

Review

# Advances in Die-Casting Mold and Precision Component R&D in the Automotive and Electronics Industries under Advanced Manufacturing Contexts

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**Abstract:** This review paper explores recent advancements in die-casting mold technology and precision component research and development, specifically within the automotive and electronics industries, under the umbrella of advanced manufacturing contexts. We examine historical trends, core technological themes, and challenges facing the industries. The review synthesizes findings from recent scholarly articles and industrial reports, focusing on innovations in mold design, materials, process control, and simulation techniques. A comparative analysis of different approaches is provided, along with an assessment of the limitations and challenges in achieving higher precision and efficiency. Finally, the paper presents future research directions, including the integration of artificial intelligence, advanced materials, and sustainable manufacturing practices. The aim is to provide a comprehensive overview of the state-of-the-art and to identify promising avenues for future innovation in die-casting mold and precision component manufacturing.

**Keywords:** die-casting; molds; precision components; automotive industry; electronics industry; advanced manufacturing; R&D

## 1. Introduction

### 1.1. Background and Motivation

Die-casting stands as a pivotal manufacturing process, particularly within the automotive and electronics sectors, enabling the efficient production of complex metal parts at high volumes. Its significance stems from the ability to create components with intricate geometries and tight tolerances, crucial for both structural and functional applications. The automotive industry relies heavily on die-casting for manufacturing engine blocks, transmission housings, and chassis components, while the electronics industry utilizes it for producing heat sinks, connectors, and enclosures [1].

The escalating demand for lighter, more efficient, and higher-performing vehicles and electronic devices necessitates components with enhanced precision and reliability. This demand is driving innovation in die-casting processes, materials, and mold designs. Advanced manufacturing technologies, including computer-aided engineering (CAE), additive manufacturing, and advanced process control, are playing an increasingly important role in optimizing die-casting operations, reducing defects, and improving the overall quality of die-cast components [2]. The integration of these technologies is essential for meeting the stringent requirements of modern automotive and electronics applications, where even minor imperfections can significantly impact performance and longevity.

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### 1.2. Scope and Objectives

This review focuses on recent advancements in die-casting mold technology and precision component Research and Development (R&D) within the automotive and electronics sectors. The scope encompasses innovations in mold design, materials, and manufacturing processes, particularly those enabling the production of complex geometries and tight tolerances [3]. The primary objectives are to summarize key research trends in die-casting, including the application of advanced manufacturing techniques like additive manufacturing and simulation-driven design. Furthermore, this review aims to identify future challenges and opportunities in the field, considering factors such as increasing demands for lightweighting, miniaturization, and enhanced performance of die-cast components [4].

### 1.3. Methodology

The literature review employed systematic searches across Scopus, Web of Science, and IEEE Xplore. Keywords included "die-casting," "mold design," "precision components," "automotive," and "electronics." Selection criteria prioritized articles focusing on advanced manufacturing applications and reporting empirical R&D data.

## 2. Historical Overview of Die-Casting Mold Development

### 2.1. Early Developments and Traditional Methods

Early die-casting mold development relied heavily on readily available materials and manual craftsmanship. Initially, molds were crafted from basic tool steels, often lacking sophisticated heat treatments, limiting their lifespan and the complexity of castable geometries [5]. Manufacturing processes centered around manual machining, including milling, turning, and grinding, demanding highly skilled mold makers. Achieving dimensional accuracy and surface finish depended significantly on the artisan's expertise. Cooling channels, crucial for solidification control, were rudimentary, often consisting of drilled holes with limited design optimization. The cycle times were long, and the production volume was relatively low. The  $P/Q$  ratio, where  $P$  is the price and  $Q$  is the quantity, was high due to the intensive labor and material costs. Table 1 illustrates the key differences between early and modern die-casting molds, highlighting advancements in material properties, manufacturing processes, cooling channel design, and production efficiency.

