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ARTICLE

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# Description of component distortion in aluminum gravity die casting as a result of hindered shrinkage and evaluation of numerical predictions

## Untersuchung des Bauteilverzugs beim Aluminium-Kokillenguss als Folge der behinderten Schrumpfung und Evaluierung von numerischen Vorhersagen

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**Abstract**

Deviation from the nominal dimension in the sense of component distortion is a quality-reducing phenomenon in the foundry. This distortion problem as a result of impeded solidification and cooling shrinkage is of particular importance for permanent mold casting with its mechanically stiff and thermally well-conducting molds. In studies, the temperature when the mold constraint is removed has already been identified as one of the dominant factors influencing the dimensional deviations of the casting. So far, however, no clear dependencies have been described. In the present work, the temperature up to the removal of the mold constraint is varied from near solidus to ambient temperature on a specially designed permanent mold casting made of AlSi7Mg0.3. This is compared with thermally and mechanically coupled finite elements method calculations of the investigated test geometry and the resulting component distortions. Finally, the applicability of the distortion prediction for the development of compensation strategies is evaluated.

**KEYWORDS**
aluminum, demolding temperature, distortion, finite elements method, gravity die casting

**Abstract**

Bauteilverzug, aufgefasst als eine Abweichung vom Sollmaß, ist ein qualitätsminderndes Merkmal im Formguss. Dieses Phänomen als Folge der behinderten Erstarrungs- und Kühlschwindung ist für den Kokillenguss mit seinen thermisch gut leitenden und mechanisch steifen Formen von besonderer Bedeutung. In Untersuchungen wurde die Gussteiltemperatur bei der Aufhebung des Formzwanges bereits als ein vorherrschender Einflussfaktor auf den

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Verzug identifiziert. Jedoch wurden keine eindeutigen Abhängigkeiten herausgearbeitet. Für die vorliegende Arbeit wird an einem speziell für die Untersuchungen ausgelegten Gussteil aus AlSi7Mg0,3 die Temperatur der Aufhebung des Formzwanges von nahe der Solidus- bis zur Umgebungstemperatur variiert. Dies wird mit thermisch und mechanisch gekoppelten Finite-Elemente-Methode-Berechnungen der untersuchten Prüfgeometrie und den daraus resultierenden Bauteilverzügen verglichen. Abschließend wird die Anwendbarkeit dieser numerischen Verzugsvorhersage als Grundlage für die Entwicklung von Kompensationsstrategien bewertet.

**SCHLÜSSELWÖRTER**
Aluminium, Entformungstemperatur, Finite-Elemente-Methode, Kokillenguss, Verzug

## 1 | INTRODUCTION

A quality-reducing phenomenon in the foundry is deviation from the nominal dimension in the sense of component distortion. This distortion problem due to impeded solidification and cooling shrinkage is relevant for practically all molded parts, but is of particular significance for permanent mold casting with its mechanically rigid and thermally highly conductive metal molds.

In the literature, the phenomenon is described as a thermally induced shrinkage after removal of the mold constraint, starting from the component geometry imprinted by the mold at that time [1, 2]. The change in shape caused by the obstruction of thermal shrinkage while still in the mold is not described in detail.

