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Enhanced Material and Part Optimization and Process Intensification

Proceedings of the third International Joint Conference on
Enhanced Material and Part Optimization and Process Intensification EMPOrIA 2026
02nd and 03rd of June 2026, Aachen, Germany

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EMPOrIA 2026

Proceedings of the third International Joint Conference
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Process Intensification

Shaker Verlag
Düren 2026

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Shaker Verlag 2026

Print-ISBN 978-3-8191-0730-6
PDF-ISBN 978-3-8191-0670-5
https://doi.org/10.2370/9783819106705

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren
Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9
Internet: www.shaker.de • e-mail: info@shaker.de

Date: 31.03.2026

Development of a compensation strategy for casting distortion in aluminum gravity die casting

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Abstract

An initial study of previous research on distortion formation in gravity casting revealed a lack of holistic descriptions, particularly regarding heat transfer between mold and casting. This work aims to better understand the various influencing factors and their mechanisms affecting distortion in aluminum gravity die casting through targeted experiments. The causal chain of heat balance, mold constraint, solidification, cooling, stresses, and component distortion was examined both individually and contextually. An experimental methodology was developed to investigate these variables. Findings indicate that thermal interaction primarily affects process stability while distortion can be largely compensated by adjusting demolding temperature. These Insights can be used to derive a strategy for compensating distortion in aluminum die casting. An initial review of this strategy in a numerical simulation concludes the work.

Keywords

Aluminum, die casting, distortion, compensation

1 Introduction

Aluminum is one of the most important engineering materials and is widely used in the foundry industry, particularly in transportation applications where lightweight design plays a key role in improving energy efficiency. With increasing demands for functional integration and structural performance, the complexity of cast components has risen significantly. As a result, requirements regarding dimensional accuracy and casting quality have become more stringent. A central challenge in this context is distortion, which originates from thermally induced shrinkage during solidification and subsequent cooling. If shrinkage occurs non-uniformly due to geometric asymmetries, local temperature gradients, or constraints from a mold, internal stresses lead to shape deviations that may exceed allowable tolerances. Although permanent mold casting offers high dimensional accuracy, shrinkage-related distortion remains a challenge due to the high thermal conductivity and mechanical rigidity of the metal mold, which lead to stress formation.

In research, this topic is mainly addressed in numerical studies on the prediction of distortion in high pressure die casting (HPDC) [1-3]. These works often point out that there are deficiencies in the understanding of the fundamental mechanisms and their analytical description. Such knowledge about the respective influences of component geometry, material, and process on component distortion is essential for the development of precise numerical models, particularly in coupled thermo-mechanical approaches [4]. One of the studies using a “triple U-shape” geometry and AlSi7,5Mg0,4 in HPDC concluded that the final geometry and distortion of the casting depend strongly on the demolding temperature, internal stresses at the time of demolding, and the thermal conditions in the mold and during cooling after demolding [2]. Related studies compared numerical simulations with experiments on component distortion and residual stresses using two special test geometries, a thick stress grid and a thin V-shaped shell [1, 5, 6]. In experimental series varied oil-cooling, holding time (and by this demolding temperature), and in some cases water quenching were investigated. The results for the grid indicated that distortion is influenced by the cast material with the mold acting as the limiting factor for heat dissipation [5]. The results of the V-shape showed stronger dependence on mold temperature control and holding time due to low high-temperature strength and resulting plastic deformation [6]. The studies also highlighted that simulation accuracy strongly depends on precise material models and correct thermal-mechanical contact descriptions. Another study investigated distortion compensation in automotive structural castings. Distortion was mitigated via geometric tool adaptations (pre-compensation) and simulated using global and local compensation factors. Results showed that applying tailored local or global compensation factors effectively reduced deviations, with trade-offs depending on undercut areas and manufacturability constraints [7].