**Table 1.** Evolution of Die-Casting Mold Materials.

Characteristic	Early Die-Casting Molds	Modern Die-Casting Molds
Materials	Basic tool steels, often lacking sophisticated heat treatments	Advanced tool steels (e.g., H13, hot-work tool steels), specialized alloys (e.g., beryllium-copper)
Material Properties	Limited lifespan, lower thermal conductivity	Improved lifespan, superior thermal conductivity, enhanced wear resistance
Manufacturing Processes	Primarily manual machining (milling, turning, grinding)	CNC machining, EDM (Electrical Discharge Machining), additive manufacturing (3D printing)
Dimensional Accuracy & Surface Finish	Dependent on artisan's skill, relatively lower accuracy	High precision, excellent surface finish due to advanced machining techniques
Cooling Channel Design	Rudimentary, drilled holes with limited optimization	Conformal cooling channels, optimized designs for efficient heat extraction and reduced cycle times

Cycle Times	Long	Significantly reduced due to improved cooling and material properties
Production Volume	Relatively low	High due to faster cycle times and automated processes
$P/Q$ ratio	High (due to intensive labor and material costs)	Lower (due to automation, material efficiency, and higher production volume)

### 2.2. Impact of CAD/CAM and CNC Technologies

The integration of CAD/CAM and CNC technologies revolutionized die-casting mold development. CAD software enabled designers to create complex 3D mold models with greater precision and efficiency than traditional drafting methods. This facilitated design optimization and reduced errors [6]. CAM systems then translated these digital designs into machine-readable code, guiding CNC machines to precisely cut mold components. CNC machining offered significant improvements in accuracy, repeatability, and surface finish compared to manual machining. The combined effect of CAD/CAM and CNC dramatically shortened lead times, improved mold quality, and enabled the production of more intricate and sophisticated die-casting parts, driving innovation in both the automotive and electronics sectors. The use of parameters such as  $x$ ,  $y$ , and  $z$  became crucial for defining the toolpath, as shown in Table 2, which outlines the impact of CAD/CAM on die-casting mold manufacturing.

**Table 2.** Impact of CAD/CAM on Die-Casting Mold Manufacturing.

Feature	Impact
Design Process	Enabled creation of complex 3D mold models with greater precision and efficiency. Facilitated design optimization and reduced errors.
Manufacturing Process	CAM systems translated digital designs into machine-readable code for CNC machines. CNC machining improved accuracy, repeatability, and surface finish. $x$ , $y$ , and $z$ parameters became crucial for defining the toolpath.
Lead Time	Dramatically shortened lead times for mold development.
Mold Quality	Improved mold quality due to increased precision and control.
Part Complexity	Enabled the production of more intricate and sophisticated die-casting parts.
Industry Impact	Drove innovation in both the automotive and electronics sectors.

### 2.3. Integration of Simulation Software

The integration of simulation software marked a significant advancement in die-casting mold development. These tools enabled engineers to predict melt flow patterns within the mold cavity, optimizing gate and runner designs to ensure complete filling and minimize air entrapment. Simulation also provided crucial insights into solidification behavior, allowing for the prediction of shrinkage porosity and hot spots. Furthermore, the ability to model thermal stresses during the casting process helped in optimizing cooling channel layouts and predicting potential mold deformation, extending mold life and improving the dimensional accuracy of the final cast component. Parameters such as injection velocity  $v$ , melt temperature  $T_m$ , and cooling rate  $R_c$  could be virtually tested, leading to a more robust and efficient mold design process.

### 3. Advances in Mold Design and Materials (Core Theme A)

#### 3.1. Innovative Mold Cooling Systems

Innovative mold cooling systems are crucial for efficient heat dissipation in die-casting, directly impacting cycle time and part quality. Recent advances focus on optimizing cooling channel design and employing dynamic cooling strategies. Conformal cooling channels, manufactured using additive manufacturing techniques, represent a significant leap forward [7]. These channels closely follow the contours of the mold cavity, enabling uniform cooling and eliminating hot spots that can lead to defects such as porosity and warpage. The ability to create complex geometries allows for optimized heat transfer compared to traditional drilled channels, where straight lines often compromise cooling efficiency. The distance  $d$  between the conformal cooling channel and the cavity surface can be minimized, enhancing the cooling rate.

