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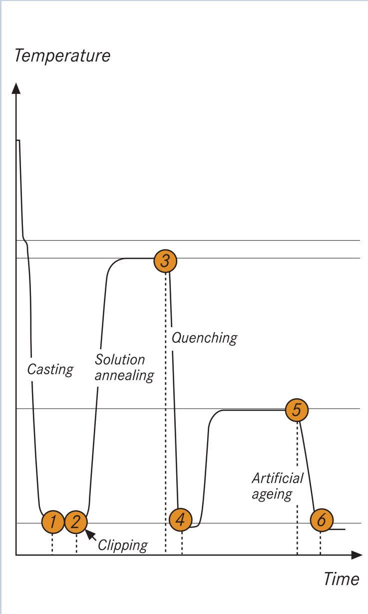
Prediction of distortion in thin-walled die castings

With the production of thin-walled, complex structural components made of aluminium and magnesium alloys, the foundry industry has succeeded in substituting many classical sheet metal components by castings. These structural components do not only feature complex geometries but also superior strength and ductility properties, which make for a good safety performance in a crash event.

Due to the fact that the section thicknesses are very small in relation to the overall component sizes, compliance with dimensional tolerances used to be a manufacturing challenge that could often only be achieved by straightening. However, such straightening operations are costly and impede to the process flow. Therefore, the objective must be to control the development of distortion throughout the complete manufacturing chain in order to avoid the straightening step.

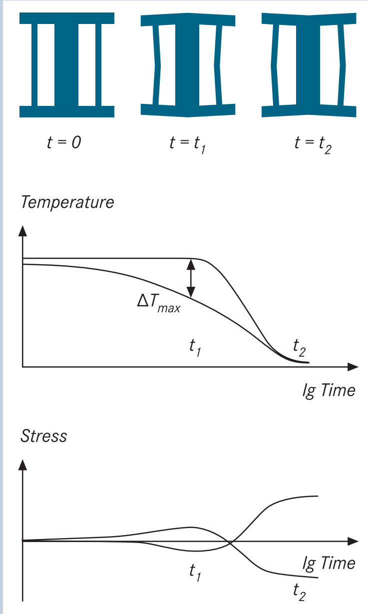
This requires profound knowledge of the mechanisms that control the development of distortion in all stages of the manufacturing chain as well as knowledge of how these mechanisms interact. Due to the wide range of parameters to be considered and taking into account a reasonable effort in terms of time and cost, this can only be accomplished by means of process simulation.

Figure 1



Temperature curve during the production chain of thin-walled structural castings

Figure 2



Underlying mechanism for the development of residual stresses and distortion by the example of a stress lattice

Development of residual stresses and distortion during structural casting production

The number of process steps required for the production of structural components depends on the selected alloy. Usually two types of alloys are used; naturally aged alloys such as Al Mg5Si2Mn and artificially aged alloys such as Al Si10MgMn.

In case of the naturally aged alloys, the manufacturing route consists of the process steps casting and clipping; in case of the artificially aged alloys of casting, clipping, solution annealing, quenching, and artificial ageing **(Figure 1)**. Each of these process steps influences the distortion of the castings.

During casting (number (1) in **Figure 1**) and quenching (4), distortion occurs as a result of inhomogeneous cooling down to room temperature leading to inhomogeneous shrinkage. If the temperature-dependent thermal shrinkage of fast-cooling areas is impeded, tensile stresses develop in these areas. Due to the – at high temperatures – low strength of the casting, stress relief takes place as a result of plastic deformation. At the highest temperature gradient between slow and fast-cooling areas of the casting, the stresses and/or plastic deformations reach their maximum values. When the plastic elongations during solidification or cooling exceed the yield point of the material, cracking occurs in the casting. As cooling proceeds the temperature gradient between slow and fast-cooling areas decreases. This results initially in stress relief, and subsequently in a sign change of the stresses. The reversing stress condition is caused by the plastic deformations due to stress relief at high temperatures. After cooling down, thin-walled areas of the casting are exposed to compression, whereas thick-walled areas are exposed to tension stresses [1]. This stress formation mechanism is illustrated in **Figure 2** by way of the stress lattice.

