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Experimental and industrial insights into distortion control for megacasting

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Abstract

Megacasting enables the production of large, structurally integrated aluminum components for automotive applications, yet the geometrical distortion remains a major challenge. This study combines industrial observations, experimental trials, and literature analysis to identify and interpret key process parameters affecting distortion in high-pressure die casting of large components. The work integrates quantitative measurements from an industrial case study with qualitative input from experienced foundry engineers. The results highlight how die temperature distribution, cooling channel placement, solidification and cooling times, and quenching strategies influence residual stresses and distortion. Stress relaxation at elevated temperatures and constraint removal during ejection are highlighted as key mechanisms contributing to distortion formation.

Building on these insights, potential approaches such as tool geometry correction and simulation-based prediction of distortion are discussed with respect to industrial feasibility. The findings contribute to improved understanding of distortion phenomena in megacasting and support future research toward predictive modeling and compensation strategies.

Keywords: Megacasting; Geometrical distortion; Distortion control; High-pressure die casting; Residual stress

1. Introduction

The automotive industry's increasing focus on lightweight and sustainable solutions has led to significant advancements in manufacturing technologies. Among these, megacasting, sometimes known gigacasting, has emerged as a transformative process, enabling the production of large, single-piece aluminum components that replace complex assemblies of numerous smaller parts. Cost savings in production are a primary driver for the adoption of megacasting [1]. In addition, sustainability benefits are associated with both weight reduction and the recyclability of aluminum [2]. Megacasting has gained attention following its industrial implementation by Tesla and has since been adopted by several automotive OEMs.

However, the adoption of megacasting introduces challenges [1]. Geometrical distortion remains a key barrier to the robust industrial implementation of megacasting for large, thin-walled automotive components and therefore constitutes the focus of this paper. Such castings are especially sensitive to distortion and residual stresses caused by non-uniform cooling and constrained shrinkage, which may result in springback, warping, and permanent deformation in complex geometries [2]. Ensuring geometrical quality is essential for structural integrity and assembly precision.

Compared to traditional sheet metal assemblies, where hundreds of parts are joined together, megacasting significantly shortens the tolerance chain by eliminating multiple joining operations. However, this also removes opportunities for geometric compensation, such as lap joints that allow non-nominal parts to be assembled while still meeting functional requirements. As a result, ensuring high geometrical quality of megacast components becomes critical, as deviations cannot be corrected during intermediate assembly stages. Addressing these challenges therefore requires a comprehensive

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understanding of the factors influencing geometrical quality, including material properties, die design, quenching techniques, and trimming processes.

This paper explores key parameters affecting geometrical quality in megacasting, drawing on literature, industrial practice, and experimental quenching tests to identify major contributors to geometrical distortion and discuss potential improvement approaches relevant to cost-efficient and sustainable automotive production. Section 2 describes the methodology, Section 3 presents insights from expert interviews and literature, Section 4 outlines the physical tests, Sections 5 and 6 provide the discussion and conclusions.

2. Methodology

The findings in this paper are based on a combination of three qualitative and experimental approaches. Insights were gathered through 12 semi-structured interviews with process engineers, designers, and quality assurance specialists from academia and industry, selected based on their experience in high-pressure die casting (HPDC) and involvement in megacasting-related development. The interviews were systematically analyzed to identify recurring themes related to geometrical distortion and process-related challenges.

In parallel, a literature review was conducted to identify contributors to geometrical distortion in HPDC, with a focus on die design, quenching techniques, and material properties.

Additionally, physical tests were performed in an industrial setting to investigate the effects of selected process parameters, such as die temperature, quench media temperature, quench orientation, and quench time, on distortion. The tested parameters were chosen based on industrial relevance and feasibility within the available process window.

3. Factors Influencing Geometrical Quality in HPDC

Megacasting is a form of HPDC, distinguished primarily by the sheer size of the components produced. Using Giga Presses capable of exerting clamping forces exceeding 9,000 tons, this process enables the creation of large, single-piece castings. However, the increased mass and geometric complexity introduce significant challenges; particularly in managing heat flow and solidification. More advanced thermal control, compared to traditional HPDC, is therefore critical to ensure uniform solidification and to reduce the risk of defects such as porosity, warping, and residual stresses.