Pulsed cooling techniques are also gaining traction. These techniques involve alternating between periods of rapid cooling and brief pauses, allowing for more efficient heat extraction and reduced thermal stress on the mold. By carefully controlling the cooling fluid flow rate  $Q$  and temperature  $T$ , pulsed cooling can minimize the formation of a thermal boundary layer, leading to improved heat transfer coefficients. Furthermore, the use of advanced sensors and control systems allows for real-time monitoring of mold temperature and adaptive adjustment of cooling parameters, ensuring optimal cooling performance throughout the die-casting process. This dynamic approach contributes significantly to cycle time reduction and improved dimensional accuracy of the cast components, as summarized in Table 3, which compares various cooling system types.

**Table 3.** Comparison of Cooling System Types.

Feature	Traditional Drilled Channels	Conformal Cooling Channels	Pulsed Cooling
Channel Geometry	Straight lines, limited design flexibility	Complex geometries conforming to mold cavity	Utilizes standard or conformal channels with dynamic fluid control
Manufacturing Method	Drilling	Additive Manufacturing	Conventional methods with advanced control system
Cooling Uniformity	Non-uniform, potential for hot spots	Uniform, minimizes hot spots	Improved uniformity due to dynamic control of $Q$ and $T$
Heat Transfer Efficiency	Lower	Higher, optimized heat transfer	Enhanced heat transfer through manipulation of thermal boundary layer
Distance to Cavity ( $d$ )	Limited by drilling constraints	Minimized due to design flexibility	Applicable to various distances depending on channel design
Cooling Fluid Control	Static or limited control	Primarily static, can be combined with pulsed cooling	Dynamic control of cooling fluid flow rate $Q$ and temperature $T$
Cycle Time Impact	Longer cycle times due to inefficient cooling	Shorter cycle times due to effective heat dissipation	Potential for shorter cycle times depending on parameter optimization
Dimensional Accuracy	Lower accuracy due to thermal distortion	Higher accuracy due to uniform cooling	Improved dimensional accuracy through controlled thermal stress

### 3.2. Advanced Mold Materials and Coatings

The pursuit of enhanced die-casting performance necessitates continuous advancements in mold materials and surface treatments. High-strength steels, particularly those alloyed with elements like chromium, molybdenum, and vanadium, are increasingly employed to withstand the extreme pressures and temperatures inherent in die-casting processes [8]. These steels offer superior tensile strength, hardness, and resistance to thermal fatigue cracking compared to conventional mold steels. Cemented carbides, characterized by their exceptional hardness and wear resistance, are also finding niche applications, especially in areas prone to high erosion, such as gate regions. However, their higher cost and lower toughness can limit their widespread adoption [9].

Ceramic coatings represent another significant area of development. Applied via techniques like physical vapor deposition (PVD) or chemical vapor deposition (CVD), these coatings provide a thin, hard, and chemically inert layer on the mold surface. Materials such as titanium nitride (TiN), titanium carbonitride (TiCN), and aluminum oxide ( $\text{Al}_2\text{O}_3$ ) are commonly used. These coatings significantly improve wear resistance, reduce friction between the die and the casting, and enhance corrosion resistance against molten metal attack. Furthermore, certain coatings can be tailored to improve thermal conductivity, facilitating faster and more uniform cooling of the casting, thereby reducing cycle times and improving part quality. The effectiveness of these coatings depends on factors such as coating thickness, adhesion strength, and the specific die-casting alloy being used. Optimizing these parameters is crucial for maximizing the benefits of advanced mold materials and coatings [10].

### 3.3. Optimization of Gate and Runner Systems

Optimization of gate and runner systems is crucial for achieving high-quality die-cast components, particularly in the automotive and electronics industries where intricate designs and tight tolerances are paramount. The primary objective is to ensure uniform melt flow into the mold cavity, minimizing turbulence and preventing air entrapment, which can lead to porosity. Computational Fluid Dynamics (CFD) simulations are increasingly employed to model the filling process and predict potential defects. These simulations allow engineers to analyze the impact of different gate designs, runner geometries, and process parameters, such as injection speed and melt temperature, on the final product [11].