The residual stress distribution that prevails after the casting process (1) changes during the subsequent clipping process (2). Consequently, the distortion of the casting will change. Additional stresses may occur due to machining or clamping forces. In the worst case, cracking already occurs during machining of the casting [2].

During solution annealing (3), the material strength decreases dramatically. The residual stresses from the casting process are almost completely relieved by creeping during the heat up process. Especially in structural components the dead weight alone leads to permanent deformations, i. e. distortion. As described above, new residual stresses and distortion occur during quenching (4) due to inhomogeneous cooling. For the production of structural castings, air quenching is a frequently applied method that causes only little residual stresses and distortion. The final artificial ageing process (5) can lead to a partial relief of the residual stresses; however, this only happens if the residual stresses exceed the minimum value required for the activation of creeping. In structural castings this is usually not the case.

The development of distortion during casting and clipping will now be described and discussed by way of the example of a door lock panel for a premium class passenger car. The distortions calculated for both process steps will be compared with measurements. Based on these values, possible solutions to reduce the development of distortion will be presented.

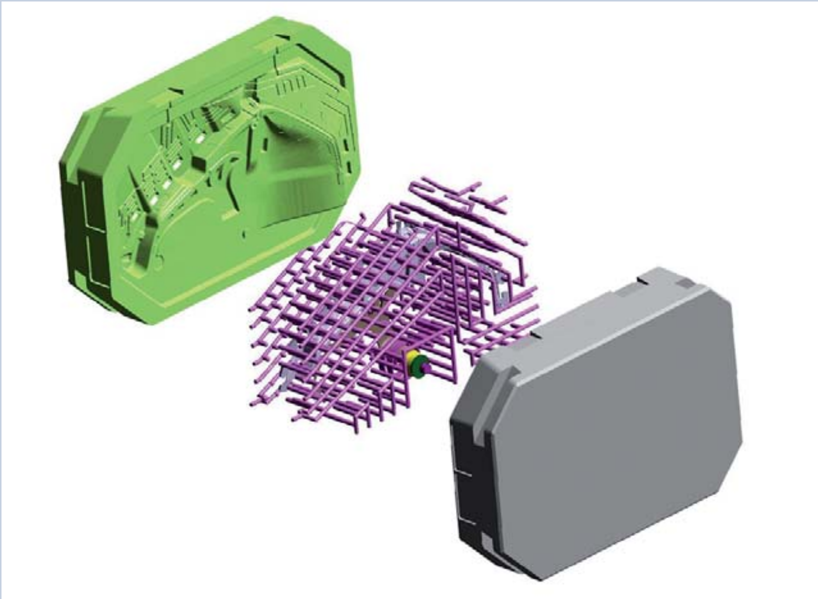
Calculation of distortion after casting a door lock panel

The calculation of distortion can be subdivided into two steps. In the first step, the casting and die temperatures are calculated by simulating the mold filling and solidification processes. In the second step, the temperatures are used as loads in the stress calculation. Decisive factors for precise calculation of distortion are the knowledge of the temperature-dependent and microstructure-related mechanical properties of the casting material as well as the consideration of shrinkage constraints caused by the die.

CAD model and enmeshment. The starting point for the simulation is a 3D model of the casting geometry including gating system, overflows, heating and cooling circuits, as well as the die casting tool (Figure 3). For the subsequent calculation, the complete geometry model will be enmeshed.