Overall, the previous studies indicate that in permanent mold casting, distortion is primarily influenced by the thermal management and holding time – and therefore demolding temperature. Practiced compensation is mostly achieved through costly tool adaptations, while the underlying mechanisms of distortion formation remain insufficiently understood. Furthermore, almost all previous studies focus on HPDC, and investigations for gravity die casting – a process with minimal disturbances such as high pressure and high flow rates – are nearly nonexistent.

2 Aim of the Investigation

The overarching objective is to establish a comprehensive empirical understanding of distortion formation in permanent mold casting and derive a compensation strategy from the findings. Specifically, this work aims to analyze the mechanisms leading to distortion in aluminum gravity die casting and to quantify the influence of relevant process parameters. For this purpose, the causal chain consisting of heat balance, mold constraint, solidification, cooling, stress development, and resulting component distortion is investigated both individually and in terms of their interactions. A systematic experimental methodology is developed to isolate and evaluate these influencing factors. This approach enables the identification of cause-effect relationships between thermal conditions, mechanical constraints, and resulting deformation behavior. Based on the experimental findings, a strategy for distortion compensation is derived. This strategy is intended to enable targeted and efficient reduction of distortion by addressing the relevant mechanisms at different stages of the casting process. Finally, the applicability of the proposed approach is evaluated through an initial validation using numerical simulation.

3 Materials and Experimental Details

To investigate these influencing factors on distortion an experimental methodology was developed and corresponding test series and individual experiments were conducted. As the geometry of the test component, a U-shaped design was selected due to its simplicity and ease of measurement [8]. The distortion can thus be quantified as a two-dimensional value based on the opening width. By extending the “U” geometry to an F-shape, a freely shrinking reference element was added. The wall thickness of the test component in the initial configuration is 10 mm, and the opening width of the “U” is 130 mm with a component height of 120 mm. This results in a casting weight of 2,4 kg in aluminum. To determine and describe the relationships, the distortion value (D) is defined as the deviation of the opening width of the “U” from the nominal value. The deviation of the inner length (Δl_i) – the connection between the two legs of the “U” – from the nominal value is used as a measure to evaluate the hindrance of shrinkage, which leads to internal stresses. The difference between the opening width (ΔO) and the inner length is considered a measure of the shape-change contribution to the distortion induced by the release of these internal stresses during demolding. The designations of the areas, variables, and measurement points are shown in *Figure 1* (left). The expected thermomechanical behavior of the test component is illustrated and explained in *Figure 1* (right). From the demolding, which corresponds to the demolding temperature, a uniform shrinkage of the entire casting is assumed until it reaches ambient temperature.