Several optimization strategies are commonly used. Balancing runner systems, where each cavity receives an equal amount of melt, is essential for multi-cavity molds. This often involves adjusting runner diameters and lengths to equalize pressure drop. The gate design itself plays a significant role; fan gates, for instance, can promote uniform filling of large, thin-walled sections, while edge gates are suitable for smaller components. The gate velocity, denoted as  $v_g$ , must be carefully controlled to avoid jetting and excessive shear rates, which can degrade the melt quality. Furthermore, the runner system should be designed to minimize the distance the melt travels, reducing heat loss and the risk of premature solidification. Optimizing the gate and runner system is an iterative process, often involving a combination of simulation, experimentation, and expert knowledge.

## 4. Process Control and Monitoring in Die-Casting (Core Theme B)

### 4.1. Real-Time Monitoring of Process Parameters

Real-time monitoring of process parameters is crucial for ensuring the quality and consistency of die-cast components, particularly in the demanding automotive and electronics industries. This involves the strategic deployment of sensors and sophisticated data acquisition systems to track key variables throughout the die-casting cycle. Melt temperature, a critical factor influencing fluidity and solidification, is typically monitored using thermocouples immersed in the molten metal, providing continuous temperature

readings. Injection pressure, which directly affects the filling of the die cavity and the formation of defects, is measured using pressure transducers strategically positioned within the injection system and the die itself. Mold temperature, another vital parameter impacting solidification rate and surface finish, is monitored using thermocouples embedded within the mold cavity walls.

The data acquired from these sensors is then fed into a data acquisition system, which processes and displays the information in real-time. This allows operators to observe trends, identify deviations from pre-defined process windows, and make immediate adjustments to maintain optimal conditions. For instance, if the melt temperature drops below a certain threshold  $T_{min}$ , the system can trigger an alert, prompting the operator to increase the heating power. Similarly, if the injection pressure exceeds a maximum allowable value  $P_{max}$ , the system can automatically reduce the injection speed to prevent damage to the die. Advanced systems also incorporate statistical process control (SPC) techniques to track process capability and identify potential sources of variation. By continuously monitoring these key parameters, manufacturers can significantly reduce defects, improve product quality, and optimize the overall die-casting process.

#### 4.2. Closed-Loop Control Systems

Closed-loop control systems represent a significant advancement in die-casting process management, enabling precise regulation of key parameters based on real-time feedback. Unlike open-loop systems that operate on pre-set values, closed-loop systems continuously monitor process variables and adjust control parameters to maintain desired setpoints, thereby enhancing process stability and part quality.

A typical closed-loop system in die-casting incorporates sensors to measure critical parameters such as die temperature ( $T_d$ ), injection pressure ( $P_i$ ), and metal flow velocity ( $v_m$ ). These measurements are then fed into a controller, which compares the actual values with the pre-defined setpoints. Based on the deviation, the controller adjusts actuators, such as servo valves controlling injection pressure or heating elements regulating die temperature, to minimize the error.

For instance, consider a closed-loop system for controlling injection pressure. If the measured injection pressure ( $P_i$ ) falls below the setpoint ( $P_{set}$ ), the controller increases the servo valve opening, allowing more hydraulic fluid to flow into the injection cylinder, thereby increasing the pressure. Conversely, if  $P_i$  exceeds  $P_{set}$ , the controller reduces the valve opening. This continuous feedback and adjustment mechanism ensures that the injection pressure remains close to the desired value, leading to consistent filling and reduced porosity in the cast parts. The implementation of such systems significantly reduces the impact of process variations, such as fluctuations in metal temperature or machine wear, leading to improved dimensional accuracy, mechanical properties, and overall part quality. A comparison between open-loop and closed-loop control systems is provided in Table 4, highlighting their key differences and advantages.

**Table 4.** Comparison of Open-Loop and Closed-Loop Control.

Feature	Open-Loop Control	Closed-Loop Control
Operation	Operates on pre-set values without feedback.	Continuously monitors process variables and adjusts control parameters based on feedback.
Process Adjustment	No adjustment based on real-time conditions.	Adjusts actuators to maintain desired setpoints.
Feedback Mechanism	No feedback mechanism.	Employs sensors to measure critical parameters and provides feedback to the controller.