In the field of permanent mold casting, the issue of component distortion is mainly considered on the basis of aluminum high pressure die casting and in a combination of simulations and experimental evaluation. Temperature control and holding time were varied on specially developed test castings and compared with finite element calculations [3–5]. For thin-walled castings, a dependence of the distortion on the temperature control of the mold insert and the holding time and thus the demolding temperature was found [5]. The accuracy of the material models used and the correct description of the thermal and mechanical contact conditions have a significant influence on the accuracy of the simulation results [3]. The latter is not considered in common simulation environments for casting simulations and the thermal and mechanical calculations that are not coupled there [4]. In another simulative approach using the finite element method, the influence of the boundary conditions of the heat balance on the prediction of distortion in a thin-walled structural casting was investigated [6]. Against the background of the major influence of the temperature distribution and local cooling on the final component distortion, the data from the software's own database used for the simulations appear to be insufficient. Thus, it was shown that for meaningful simulation results of the distortion simulations, these must be matched with the values of the real casting process in a first step. The common denominator of the investigations is that the temperature at the time of demolding can be identified as one of the dominant influencing factors on the dimensional deviations of the casting [7, 8]. The thermal expansion of the mold in the process largely corresponds to the amount of free shrinkage of the part after demolding, but this can lead to distortion due to non-uniformity in parts that are not ideally symmetrical [7]. In related fundamental works approaching the subject, the influence of the mold material and thus also of the mold constraint on the casting geometry was investigated and correlations were established, e.g. in cast iron sand casting [9]. In a connected work, a good agreement between experiments and by means of finite difference method calculated values was found, after adjustment of the material model [10].

It is often stated that there are deficits in the knowledge of the fundamentals and their analytical description. Knowledge of the proportional influences of component, material and process on component distortion is essential for the development of accurate numerical models, especially for coupled thermal-mechanical approaches. Likewise, a gap in the knowledge base is evident for gravity die casting as opposed to the high pressure die casting addressed often in research.

In the project on which this publication is based, various parameters influencing casting distortion, such as component geometry and wall thickness, the thermal balance of the process and the influence of mold constraint, are being investigated on a specimen specially developed for this purpose. This allows the various mechanisms of distortion to be considered separately

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and also makes it possible to quantitatively compare the contributions of the various influencing variables to overall component distortion. The aim is to create a broader knowledge, based on the fundamental correlations for optimizing numerical models for more precise predictive casting and process design and subsequently compensating for component distortion. In a first step, gravity die casting of aluminum is investigated as a basis for the consideration of permanent mold casting processes. In the experimental set-up used here, the influences of the heat-balance on component distortion have already been considered and published [11, 12]. In these investigations, in which the casting was demolded at room temperature, only minor influences on the magnitude of the resulting distortion were found. Following on from this, in the work presented here the influence of the demolding temperature and thus the temperature intervals in which the in-mold restrained and the free shrinkage of the casting occurs is considered and corresponding relationships are worked out.

Since the quality of the numerical prediction of the distortion depends significantly on factors such as the choice of the numerical method and the material model, it is important to compare the results with the experimental results [13]. Here in the paper, a first approach of a direct coupled thermomechanical simulation is compared with the experimental results when the demolding temperature is varied.

## 2 | EXPERIMENTS AND MATERIALS

Considerations on the simple detectability of the component distortion led to a geometry of the specimen as a "U", in that the distortion can be determined as a simple linear measure of the opening width. To record the unrestrained shrinkage, the connecting web of the "U" is extended on one side, resulting in an "F" lying on its side as the test geometry. The specimen has a casting weight of 2.4 kg aluminum, Figure 1 on the left. Thus, the dimension "d1" is the one whose deviation from the nominal value is defined as the component distortion $D$. The deviation of the inner length of the joint between the sides of the "U" - which is the dimension "d2" - from the nominal value is used as a measure for the shrinkage hindrance $\Delta L_h$. The difference between the opening width "d1" and the inner length "d2" is used as a measure of the change of shape $\Delta C_s$. For comparison with free shrinkage $\Delta L_f$, the latter is measured in the region of unrestrained contraction at the free end of the casting, the dimension "l1". It should be noted that the measurements were taken as an average over the part height and that the manufacturing deviations of the mold modules and the draft angles were considered, Table 1. For the evaluation, series of eight castings of the same condition were used in each case. For the experiments, the modular experimental mold from the earlier work on the influence of heat balance was reused together with the oil flow temperature control [11, 12]. The modules used in this work allow demolding up to temperatures close to the solidus temperature by using a tear-off inlet, and ejectors, Figure 1 on the right.