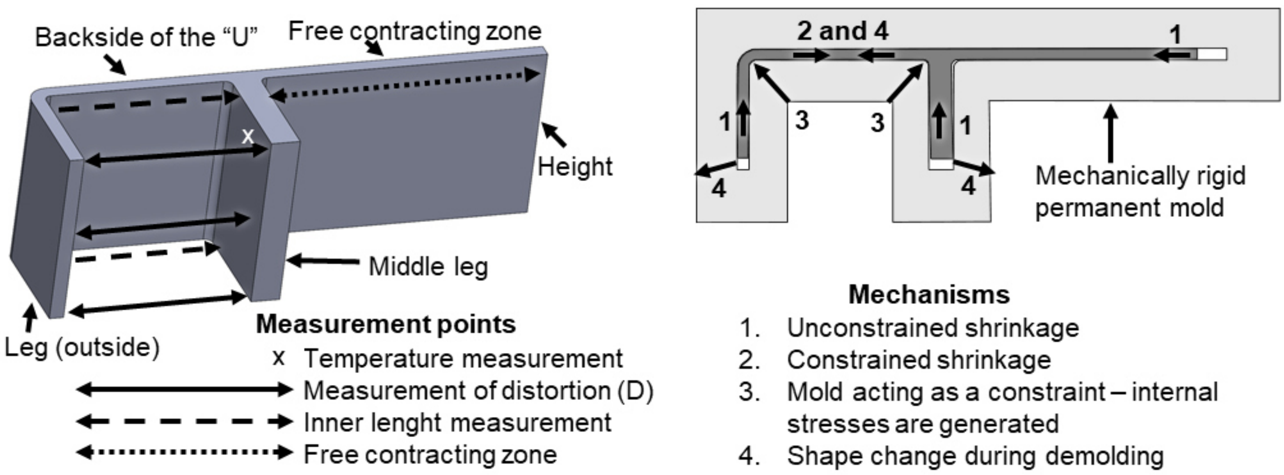


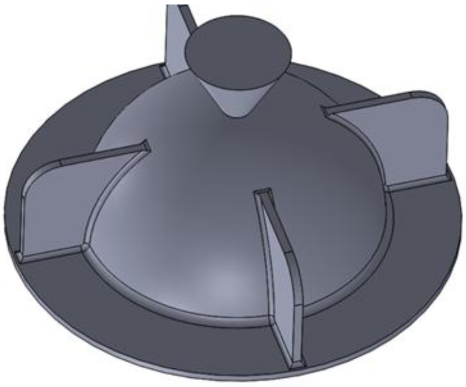
Figure 1: Test geometry with measurement points (left) and schematic representation of the governing distortion mechanisms (right). The distortion results from the interaction of unconstrained and constrained shrinkage, stress formation due to mold constraint, and subsequent shape change when the mold constraint is lifted.

The casting is enclosed by steel die modules arranged along the circumference of the "F", incorporating cooling channels equidistant from its surface. The influence of geometry, such as global and local wall thickness variations, inherent shrinkage restraint of the component, or geometric pre-compensation, can be investigated through modifications of the die. For most variations, this can be achieved by replacing a die module located between the two legs of the “U”, which is referred to in the following as the core [8]. This module, which in the base configuration is a conventionally manufactured tool steel insert, can also be replaced by an additive manufactured steel insert or by a sand core. The preheating temperature of the die can be adjusted via cooling circuits. For locally differentiated temperature control, the region of the core module can be regulated independently from the rest of the die. For detailed process analysis, an in-situ measurement system consisting of multiple temperature and displacement sensors is implemented. The casting alloy used in all experiments is the industry-standard AlSi7Mg0,3, with a pouring temperature of 720 °C. Unless otherwise specified, castings are demolded after cooling to ambient temperature, and each series of castings consists of 5 to 8 samples. The experimental program is structured into three main areas:

- Variation of thermal conditions: Global and local different die preheating was investigated (30 to 150 °C). To verify whether the hypothesis established in the SFB1120 for plastic injection molding – that a more uniformly solidifying component develops less distortion [9, 10] – can be transferred to metal casting, the methodology developed there for heat-balance-optimized cooling channels was applied to an additively manufactured core module.
- Variation of mold constraint: One variation of the mold constraint effect was realized by variation of the demolding temperature. As an additional variation, the influence of mold constraint was examined by using a sand core instead of the steel core module.
- Variation of component geometry: To investigate the influence of component volume through a global reduction of wall thickness, corresponding experimental series were carried out. Additional individual experiments were conducted to study the influence of local wall thickness variations, achieved by thickening the middle leg. To investigate the influence of geometric pre-compensation experimental series were carried out using a core module with a geometry adapted according to an empirically determined compensation value.

Apart from distortion, the evaluation includes solidification and cooling, metallographic analysis and a process stability assessment. The latter is quantified using the relative scatter of distortion, defined as the normalized standard deviation within a test series.