The casting process contains many steps, each of them providing its own challenges and contributors to distortion in the megacast component. The main process steps are considered in this section, together with a discussion based on interviews and literature about the factors affecting geometrical quality. Some steps have been consolidated, or even excluded, to align with the objectives of this paper.

Figure 1 introduces key terminology for a megacast component. Figure 2 summarizes the design and process factors discussed in this section; the labels *i*, *l*, and *t* indicate the information source (interviews, literature, and physical tests), and flagged parameters denote those identified as most influential (as discussed in the following paper). Die-casting machine characteristics, such as die stiffness, maximum locking force, and injection pressure, are excluded from the analysis.

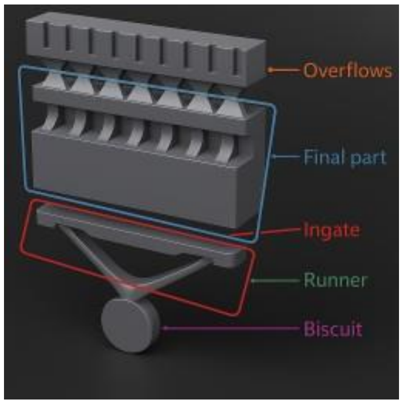

Figure 1: Terminology of a megacast component

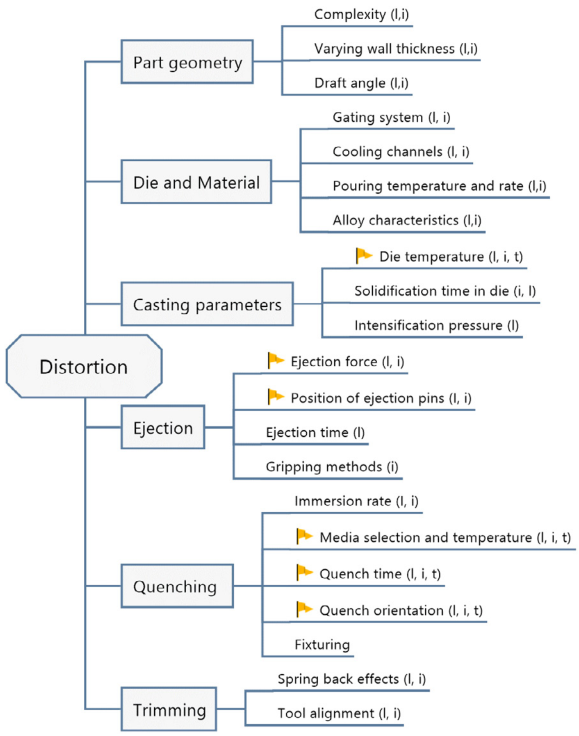

Figure 2: Design and process parameters critical to distortion in a megacast component; flags denote the most influential ones (see Discussion).

Part Geometry: The design of the megacast component fundamentally influences geometrical quality through its effects on heat transfer, residual stress development, and distortion. While functional, cost, and producibility requirements must also be considered, the focus here is on distortion risk. *Complex geometries*, particularly in large components, promote non-uniform heat transfer and constrained contraction during solidification and cooling, which can lead to the development of residual stresses and subsequent distortion [2].

In addition, variations in *wall thickness* result in uneven cooling rates, giving rise to thermal gradients and localized plastic strain that may cause permanent deformation [2]. During the interviews, it was also noted that the cooling system can be used to partially compensate for thickness variations by promoting more uniform cooling conditions.

Interviewees highlighted *draft angles* as beneficial for geometry assurance, as they reduce adhesion between the casting and the die, lowering ejection forces and the risk of deformation during ejection.