### 2.1 | Determination of the correlations

The expected thermomechanical behavior of the test part solidifying and further cooling to demolding temperature $T_{dm}$ in the mold which is assumed to be mechanically rigid can be described as follows: There are simultaneously areas which can shrink freely and those which are hindered from shrinking as long as the casting is in the mold, Figure 2. From the time of demolding, synonymous with the temperature of demolding, uniform shrinkage of the entire casting is assumed. The aim is now to show the change of shape as a function of the shrinkage restraint and, in a final step, to compare the numerically calculated distortion with the experimentally determined values.

### 2.2 | Experimentation

For the experiments of the present work, AlSi7Mg0.3 was selected as the material, since it is one of the most commonly used aluminum alloys in the casting process, for which a very broad knowledge base exists. As a starting point, the castings made as part of the work on the influence of the heat balance are used as the first series of experiments. These were cast at different mold temperatures of 30 °C, 150 °C and 300 °C and demolded the next day at room temperature (here assumed to be 30 °C). No

**TABLE 1** Geometric values of the test component.

| Label | Name | Nominal dimension [mm] |
|---|---|---|
| d1 | Distortion measurement | 130 |
| d2 | Inner length measurement | 130 |
| t1 | Thickness | 10 |
| t2 | Thickness wider middle rib | 20 |
| l1 | Free shrinking length | 200 |
| l2 | Short outer length | 90 |
| h | High | 120 |

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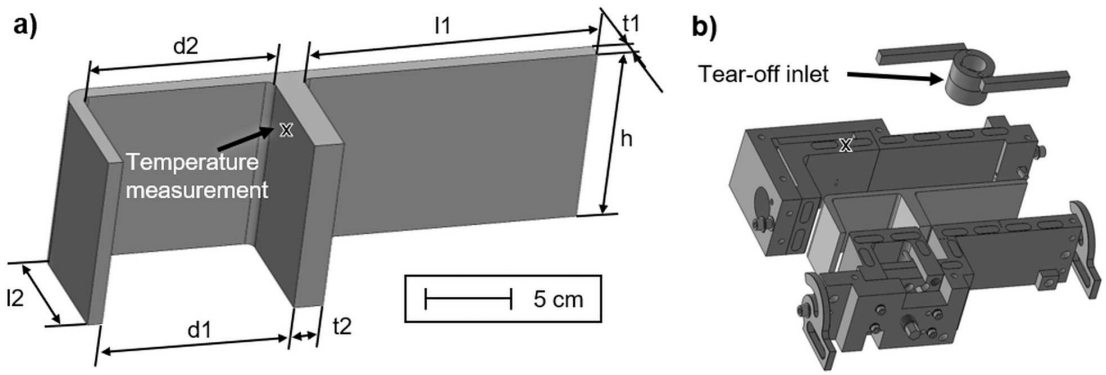



**FIGURE 1** a) Cast specimen and b) Mold for temperature-variable demolding in open condition around the casting. The location of the temperature measurement in the casting and in mold are marked (X), whereby the lower and upper calcium silicate plates of the mold are not shown for better illustration.

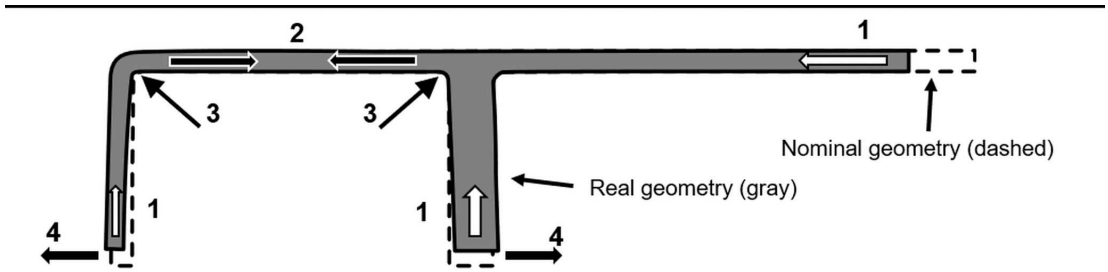



**FIGURE 2** Relevant physical relationships: 1. Areas and directions of unhindered shrinkage; 2. Area of shrinkage hindered by the mold; 3. Areas of the mold over which forces act on the casting due to the hindrance of shrinkage - residual stresses are generated in the casting; 4. Expected directions of the changes in shape after demolding resulting from the removal of mold constraint.