Based on the insights gained from these individual series of experiments regarding the formation of distortion, a compensation strategy is subsequently derived. This strategy is intended to enable the targeted and localized compensation of distortion in a cast component by applying interventions at different stages in the chain – namely, component design, process design, and process-inherent factors. To verify this strategy, a complex cast component, modeled after an automotive structural casting part, is simulated in MAGMASOFT®, which had already been used during the design of the experimental setup. In *Figure 2*, the corresponding cast component is shown on the left as a CAD model with the inlet on top, and on the right as a sketch for visualization of the associated dimensions. Flatness of the circumferential annular flange is used here as a measure of distortion. As a means of process-inherent control, the different regions of the steel mold surrounding the component can be temperature-controlled locally and temporally along the circumference.



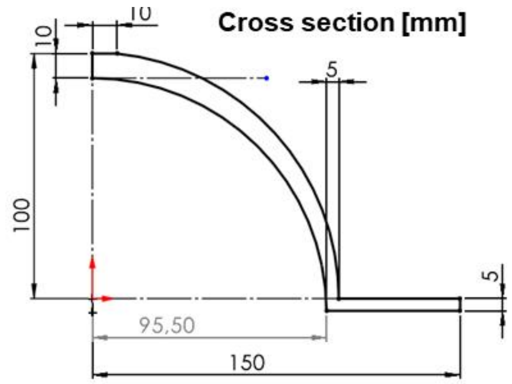


Figure 2: The complex cast component to verify the compensation strategy.

4 Results and Discussion

The results of individual influencing factors and their mechanisms of action are partly presented in separate earlier publications in more detail and are incorporated below as required for the development of the compensation strategy.

The variation of die temperature shows no direct correlation with the absolute magnitude of distortion [8]. However, an effect on process stability is observed. Using the conventional core lower die temperatures lead to increased scatter in distortion, indicating more heterogeneous solidification and stress development. The use of optimized cooling channels results in more homogeneous solidification conditions. This leads to an increase in mean distortion, which can be attributed to the formation of a continuous load-bearing dendritic network over a larger temperature range. At the same time, the relative scatter decreases, indicating improved process stability due to more uniform stress evolution [11]. *Figure 3* shows the distortion results for different mold temperature control configurations: on the left for conventional cooling, and on the right for the optimized cooling channels.

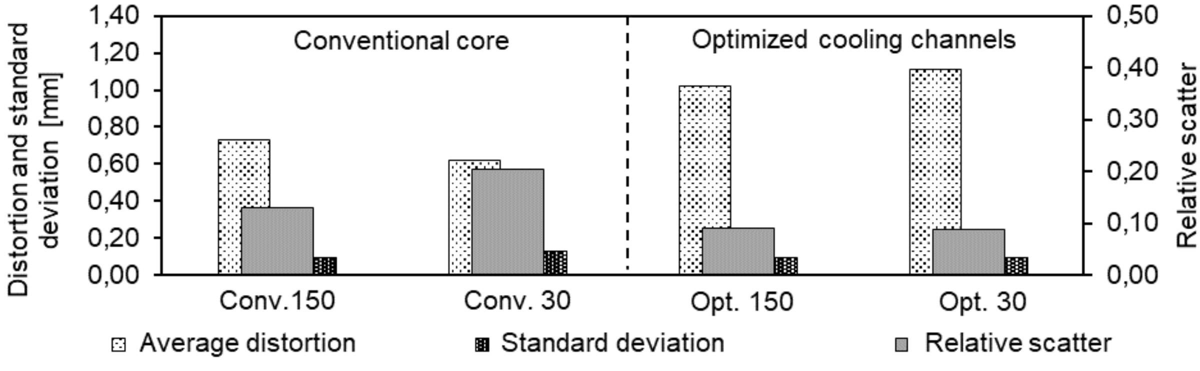


Figure 3: Mean distortion, its standard deviation, and the resulting relative scatter for the influence of temperature control (30 and 150 °C) and optimized cooling channels.