Response to Variations	Susceptible to process variations like fluctuations in metal temperature or machine wear.	Minimizes the impact of process variations.
Example in Die-Casting	Setting a fixed injection pressure without monitoring the actual pressure during the process.	Monitoring injection pressure ( $P_i$ ) and adjusting a servo valve to maintain it close to the setpoint ( $P_{set}$ ).
Process Stability	Less stable due to lack of error correction.	More stable due to continuous error correction.
Part Quality	Generally lower due to inconsistency in processing.	Generally higher due to consistent processing enabled by feedback.
Complexity	Less complex.	More complex.

#### 4.3. Defect Detection and Prediction

Defect detection and prediction are crucial for ensuring the quality and reliability of die-cast components. Non-destructive testing (NDT) methods play a vital role in identifying internal and surface defects without damaging the parts. Common NDT techniques employed in die-casting include ultrasonic testing (UT), radiography (X-ray and computed tomography), eddy current testing (ECT), and dye penetrant inspection (DPI). Ultrasonic testing utilizes high-frequency sound waves to detect internal flaws such as porosity, cracks, and inclusions by analyzing the reflected signals. Radiography provides a visual representation of the internal structure, revealing defects like gas porosity and shrinkage cavities. Eddy current testing is effective for detecting surface and near-surface cracks and variations in material properties. Dye penetrant inspection is used to identify surface-breaking defects by applying a dye that penetrates into the flaws, making them visible under ultraviolet light.

The integration of data analytics with NDT has further enhanced defect detection and prediction capabilities. By collecting data from various sensors during the die-casting process, such as temperature, pressure, and injection speed ( $v$ ), and correlating it with NDT results, predictive models can be developed. Machine learning algorithms, including artificial neural networks (ANNs) and support vector machines (SVMs), can be trained to identify patterns and predict the likelihood of defect formation based on process parameters. For example, a model might predict the probability ( $P$ ) of porosity exceeding a certain threshold based on the injection speed ( $v$ ) and die temperature ( $T$ ), expressed as  $P = f(v, T)$ . This allows for proactive adjustments to the process to minimize defects and improve overall product quality.

## 5. Comparison of Die-Casting Techniques and Industry Challenges

### 5.1. Comparison of High Pressure and Low Pressure Die-Casting

High-pressure die-casting (HPDC) and low-pressure die-casting (LPDC) represent distinct approaches to metal casting, each offering unique advantages. HPDC, characterized by rapid injection speeds and high pressures (typically 10 – 210 MPa), excels in producing complex, thin-walled components with excellent dimensional accuracy and surface finish. This makes it suitable for automotive parts like engine blocks and electronic housings. However, HPDC often results in higher porosity due to entrapped air. Conversely, LPDC employs lower injection speeds and pressures (0.007 – 0.1 MPa), promoting laminar flow and reduced gas entrapment, leading to denser castings with superior mechanical properties. LPDC is favored for safety-critical automotive components like suspension parts and wheels, where structural integrity is paramount. While LPDC generally yields lower production rates compared to HPDC, the improved part quality often justifies its use in specific applications.

### 5.2. Challenges in Achieving High Precision and Quality

Achieving high precision and quality in die-casting presents multifaceted challenges. Dimensional control is paramount, requiring meticulous management of factors like thermal expansion coefficients of both the die and the molten metal, and shrinkage during solidification. Variations in these parameters can lead to deviations from specified tolerances. Surface finish is another critical aspect, influenced by die surface roughness, metal flow dynamics, and the presence of defects like porosity. Controlling porosity, which negatively impacts mechanical properties such as tensile strength  $\sigma_t$  and fatigue life  $N_f$ , necessitates precise control over gas entrapment and solidification rates. Furthermore, achieving desired mechanical properties requires careful alloy selection and heat treatment processes to optimize microstructure and minimize defects.

