://doi.org/10.2320/matertrans.F-M2013838

J. Gilbert Kaufman;, & Elwin L. Rooy. (2004). Aluminum Casting Alloys. In *Aluminum Alloy Castings* (pp. 7–20). ASM International. https://doi.org/10.31399/asm.tb.aacppa.t51140007

Jadhav, A. R., Hujare, D. P., & Hujare, P. P. (2021a). Design and optimization of gating system, modification of cooling system position and flow simulation for cold chamber high pressure die casting machine. *Materials Today: Proceedings*, *46*(xxxx), 7175–7181. https://doi.org/10.1016/j.matpr.2020.11.346

Jadhav, A. R., Hujare, D. P., & Hujare, P. P. (2021b). Design and optimization of gating system, modification of cooling system position and flow simulation for cold chamber high pressure die casting machine. *Materials Today: Proceedings*, *46*(xxxx), 7175–7181. https://doi.org/10.1016/j.matpr.2020.11.346

Jenny Estrada. (2018, April). *Parts of Your Wheels/Rims*. OEM Wheel Shops.

Kırmızıgöl S. Fatih, Özaydın Onur, Acarer Sercan, & Armakan Elvan. (2019a). Fluid Flow and Heat Transfer Simulations of the Cooling System in Low Pressure Die Casting. *Celal Bayar University Journal of Science*, *16*(2), 161–166. https://doi.org/10.18466/cbayarfbe.641177

Kırmızıgöl S. Fatih, Özaydın Onur, Acarer Sercan, & Armakan Elvan. (2019b). Fluid Flow and Heat Transfer Simulations of the Cooling System in Low Pressure Die Casting. *Celal Bayar University Journal of Science*, *16*(2), 161–166. https://doi.org/10.18466/cbayarfbe.641177

Kridli, G. T., Friedman, P. A., & Boileau, J. M. (2020a). Manufacturing processes for light alloys. In *Materials, Design and Manufacturing for Lightweight Vehicles*. LTD. https://doi.org/10.1016/B978-0-12-818712-8.00007-0

Kridli, G. T., Friedman, P. A., & Boileau, J. M. (2020b). Manufacturing processes for light alloys. In *Materials, Design and Manufacturing for Lightweight Vehicles*. LTD. https://doi.org/10.1016/B978-0-12-818712-8.00007-0

Kumar, J. Y., Gopi, S., & Amirthagadeswaran, K. (2023a). Redesigning and numerical simulation of gating system to reduce cold shut defect in submersible pump part castings. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *237*(3), 971–981. https://doi.org/10.1177/09544089221142185

Kumar, J. Y., Gopi, S., & Amirthagadeswaran, K. (2023b). Redesigning and numerical simulation of gating system to reduce cold shut defect in submersible pump part castings. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *237*(3), 971–981. https://doi.org/10.1177/09544089221142185

Kusnowo, R., Budiarto, H., Ruskandi, C., & Hermana, G. (2023a). *Comparative Study of Microstructure and Mechanical Properties of Hot Work Tool Steel SKD 6 with Different Manufacturing Process*. 746–750. https://doi.org/10.5220/0011876100003575

Kusnowo, R., Budiarto, H., Ruskandi, C., & Hermana, G. (2023b). *Comparative Study of Microstructure and Mechanical Properties of Hot Work Tool Steel SKD 6 with Different Manufacturing Process*. 746–750. https://doi.org/10.5220/0011876100003575

Kusnowo, R., & Hidayat, E. (2021). Perancangan Coran Baja Cor SKD6 Menggunakan Simulasi Perangkat Lunak Pada Produk Side Core SD25R. *Jurnal Teknologi Manufaktur*, *13*(01).

Kusnowo, R., Hidayat, E., & Bandung, P. M. (2021). Perancangan Coran Baja Cor SKD6 Menggunakan Simulasi Perangkat Lunak Pada Produk Side Core SD25R. *Jurnal Teknologi Manufaktur*, *13*(01).