A particularly strong influence is observed for the demolding temperature [12]. The results show an almost linear relationship between demolding temperature and distortion. With increasing demolding temperature, the deformation behavior transitions from opening to closing of the U-geometry. At a specific temperature (285 °C), nearly distortion-free conditions can be achieved, see *Figure 4*. The deviation of the inner length also shows an almost linear behavior, but without a sign change. Its magnitude, compared with the shrinkage of the free end, indicates that significant shrinkage constraint occurs within the mold. This behavior suggests that distortion is governed by a combination of elastic and plastic deformation mechanisms, with stress relaxation occurring predominantly during the constrained state in the mold. The influence of mold material is investigated by the comparison between steel and sand cores. Sand cores exhibit significantly lower shrinkage restraint, resulting in reduced distortion but increased relative scatter [13]. In the experiments with sand cores, higher preheating temperatures lead to smaller distortion magnitudes. This behavior highlights the importance of thermomechanical material properties and their temperature dependence.

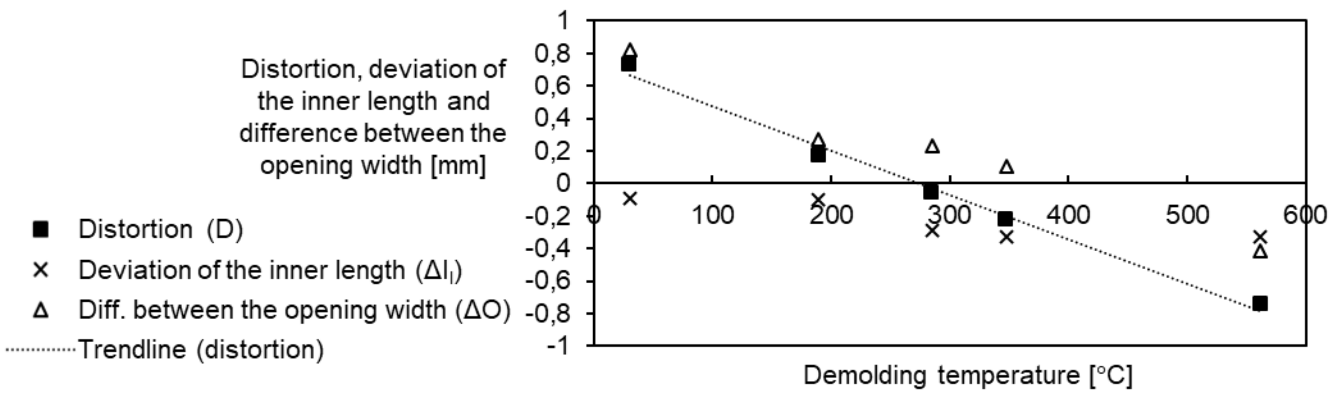


Figure 4: Measured values plotted against the temperature at which the mold constraint is released (demolding).

Geometric variations further illustrate the sensitivity of distortion to component design [13]. Reduced wall thickness shows with the initial nominal core no influence on distortion, while local mass accumulations increase distortion due to delayed solidification and localized stress formation. Geometric pre-compensation proves to be an effective measure for distortion reduction, although its efficiency depends on the specific geometry and boundary conditions, see *Figure 5*.