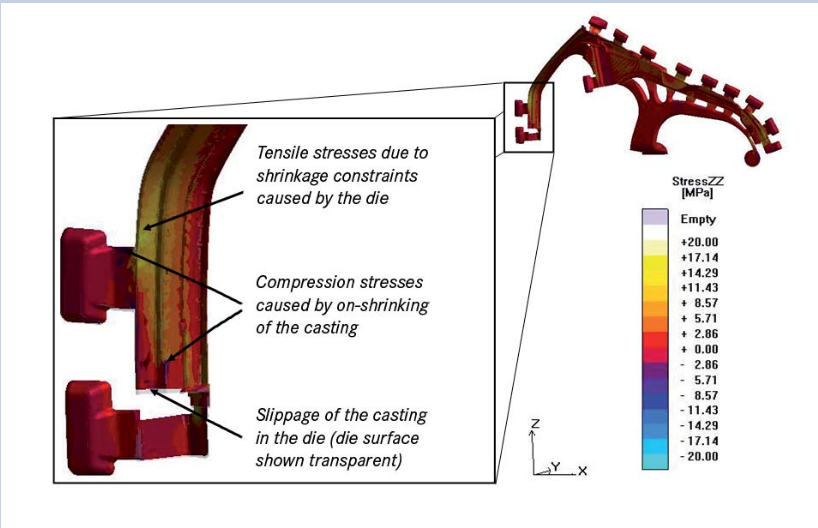
Mold filling and solidification simulation. The simulation takes into account all relevant process parameters such as shot curve, temperatures of the molten metal, heating channel, and die, as well as the timing of the casting cycle including spraying of the release agent. As the simulation represents the real casting conditions, it also displays the "warming up" of the tooling during a number of cycles. Consequently, the mold filling, the solidification, and the cooling of the casting are calculated.

Figure 3



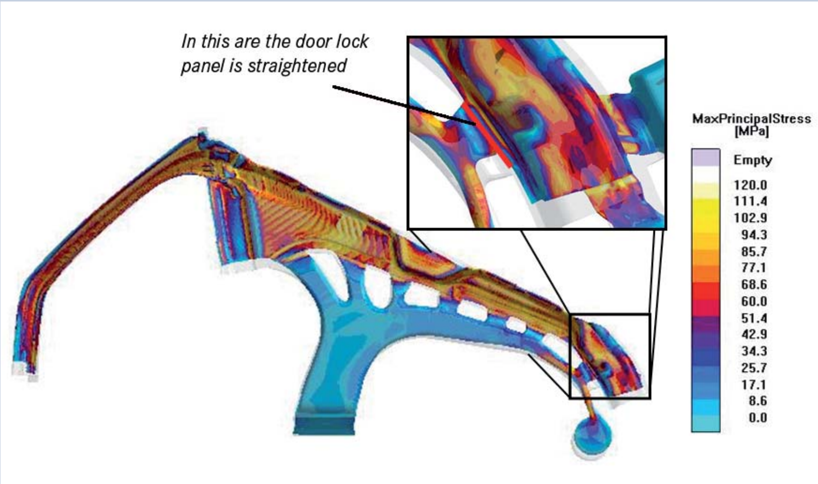
CAD model of the casting including runner system, cooling and heating channels and the two die halves

Figure 4



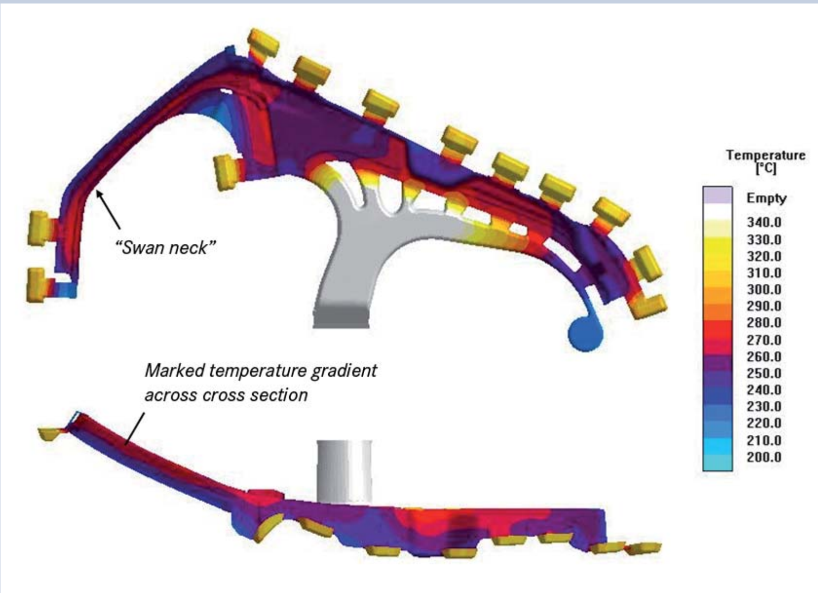
Stress distribution in the z direction in the door lock panel during cooling in the die