significant correlations between mold temperature and the magnitude of distortion were found [12]. Subsequently, four more series of eight castings each were poured. The demolding temperature for these series was varied over the dwell time in the mold up to the solidus temperature range (for AlSi7Mg0.3 this is 573 °C), measured in the mass richest area of the casting, Figure 1. In detail, the following procedure was followed for the four test series:

1. demolding with the mold set to 250 °C, when the temperature in the feeder reaches approx. 550 °C - demolding temperature in the casting approximately 347 °C
2. demolding with the mold set to 250 °C 360 seconds after casting - demolding temperature in the casting approximately 285 °C
3. demolding with the help of the breakaway sprue 70 seconds after casting with the mold set to 250 °C demolding temperature in the casting approximately 562 °C
4. mold initially set to 250 °C and switched to 150 °C oil flow temperature 60 seconds after casting. Demolding 420 seconds after casting. This leads to a demolding temperature approximately 190 °C in the casting.

## 2.3 | Numerical simulation

The two-dimensional coupled thermomechanical simulation used in this work was performed in the commercially available program "ABAQUS" to reproduce the mechanisms behind the experimental correlations. Linear hexahedral elements were used to avoid convergence problems at the contact between mold and casting. A mesh refinement study was performed, and the best refinement level was selected for the simulations. A tetrahedral linear type was chosen as the element type for the mold, since the deformation in the mold is not of interest, thus reducing the computation time. The total number of elements is thus 16,460. Furthermore, the liquid melt is considered as a viscous solid during solidification. The temperature-dependent material properties required for a coupled simulation, such as density, specific heat, elastic modulus, thermal conductivity and coefficient of expansion, were used in this simulation. The data for the plastic behavior of the material are taken from the literature [14, 15]. It is assumed that the plastic deformation does not depend on the strain rate, since very low strain rates are observed in the gravity die casting process. Cooling rate dependent material properties

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are used, since different cooling rates eventually results in different flow curves [13]. Furthermore, latent heat release due to phase change is considered.

## 3 | RESULTS

### 3.1 | Distortion – Experimental and numerical results

The five-experiment series considered below delivered averaged demolding temperatures of 190 °C, 285 °C, 347 °C, 562 °C and room temperature (assumed to be 30 °C). The distortion analysis of the five series for the temperature-variable removal of the mold constraint gives the following picture: The mean values show an almost linear course of the distortion over the demolding temperature from 0.73 mm at 30 °C to −0.74 mm at 562 °C, whereby at 285 °C with −0.06 mm almost the nominal dimension is met, Figure 3.

The trend of the distortion over the demolding temperature observed in the simulation is very similar to the experimental one. It is similarly linear and shows an almost equal slope for decreasing demolding temperature. Nevertheless, there is a significant deviation between the experimental and simulated values, in the form of an almost constant offset of the simulation results of about 0.5 mm towards a smaller distortion measurement, Figure 3.

### 3.2 | Change of shape as a function of hindered shrinkage

The measured deviation of the inner length, as a measure for the hindrance of shrinkage, shows a clear trend from 0.09 mm at room temperature to −0.33 mm at 347 °C (and correspondingly a linear percentual shrinkage of 0.07 % and 0.26 %), only the value of −0.32 mm at 562 °C deviates from this. It should be noted that this is close to the determined standard deviations of 0.04 mm to 0.06 mm. The change of shape as the difference of the inner length to the deformation dimension, again results in an almost linear development from 0.82 mm at room temperature to −0.42 mm at 562 °C demolding temperature. It should be noted that in addition to the alteration in the change of shape from expansion (positive values) to closure (negative values) of the "U", the opening width at 347 °C is largely constant at 0.11 mm. The shrinkage of the free end was found to be 2.28 mm with a standard deviation of 0.07 mm, corresponding to a percentual shrinkage of 1.14 %, which was found to be independent of the demolding temperature.