Latte, M. R., & Chougule, P. D. (2017). Blow-hole Defect Analysis of Cylinder Block-A Case Study. *International Journal of Engineering Research and Technology*, *10*. http://www.irphouse.com

Li, S., Xiong, S., Mei, L., & Allison, J. (2010). Numerical simulation of air entrapment phenomenon during mold filling of high pressure die casting process. *Jinshu Xuebao/Acta Metallurgica Sinica*, *46*(5), 554–560. https://doi.org/10.3724/SP.J.1037.2009.00683

Li, Y., Liu, J., Zhou, H., & Huang, W. (2022). Study on the Distribution Characteristics of Microstructure and Mechanical Properties Within the Cylinder Head of Low-Pressure Sand Cast Aluminum Alloy. *International Journal of Metalcasting*, *16*(3), 1252–1264. https://doi.org/10.1007/s40962-021-00678-5

Liu, X., Cai, Z., Zheng, Y., El Fakir, O., Gandra, J., & Wang, L. (2020). A general IHTC model for hot/warm aluminium stamping. *Applied Thermal Engineering*, *181*, 115619. https://doi.org/10.1016/j.applthermaleng.2020.115619

Majerník, J., & Podaril, M. (2019). Influence of runner geometry on the gas entrapment in volume of pressure die cast. *Archives of Foundry Engineering*, *19*(3), 33–38. https://doi.org/10.24425/afe.2019.129626

Meng, Y., Sugiyama, S., & Yanagimoto, J. (2012). Journal of Materials Processing Technology Microstructural evolution during RAP process and deformation behavior of semi-solid SKD61 tool steel. *Journal of Materials Processing Tech.*, *212*(8), 1731–1741. https://doi.org/10.1016/j.jmatprotec.2012.04.003

Mi, G., Liu, X., Wang, K., & Fu, H. (2009). Numerical simulation of low pressure die-casting aluminum wheel. *China Foundry*, *6*(1), 48–52.

Nagasankar P, Sathiyamoorthy V, Gurusamy P, Vinothkanna P, & Manibharathi D. (2018). Reduction of Blowholesin Aluminium High Pressure Die Casting Machine. In *International Journal of Engineering & Technology* (Vol. 7). www.sciencepubco.com/index.php/IJET

Ou, J., Wei, C., Cockcroft, S., Maijer, D., Zhu, L., Lateng, A., Li, C., & Zhu, Z. (2020). Advanced process simulation of low pressure die cast a356 aluminum automotive wheels—part ii modeling methodology and validation. *Metals*, *10*(11), 1–24. https://doi.org/10.3390/met10111418

Romansyah, R. Y., Budiarto, H. A., Erlangga, Y. Y., & Safrudin, Y. N. (2023). FAILURE INVESTIGATION OF BLANK HOLDER FORCE (BHF) CONTROL IN THE OUTSIDE BRACKET FOR FRONT SEAT. *Journal of Applied Engineering and Technological Science*, *4*(2). https://doi.org/10.37385/jaets.v4i2.1779

Samuel, A. M., Samuel, E., Songmene, V., & Samuel, F. H. (2023a). A Review on Porosity Formation in Aluminum-Based Alloys. *Materials*, *16*(5), 2047. https://doi.org/10.3390/ma16052047

Samuel, A. M., Samuel, E., Songmene, V., & Samuel, F. H. (2023b). A Review on Porosity Formation in Aluminum-Based Alloys. *Materials*, *16*(5), 2047. https://doi.org/10.3390/ma16052047

Seydani, M. Z., Krimi, A., Khelladi, S., Bedel, M., & El Mansori, M. (2024). 3D numerical simulation and experimental validation of resin-bonded sand gravity casting: Filling, cooling, and solidification with SPH and ProCAST approaches. *Thermal Science and Engineering Progress*, *47*, 102329. https://doi.org/10.1016/j.tsep.2023.102329