Die and Material: Die design plays a crucial role in the quality of HPDC components, as it directly impacts material flow, solidification, and cooling. The *gating system*, with its key features such as runners, ingates, and the biscuit, is carefully designed to ensure that the molten metal fills the die cavity uniformly and without turbulence, minimizing defects such as air entrapment or cold shuts. The runners guide the molten metal into the die, while the ingate controls the entry of metal into the cavity, balancing flow and pressure. The biscuit, located at the end of the shot sleeve, acts as a reservoir to maintain pressure during solidification, thereby reducing shrinkage-related defects. Proper design of these features also contributes to optimized thermal behavior and reduced residual stress development. Furthermore, contraction of the gating system during solidification may mechanically interact with other sections of the casting, potentially contributing to distortion and hot tearing [3]. The interviewees also emphasized the significance of the gating system, particularly the thickness of the gating. As the gating solidifies together with the casting, it retains substantial heat, influencing the overall temperature distribution of the megacast component and, consequently, the degree of distortion in the final part.

The position of *cooling channels*, which regulate the temperature of different regions of the die, plays a crucial role in controlling the solidification rate. One respondent noted that if die design focuses on minimizing residual stresses, cooling channels should be positioned closer to thicker sections to promote more balanced cooling.

A consistent *pouring temperature* and *flow rate* help prevent defects such as misruns and cold shuts [4]. In the interviews, it was further noted that uneven pouring may contribute to residual stress accumulation. The pouring temperature influences hardness, microstructure, and potentially geometrical quality by affecting metal flow and cooling conditions. Pre-heating the die is also important to establish uniform thermal conditions, thereby reducing temperature gradients and minimizing distortion.

The characteristics of *aluminum alloys* influence casting outcomes, including the tendency for die soldering, which can contribute to distortion [5]. In addition, the ability to use recycled aluminum is important for both sustainability and cost considerations. Recycle-friendly alloys with higher tolerance to impurities will therefore be required [6].

Casting parameters: *Die temperature* and cooling rate affect geometrical quality, as uneven cooling during solidification creates thermal gradients leading to residual stresses and distortion [2, 7]. In the interviews, the importance of closely monitoring die temperature to prevent the formation of local hot spots during solidification was emphasized.

The *solidification time* and the behavior within the die cavity have a strong influence on the geometrical quality of cast parts. In the interviews, it was noted that ejecting the part too early can result in bending due to insufficient stiffness, whereas excessive dwell times increase the risk of ejection difficulties caused by shrinkage onto the die surface. Solidification-related effects were also highlighted as contributors to distortion, particularly for components with thin sections that solidify earlier than the biscuit, requiring sufficient dwell time to ensure complete solidification of the feeding system.

Interviewees further mentioned that reducing the dwell time in the die, corresponding to an insufficient solidification time (e.g. from 20 to 10 s), may leave the part semi-solid and prone to deformation during ejection. However, increasing the dwell time beyond a certain level may not further improve geometrical accuracy, while negatively affecting productivity. Shrinkage-related effects are generally considered to be more strongly influenced by temperature gradients and local solidification rates than by the total time the part spends in the cavity. In contrast, [8] reported that solidification time was not a significant contributor to geometrical accuracy for a HPDC magnesium alloy (AZ91D) component.

Intensification pressure is applied after cavity filling and during the solidification stage in HPDC. Its influence on geometrical accuracy depends on part size, geometry, and design. In the interviews, four respondents noted that intensification pressure mainly affects regions close to the ingate and may not be fully transmitted to all sections in components with varying wall thicknesses, potentially influencing local quality. One interviewee argued that its overall influence on geometrical accuracy is limited.

Ejection: The ejection stage is a critical phase in the casting process, as it introduces significant risks of mechanical deformation if not carefully managed [9]. The ejection mechanism is also related to draft angles, discussed in the section about part geometry. The ejection phase involves using *ejection forces* to remove the part from the die after it has solidified and cooled. Ejector forces depend on factors such as the alloy, release agent composition, locking time, intensification pressure, and the ejectors' pressure and speed [10]. The impact from the ejection forces on geometrical accuracy was also stressed during the interviews. Ideally, the forces should cause bending at the gate but can potentially lead to twisting of the part. Proper placement of the *ejection pins* is critical to ensure that the forces are evenly distributed and do not cause warping or distortion of the casting, as mentioned by the interviewees and in [11]. During the interviews, one respondent highlighted that the number and placement of ejection pins should be designed to minimize ejection forces during the ejection phase.