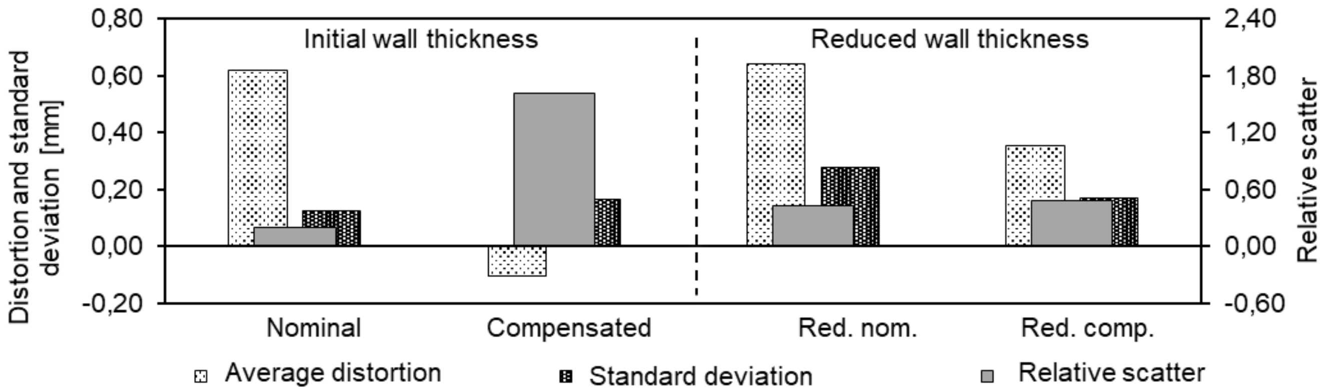


Figure 5: On the left, the results for the experiments with the original wall thickness, each shown for the core with the nominal geometry and for the variant with geometric pre-compensation. On the right, the corresponding values for the globally reduced wall thickness.

Comparative Evaluation

The results show that thermal interactions mainly influence process stability, while mechanical interactions (e. g. mold constraint and demolding temperature) primarily affect the magnitude of distortion. Distortion can therefore be largely compensated through a combination of controlled demolding temperature and geometric pre-compensation, after separating the phenomenon into linear shrinkage and shape change components. For the development of a targeted compensation strategy, it is also essential to identify when each influencing factor acts: during component design, casting process design, or the ongoing casting process.

Derivation of a Compensation Strategy

Based on the findings a path toward complete distortion compensation can be derived by compensating both linear shrinkage and shape change. The means for distortion compensation are divided by the stage of their appearance, see *Figure 6*. In practice, component geometry, including wall thicknesses, mass centers, and inherent shrinkage restraints, is treated as a fixed input parameter. Distortion compensation can be achieved through a combination of geometric pre-compensation during design and control of the demolding temperature during the process. The predictive geometric pre-compensation is applied so that relevant casting dimensions are in a way that in the process the final compensation is possible with time and place differentiated cooling and thereby demolding temperatures. This enables localized adjustment and compensation of dimensional deviations within complex castings. At the same time, thermal control can be used to create a more homogeneous temperature field at the end of solidification, thereby reducing the scatter of distortion and improving process stability.