Figure 5



Maximal tensile stresses immediately before casting ejection. For illustration purposes the deformed and the non-deformed (transparent) geometries are shown.

Figure 6



Temperature distribution in the casting and in the gate after ejection.

Calculation of residual stresses and distortion. In subsequent stress calculations, the calculated temperatures are taken as external loads acting on the casting and the gate. The areas with the highest cooling rates start to contract immediately after solidification. Contraction is at least partly constrained by the die. In such areas tensile stresses build up in the tangential direction (Figure 4). At locations where the casting shrinks onto the die, compression stresses normal to the surface arise. Due to the very low strength values prevailing at these temperatures, stresses are still very low at this point. As cooling advances and strength values increase, the stresses start to rise markedly. Immediately before being removed from the die, almost the complete cast frame is subjected to tensile stresses (Figure 5).

After releasing the casting from the die, the constraining effect of the die no longer exists giving the casting freedom to distort. Only the gate prevents the casting from contracting. This effect causes the casting to be contracted towards the gate. The temperature condition at the process stage "Removal from the die" forms the basis for the build-up of stresses and deformations during cooling down to room temperature (Figure 6).

During cooling, the contraction of the casting towards the gate continues (Figure 7). The so-called "swan neck" is pulled upwards, because after removal from the die the upper side of the door lock panel facing the biscuit is warmer than the lower side.

Processing the simulation results. In practice, distortion is measured by means of a coordinate measuring machine, which measures the displacement of the actual geometry from the underlying target geometry for selected points. However, in the simulation the shifting of the elements (or nodes) is calculated in relation to the starting geometry. Therefore, the results from measurement and calculation cannot be directly compared.

To enable comparability of the results, the measurement operation needs to be recalculated. For this purpose, in a first step the deformed mesh is positioned on the reference points of the distortion measurement. This involves an iteration process because the positions of the reference points on the deformed casting are not known. As soon as the deformed mesh has found its final position, the distances of the measured points from the target geometry can be determined in a second step.

Comparison of measured and calculated deformations. Figure 8 shows the deviations from the target geometry for 23 measuring points after casting. The plotted curves represent the mean of all 15 measurements (blue curve), maxima and minima of the measurements (dotted lines), and the simulation results (red curve). Also the positions of the measuring and reference points (RPS) are given.

It is evident that there is a very high degree of coincidence between calculated and measured distortions.

Upon clipping of the gating system the casting springs back **(Figure 9)**. Nevertheless, some curvature towards the gating position remains. Generally, the values of measured and calculated distortion are highly congruent.

Measures to minimize distortion. After having successfully proved the coincidence of calculation and measurement, the next challenge is the minimization of distortion. For this purpose a parameter analysis was conducted:

- Influence of the ejection time (the door lock panel is removed from the die after 16 s already, not after 24 s);
- Influence of the casting temperature (the casting temperature is increased from 640 °C to 690 °C).