The *ejection time* indirectly influences defects such as soldering, which occurs when the casting sticks to the die surface. Soldering is especially problematic in hotter areas of the die, leading to surface damage, dimensional inaccuracies, and increased production downtime. Managing the ejection timing can help mitigate soldering by allowing the casting to cool sufficiently before removal, thereby reducing adhesion to the die. Moreover, ensuring adequate lubrication prior to injection can aid in controlling this issue by forming a protective barrier that eases the release of the casting [12].

Gripping methods can significantly affect the ejection phase by impacting how uniformly the casting is released from the die. In the interviews, it was noted that gripping methods are important, with robots typically gripping the biscuit for simplicity. However, alternative methods may be needed for certain designs, such as long and thin castings, to prevent distortion during handling [12].

Quenching: The quenching process strongly affects the geometrical quality of megacast components, as media temperature, immersion rate, and quench delay influence the development of residual stresses and distortion. Both literature and interviews indicate that a slow *immersion rate* increases the risk of severe distortion, particularly in components with non-uniform wall thickness, where large temperature differences promote internal stress development [13], [14].

The importance of quenching *media selection and temperature* is highlighted in both literature [14] and the interviews, where the temperature difference between the casting and the quenching media emerged as a key factor. Excessively low media temperatures may lead to increased residual stresses, especially in parts with uneven thickness. Several interviewees hypothesized that larger temperature differences increase the risk of distortion, as lower water temperatures intensify thermal gradients and residual stress development. It was further noted that, to balance mechanical properties and geometrical quality, the quench delay, i.e. the time between ejection from the die and immersion in the quenching media, should be minimized.

Quench time and *quench orientation* are also frequently discussed in the literature [14]. During the interviews, some respondents suggested that optimizing quench orientation could reduce warping, while others believed that orientation has limited influence provided that the entire casting is fully submerged. In contrast, the duration of immersion in the quenching bath was consistently highlighted as critical for controlling heat extraction and cooling uniformity.

Fixturing during quenching was addressed by company experts through the use of a gripper with multiple clamps that support the part throughout the process. The gripper is designed to withstand the forces arising during quenching that could otherwise deform the megacast component, thereby helping the part retain its intended shape. Further testing of this approach is planned. In the literature, racking of parts during quenching has been discussed as a means to promote uniform cooling conditions when multiple components are quenched simultaneously [14]. In the present context, the primary focus of fixturing is to allow uniform heat flow around the component while providing mechanical support during quenching.

Trimming: Trimming removes excess material such as overflows, runners, and biscuits, but may also release residual stresses, leading to *springback* effects [1]. During the interviews, differing views were expressed regarding the impact of trimming on geometrical accuracy. While some interviewees stated that stress release during trimming does not introduce new stresses or significantly affect geometry, others argued that deformation may occur, particularly if removed features, such as elements of the gating system, previously provided structural support to the casting.

Tool alignment was also highlighted as a critical factor during trimming. The use of a trim press is standard practice, although alternative solutions such as laser cutting were also discussed. Misalignment of trimming tools can lead to uneven material removal, which may negatively affect the final geometry. Overall, the interviews indicate that while trimming is often treated as a secondary operation, it can contribute to geometrical variation and distortion if not carefully controlled.

4. Industrial Case Study and Experimental Tests

As discussed in the previous section, megacasting is a complex process where improving geometrical quality is challenging due to strong interdependencies between process parameters, part geometry, material properties, and die conditions. Requirements on final material properties further restrict parameter adjustments, while the high cost of casting machines and tooling makes extensive trial-and-error approaches impractical.

Figure 3 shows the megacast component used in the study, where the geometrical quality did not meet specifications. The arrows indicate distortion in the wheelhouse and front-leg regions. A series of quenching-focused tests was conducted to reduce distortion while maintaining required material properties. Some tests were excluded due to process-related disturbances, resulting in unequal sample sizes between tests. The six evaluated test conditions were selected based on industrial feasibility within the available process window rather than through a full factorial design. The objective was to explore practically adjustable quenching-related parameters under production constraints; consequently, the statistical analysis is descriptive and focused on identifying trends rather than performing formal hypothesis testing.