With the aim of making the change in shape dependent on the hindered shrinkage and the linear approximations found, the deviation of the inner length can be expressed as a function of the demolding temperature. Thus, the change in shape can also be described as a linear function of the deviation of the inner length and thus of the hindered shrinkage, Figure 4.

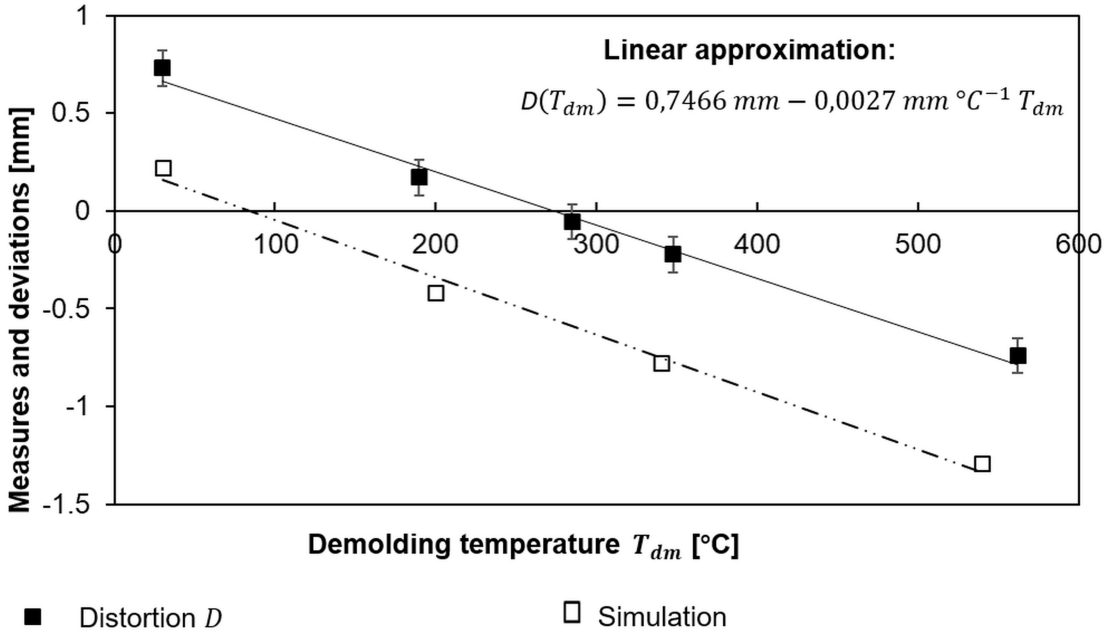



**FIGURE 3** Experimental distortion values for the different demolding temperatures and their standard deviations together with their associated linear approximation as well as simulated values.

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## 4 | DISCUSSION

The experiments show an almost linear dependence of the distortion on the demolding temperature. The case of demolding at room temperature, after one day in the mold, also fits this observation. It is not the duration of the mold constraint but the temperature of demolding that is decisive. The deviation of the numerical deformation results compared to the experimental results indicates that the assumptions made for the modeling or the material used may not be optimally suited.

The deviation of the inner length shows a similar temperature dependence, with slight deviations from it at the middle demolding temperatures. Inaccuracies in the temperature assignment are to be assumed here, since the temperature measurement was carried out in a different area of the component than the distortion formation, and even small differences can lead to deviations in the process. Therefore, a linear dependence on the demolding temperature can also be assumed here, which is consistent with statements in the literature. Consequently, a similar linear temperature-dependent behavior is also evident for the change of shape. Considering these dependencies in combination, especially the linear dependence on temperature, it can be concluded that for a mold assumed to be mechanically rigid, plastic deformation is a directly proportional consequence of shrinkage restraint. It should be noted that the values of the deviation of the inner length for all demolding temperatures from 0.09 mm to 0.33 mm are closer to the fully constrained shrinkage than to the free shrinkage (0.07% and 0.26% shrinkage, respectively, versus 1.14%). This can also be explained by the fact that the temperature was measured in the mass richest area of the casting and not in the area of constrained shrinkage. In the area of constrained shrinkage, the temperature has already decreased further at the same time due to the thinner wall thickness.