The earlier removal of the casting from the die reduces the temperature gradient across the cross section of the "swan neck", decreasing the distortion by approx. 35 % at measuring point 1 **(Figure 10)**. On the other hand, the temperature gradient between the runner and the casting after 16 s is still somewhat higher than after 24 s. This slightly increases the distortion at measuring point 21 from 0.6 mm to 0.75 mm (25 %). A higher casting temperature has a similar qualitative effect. However, distortion is reduced by only about 0.1 mm at measuring point 1.

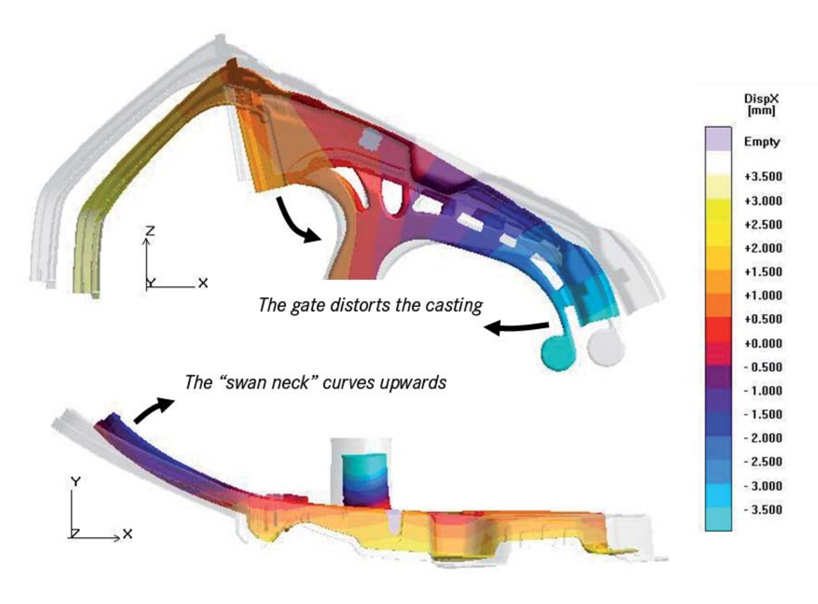
The parameter analysis shows that the distortion cannot be reduced merely by modifying the process parameters. The main cause for the distortion of the "swan neck" is the local temperature gradient across the casting cross section. Therefore, in a second step it was tried to reduce the temperature gradient by adding bean-shaped side recesses to the cold edges **(Figure 11)**.

According to the calculation this measure alone reduces distortion by 42 % **(Figure 12)**.

Calculation of distortion in heat-treated bulk head

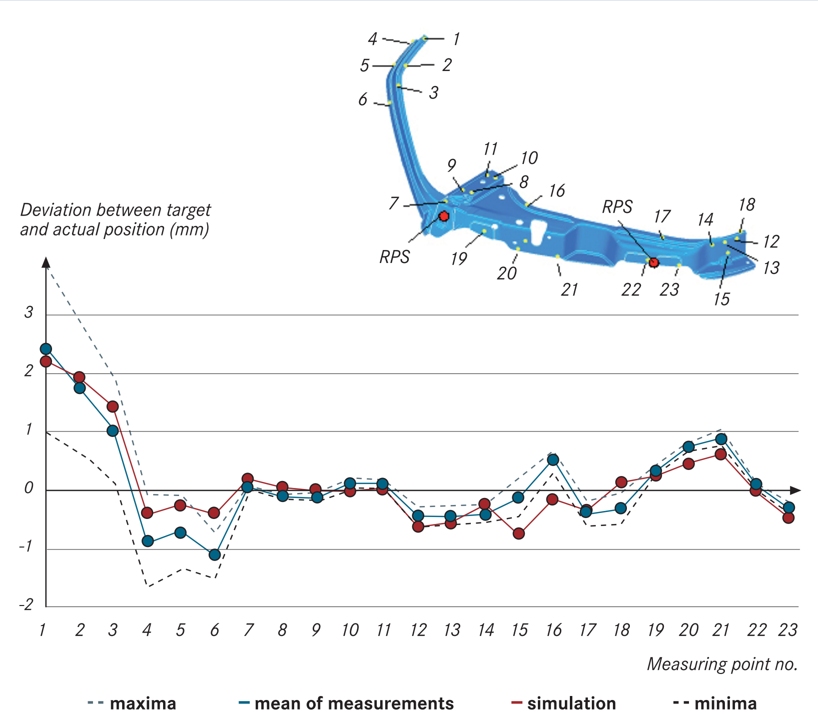
In the following, the development of distortion will be described and discussed by way of the example of a bulk head for a premium-class car. The calculation of the distortion is concentrated on the process step of solution annealing, because previous measurements of the other process steps have demonstrated that the solution annealing