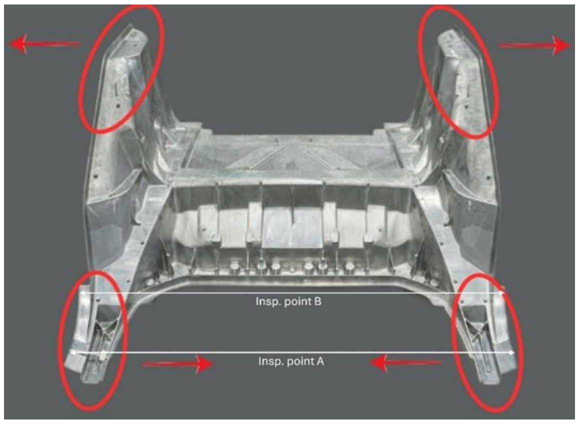

Figure 3: The tested megacast component. The arrows indicate unwanted distortion patterns in the wheelhouse area and in the 'front leg' area.

All parts were scanned to assess distortion patterns, with particular focus on the wheelhouse and front-leg areas. The analysis showed that the wheelhouse region was relatively insensitive to the applied process changes, whereas larger variations were observed in the front-leg area. For this region, manual measurements of the distance between the two legs were therefore performed, as illustrated in Figure 3.

While absolute measurement values are not disclosed due to confidentiality, trends and distributions were analyzed statistically. The measurement results for the distance between the legs are presented in Figure 4a-b (Inspection Point A/B). Each figure includes a bubble plot, indicating the frequency of observed values for each test condition, and a boxplot. In the boxplots, the central box spans the 25th to 75th percentiles, with the median indicated by a horizontal line. Smaller deviations from nominal geometry indicate improved geometrical quality.

Test	Description	Sample size
1	Short quenching time - biscuit, ingate and "legs" not dipped.	6
2	Sequential/partial quenching: leg1 & wheelhouse1, then leg2, then wheelhouse2	6
3	As 2, but die temperature increased by 30°C	34
4	As 3, but no quenching of biscuit and runners	3
5	As 3, but solidification time in die increased	4
6	Increased die temperature, higher quench media temperature, longer quench time	8

Table 1: Overview of the physical tests.

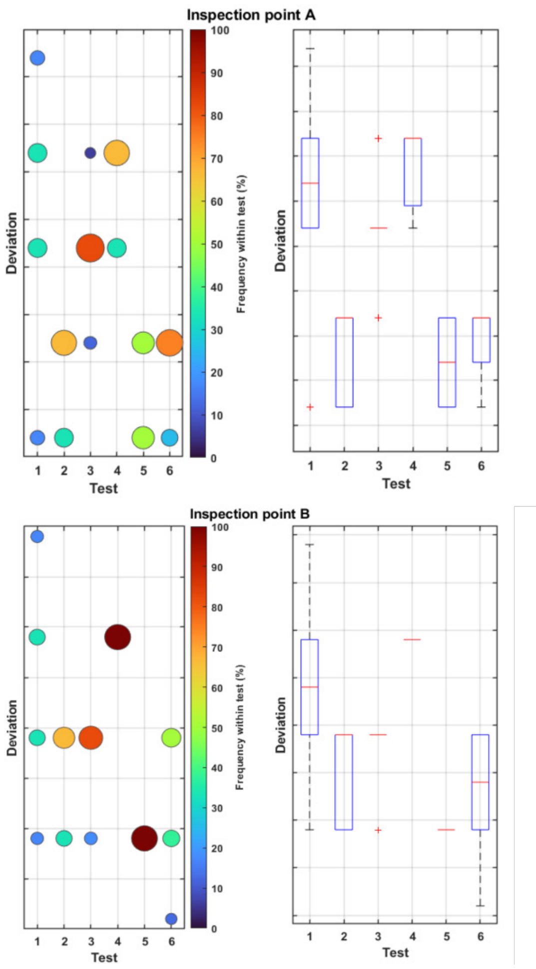

Figure 4a-b: Bubble plots and boxplots showing the distribution of measured deviations for the six test conditions at two inspection points.