The shift of the change of shape during demolding at high temperatures into the clearly negative range contradicts expectations. Here, as postulated in the literature, it was expected that the higher the temperature at which the mold constraint is removed, the free and thus uniform shrinkage of the component occurs without formation of a change shape component.

## 5 | CONCLUSIONS

As a result of the clear proportional dependencies, the tests with demolding at 285 °C give the castings with the lowest deformation (−0.06 mm) and for a removal of the mold constraint at 347 °C the lowest amount of change of shape with 0.11 mm and thus an almost parallel "U". These results of the tests clearly show that the distortion as a result of the hindered shrinkage can be minimized by targeted control via the temperature variable removal of the mold constraint.

The shift of the change of shape at high demolding temperatures into the negative range indicates further

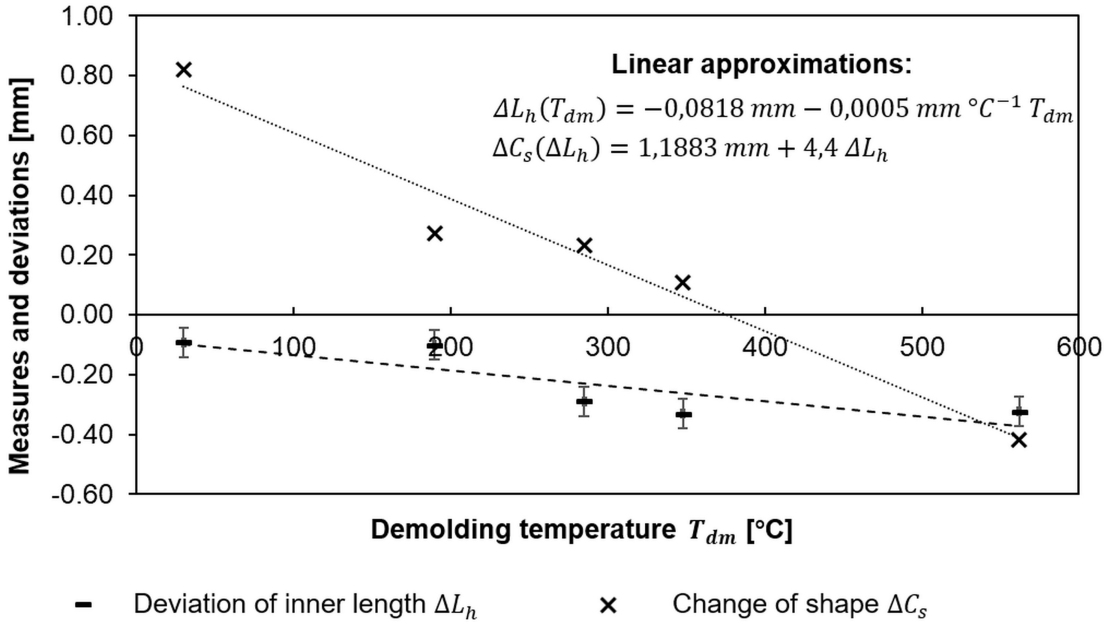



**FIGURE 4** Experimentally determined values of the deviation of the inner length with their standard deviations and the deformation rate determined from it and the warpage measure for the different demolding temperatures.

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mechanisms of plastic deformation that become effective during or shortly after solidification and need to be specifically investigated in future work.

In the simulation, the next step is to investigate the effects of different numerical parameters, such as the mesh element type or different material properties, on the observed offset to the experimental results. The qualitative match between the experiments and the simulation of the negative change of shape at high demolding temperatures clearly shows that the coupled thermo-mechanical calculation methodology used is leading in the right direction.

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