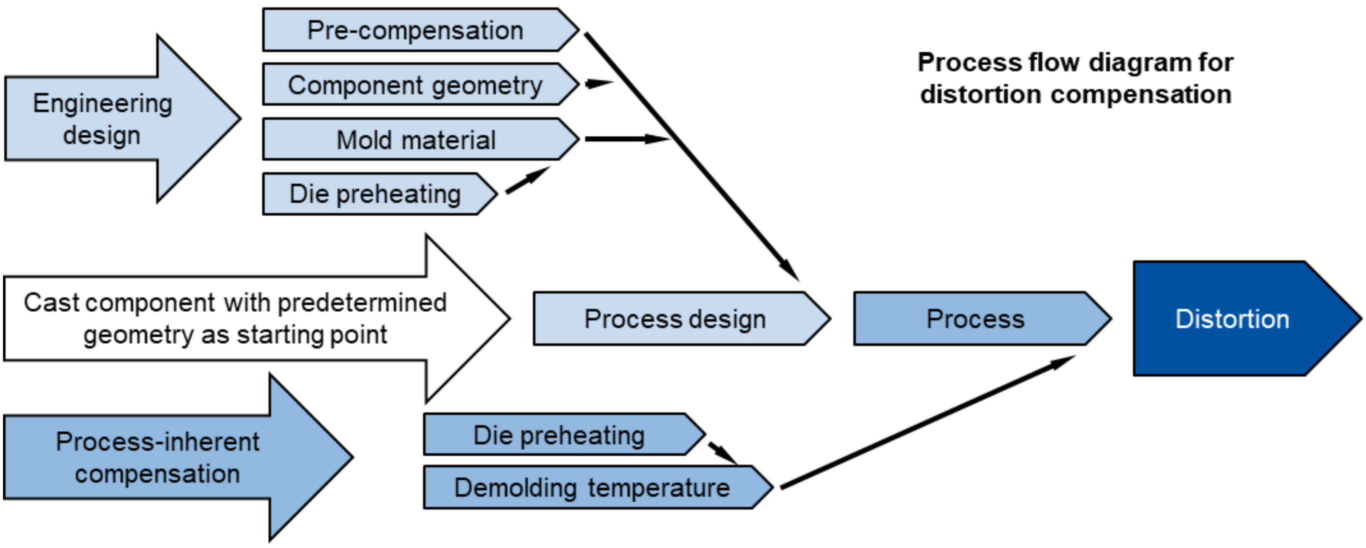


Figure 6: Distortion is influenced by design-related factors such as component geometry, mold material, and geometric pre-compensation, as well as by process-inherent parameters, including die preheating and demolding temperature.

Applying the compensation strategy outlined above to a complex cast component demonstrates in simulations that local distortion can be reduced through process-immanent adjustment of the local demolding temperature. The top of *Figure 7* shows the temperature fields at the moment when the mold constraint is released. On the left, a nearly homogeneous temperature distribution along the circumference is depicted, whereas on the right locally differentiated temperatures are applied, distinguishing between the regions of the outer ribs and the intermediate sections. The resulting distortion is illustrated in the center with a 25-fold magnification, where the flange remains visibly flatter. A flatness analysis indicates that the deviation of the flange from an ideal plane is reduced from 0,34 mm to 0,12 mm (bottom).