The visualizations indicate several distinct trends across the tested conditions. Test 1 shows a relatively large spread of measured values and a comparatively high median. Test 2 is associated with reduced variation and a lower median compared to Test 1. Test 3, which was repeated a larger number of times, exhibits consistent distributions; however, the median remains higher than that of Test 2, particularly at Inspection Point A. Test 4 is characterized by increased deviation, indicating a higher level of distortion. Tests 5 and 6 both show comparatively stable distributions with lower variation and lower median values, suggesting more consistent geometrical outcomes under these conditions. Considering the limited and uneven sample sizes, Tests 5 and 6 exhibited the most favorable geometrical outcomes among the evaluated conditions.

These patterns are consistent with insights from interviews and literature in terms of trends. Tests 5 and 6 involved longer solidification time and less severe quenching conditions. Longer solidification time allows the temperature distribution in the casting to become more uniform before ejection [8], while higher die temperature reduces the temperature difference between the melt and the die and thereby influences thermal gradients during solidification [7]. In addition, higher quench media temperature leads to less aggressive cooling during quenching [14], which reduces thermal mismatches during cooling. These mechanisms contribute to more uniform cooling conditions and reduced thermal gradients, which in turn reduces residual stresses and distortion.

However, the potential effects of these process conditions on mechanical properties and overall material performance require further investigation.

Due to cost and availability constraints, a comprehensive experimental study with systematic variation of all process parameters was not feasible. Nevertheless, within the scope of the conducted tests, several process adjustments were associated with reduced distortion and improved geometrical quality. The following parameter changes, applied within the available process window, were observed to contribute to more favorable geometrical outcomes:

- Increasing die temperature
- Increasing solidification time in the die
- Increasing quench media temperature
- Increasing quench time

It should be noted that these parameters are interdependent, and their combined influence on distortion must be considered alongside potential effects on mechanical properties and production efficiency.

5. Results and Discussion

The results show that distortion in megacasting is governed by multiple interdependent design and process parameters and must be balanced against other critical requirements such as material strength, durability, and crack prevention. These requirements are strongly influenced by cooling and quenching conditions, while cycle time constraints limit the feasibility of solutions involving long solidification or quenching times. Within the scope of this study, die temperature, ejection pin position, ejection force, and the quenching process emerged as influential and partially adjustable parameters and are therefore flagged in Figure 2. Improved geometrical quality requires coordinated adjustment of these parameters rather than isolated changes.

Distortion may be managed through a combination of tool compensation and process control. Tool compensation can be achieved by modifying tool geometry to account for predictable deformation, supported by numerical simulation to reduce costly trial-and-error iterations. However, this approach places high demands on simulation model accuracy due to the complex thermo-mechanical behavior involved.

Beyond component-level distortion prediction, variation simulation at the assembly level can be used to evaluate how geometrical deviations in megacast components propagate through assemblies [15, 16]. This enables informed tolerance allocation, supporting both robust assembly performance and cost-efficient manufacturing.

In addition, supportive fixturing during quenching may help limit distortion but must accommodate thermal expansion to avoid introducing additional stresses.

Overall, the results indicate that distortion control in megacasting relies on combining compensation strategies, targeted process parameter adjustments, and controlled quenching, while further experimental studies are required to validate simulation models and deepen understanding of parameter interactions.

6. Conclusions

Megacasting is a complex manufacturing process, and controlling distortion in large castings with varying wall thicknesses is a significant challenge. This study combined insights from interviews, literature, and physical tests to investigate factors influencing distortion. In the study, several design and process parameters were highlighted as particularly influential for geometrical quality, while also being adjustable to some extent in industrial production. The results emphasize the importance of considering interactions between parameters rather than isolated effects.

The findings contribute to an improved understanding of distortion phenomena in megacasting and support the discussion of potential approaches such as tool compensation, process parameter tuning, and supportive fixturing during quenching. While further experimental validation and simulation development are required, the study provides a basis for continued research and industrial development toward improved distortion control in megacasting.

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