Su, L. P., Zeng, J. M., Chen, J., & Gan, W. K. (2012). Research on Simplified Reverse Method for Interfacial Heat Transfer Coefficient (IHTC). *Applied Mechanics and Materials*, *268–270*, 974–977. https://doi.org/10.4028/www.scientific.net/AMM.268-270.974

Uyan, T., Otto, K., Silva, M. S., Vilaça, P., & Armakan, E. (2023a). Industry 4.0 Foundry Data Management and Supervised Machine Learning in Low-Pressure Die Casting Quality Improvement. *International Journal of Metalcasting*, *17*(1), 414–429. https://doi.org/10.1007/s40962-022-00783-z

Uyan, T., Otto, K., Silva, M. S., Vilaça, P., & Armakan, E. (2023b). Industry 4.0 Foundry Data Management and Supervised Machine Learning in Low-Pressure Die Casting Quality Improvement. *International Journal of Metalcasting*, *17*(1), 414–429. https://doi.org/10.1007/s40962-022-00783-z

Vandersluis, E., Bois-Brochu, A., Ravindran, C., & Chiesa, F. (2020). Mechanical Properties and Conductivity of Low-Pressure Die-Cast 319 Aluminum Prepared with Hot Isostatic Pressing, Thermal Treatment, or Chemical Treatment. *Journal of Materials Engineering and Performance*, *29*(4), 2335–2345. https://doi.org/10.1007/s11665-020-04743-8

Vossel, T., Wolff, N., Pustal, B., & Bührig-Polaczek, A. (2020). Influence of Die Temperature Control on Solidification and the Casting Process. *International Journal of Metalcasting*, *14*(4), 907–925. https://doi.org/10.1007/s40962-019-00391-4

Waghmare, D. B., & Bhatia, S. (2019). Industrial Case Study of Low-Pressure Die Casting of AlSi9Cu1Mg Aluminium Alloy to Reduce Casting Defects. *Reason-A Technical Journal*, *18*(0), 50. https://doi.org/10.21843/reas/2019/50-60/196166

Wang, G. G., & Weiler, J. P. (2023). Recent developments in high-pressure die-cast magnesium alloys for automotive and future applications. *Journal of Magnesium and Alloys*, *11*(1), 78–87. https://doi.org/10.1016/j.jma.2022.10.001

Wang, X., Chen, R., Wang, Q., Wang, S., Li, Y., Su, Y., Xia, Y., Zhou, G., Li, G., & Qu, Y. (2023). Influence of Casting Temperature and Mold Preheating Temperature on Centrifugal Casting by Numerical Simulation. *Journal of Materials Engineering and Performance*, *32*(15), 6786–6809. https://doi.org/10.1007/s11665-022-07608-4

Xue, S., Yang, T., Guo, R., Deng, A., Liu, X., & Zheng, L. (2021). Crack analysis of Cr-Mo-V-Si medium-carbon alloy steel in casting die. *Engineering Failure Analysis*, *120*(July 2020), 105083. https://doi.org/10.1016/j.engfailanal.2020.105083

Yağcı, T., Cöcen, Ü., & Çulha, O. (2021a). Aluminum Alloy Development for Wheel Production by Low Pressure Die Casting with New Generation Computational Materials Engineering Approaches. *Archives of Foundry Engineering*, 35–46. https://doi.org/10.24425/afe.2021.138677

Yağcı, T., Cöcen, Ü., & Çulha, O. (2021b). Aluminum Alloy Development for Wheel Production by Low Pressure Die Casting with New Generation Computational Materials Engineering Approaches. *Archives of Foundry Engineering*, 35–46. https://doi.org/10.24425/afe.2021.138677

Zhang, Z., Liu, J., Chen, J., Wen, F., Jia, R., & Ma, Q. (2023). Optimization of residual stress in low-pressure casting of ZL205A alloys. *Journal of Manufacturing Processes*, *99*, 338–350. https://doi.org/10.1016/j.jmapro.2023.05.040