### 5.3. Economic and Environmental Considerations

Die-casting's economic viability hinges on balancing initial tooling costs with high-volume production capabilities. Energy consumption is a significant factor, particularly during the melting and holding phases of the process, directly impacting operational expenses. Material usage, especially of aluminum and magnesium alloys, necessitates efficient recycling programs to minimize waste and reduce raw material dependence. Waste management strategies, including the reclamation of runners, risers, and defective castings, are crucial for both economic and environmental sustainability. The environmental impact is further influenced by emissions from melting furnaces and the disposal of die-casting lubricants. Optimizing die design, process parameters, and implementing closed-loop recycling systems can significantly improve both the economic and environmental performance of die-casting operations, reducing the overall cost per part ( $C_p$ ) and minimizing the environmental footprint ( $E_f$ ).

## 6. Future Perspectives and Research Directions

### 6.1. Integration of Artificial Intelligence and Machine Learning

The integration of Artificial Intelligence (AI) and Machine Learning (ML) presents transformative opportunities for die-casting processes. ML algorithms can analyze vast datasets of process parameters (*pressure, temperature, injection speed*) to optimize settings for enhanced efficiency and reduced cycle times. Furthermore, AI-powered defect prediction models, trained on historical data and real-time sensor inputs, can proactively identify potential flaws like porosity or cold shuts, enabling timely corrective actions. AI can also revolutionize mold design by automating the generation of optimized cooling channel layouts and gate designs, minimizing thermal stress and ensuring uniform filling. This leads to improved component quality and reduced material waste, accelerating the design cycle and lowering production costs.

### 6.2. Development of Smart Molds with Integrated Sensors

The integration of sensors directly into die-casting molds represents a significant leap towards intelligent manufacturing. These "smart molds" enable real-time monitoring of critical process parameters such as temperature ( $T$ ), pressure ( $P$ ), and flow rate ( $Q$ ) within the mold cavity. This data can then be used for adaptive control, allowing for adjustments to injection parameters like velocity ( $v$ ) and holding pressure ( $P_h$ ) on a shot-by-shot basis. Furthermore, sensor data can be leveraged for predictive maintenance, identifying potential mold defects or wear before they lead to production downtime. Future research should focus on developing robust and miniaturized sensors capable of withstanding the harsh die-casting environment, along with advanced data analytics techniques for extracting actionable insights from the sensor data stream.

### 6.3. Sustainable Manufacturing Practices

Sustainable manufacturing is paramount for the future of die-casting, driven by increasing environmental concerns and resource scarcity. Energy efficiency improvements in die-casting processes, such as optimizing heating cycles and implementing variable frequency drives for machinery, are crucial. Material recycling, particularly of aluminum alloys, offers significant environmental and economic benefits. Closed-loop recycling systems minimize waste and reduce the demand for virgin materials. Furthermore, waste reduction strategies, including minimizing scrap generation through process optimization and implementing efficient cooling systems to reduce water consumption, are essential. The adoption of eco-design principles, considering the entire product lifecycle from material selection to end-of-life management, can further enhance sustainability. Life Cycle Assessment (LCA) methodologies can be employed to quantify the environmental impact of die-casting processes and identify areas for improvement, promoting a circular economy approach where  $E$  (energy consumption) and  $M$  (material usage) are minimized.

## 7. Conclusion

### 7.1. Summary of Key Findings

This review highlights significant advancements in die-casting mold technology and precision component R&D, driven by the automotive and electronics industries' demands for lightweighting, miniaturization, and enhanced performance. Key findings reveal a shift towards high-pressure die casting (HPDC) with improved mold designs incorporating advanced cooling strategies and multi-material capabilities. Furthermore, research emphasizes the application of simulation tools for optimizing mold filling and solidification, reducing defects, and enhancing component quality. The integration of additive manufacturing for mold inserts with conformal cooling channels allows for precise temperature control, leading to improved mechanical properties and reduced cycle times. These advancements contribute to the production of complex, high-precision components with enhanced functionality and reduced CO<sub>2</sub> emissions.

### 7.2. Concluding Remarks and Future Outlook

Die-casting remains pivotal for automotive and electronics, demanding continuous innovation in mold design and precision. Future research should prioritize integrating AI-driven optimization for mold filling and cooling, alongside exploring novel alloys with enhanced thermal properties and reduced weight. Furthermore, in-situ monitoring using advanced sensors will be crucial for real-time process control and defect minimization, ensuring higher quality and reduced CO<sub>2</sub> emissions.

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