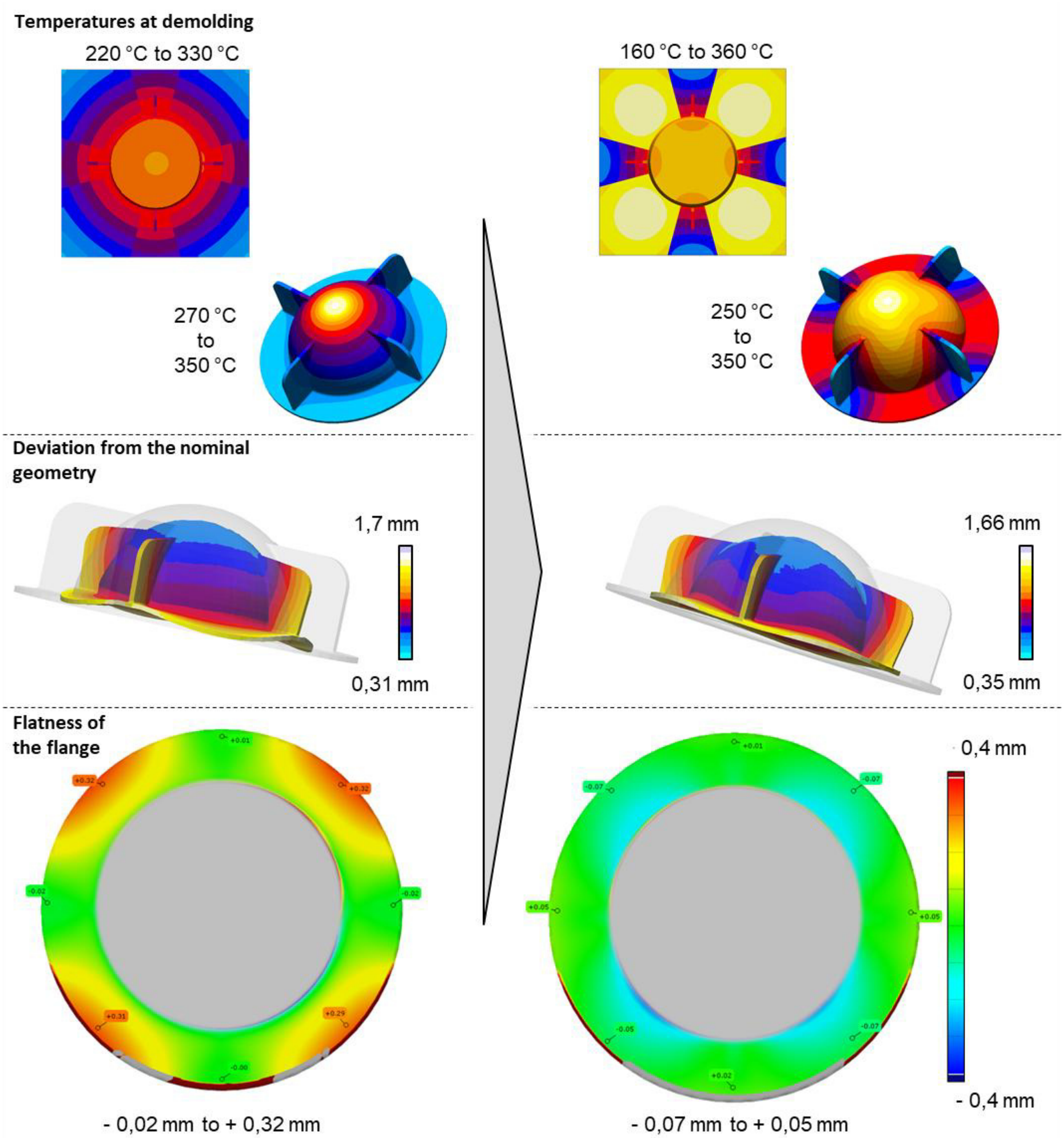


Figure 7: Compensation of the distortion of the complex cast component through locally differentiated demolding temperatures. The left side shows the initial condition, and the right side the compensated variation.

5 Summary

By systematically analyzing the causal chain of thermal and mechanical effects, a deeper understanding of the underlying mechanisms is achieved. The results show that demolding temperature and mold constraint are the dominant factors influencing distortion, while thermal conditions mainly affect process stability. This approach provides a deeper understanding of distortion formation in aluminum die casting by linking linear shrinkage, its hindrance, and shape change, thereby yielding insights beyond the current state of knowledge. Based on these findings, a novel combined compensation strategy was developed, integrating geometric pre-compensation and locally controlled demolding conditions. Initial validation through numerical simulation demonstrates that locally adjusted thermal boundary conditions can improve dimensional accuracy in complex cast components. The presented methodology provides a foundation for the development of predictive thermo-mechanical models and offers a pathway toward near distortion-free casting processes. The consistent experimental methodology enabled the first quantitative comparison of various influencing factors and their contributions to distortion, while the introduced relative scatter allows assessment of process stability. Analysis of mechanisms and interactions facilitates the attribution of factors to either part design or the casting process, providing a foundation for effective distortion compensation strategies. The developed compensation strategy was identified in a study as being goal-oriented.

Looking forward, the modular mold setup supports further investigation of input variations. Ultimately, a multi-step approach combining predictive design and locally adjustable demolding temperatures can achieve near-complete distortion-free castings, with thermal management further reducing variability through a more homogeneous solidification temperature field.

Acknowledgements

The presented investigations were carried out at RWTH Aachen University within the frame-work of the Collaborative Research Centre SFB1120-236616214 “Bauteilpräzision durch Beherrschung von Schmelze und Erstarrung in Produktionsprozessen” and funded by the Deutsche Forschungsgemeinschaft e.V. (DFG, German Research Foundation). The sponsorship and support is gratefully acknowledged.

Conflict of Interest

The author declares no conflict of interest.

Data Availability Statement

The underlying data are available upon request at: http://hdl.handle.net/21.11102/bcea071e-b41a-4c1f-82d0-7a3e7bd94e18

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