Figure 7



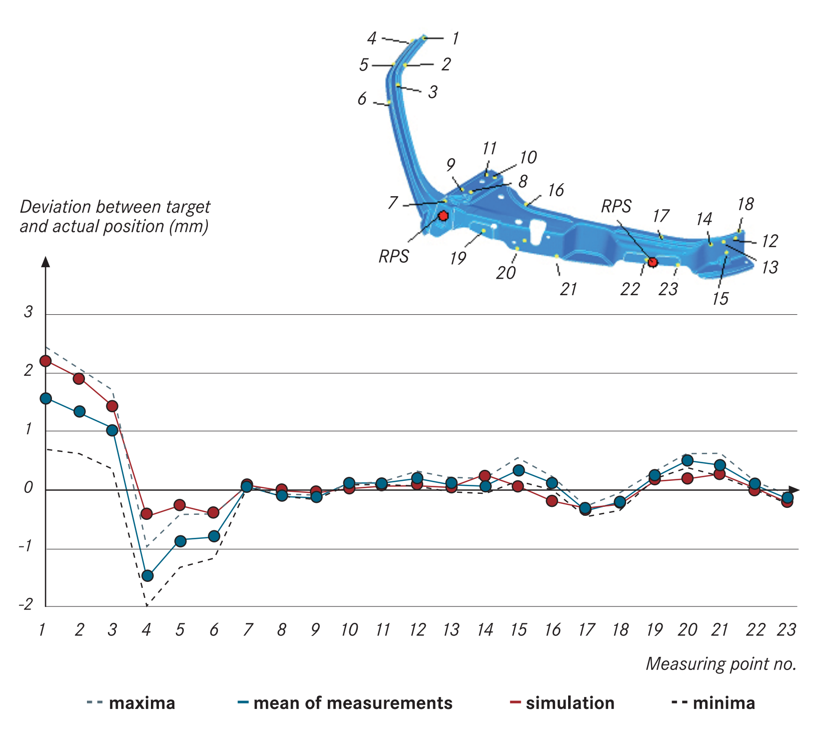
Deformation of the casting after cooling down. For illustration purposes the deformed and non-deformed geometries of the casting are shown.

Figure 8



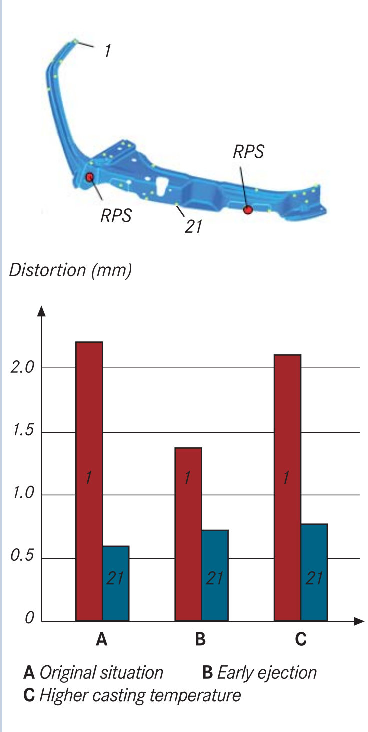
Measured versus calculated deviations from the target geometry for 23 measuring points of the door lock panel

Figure 9



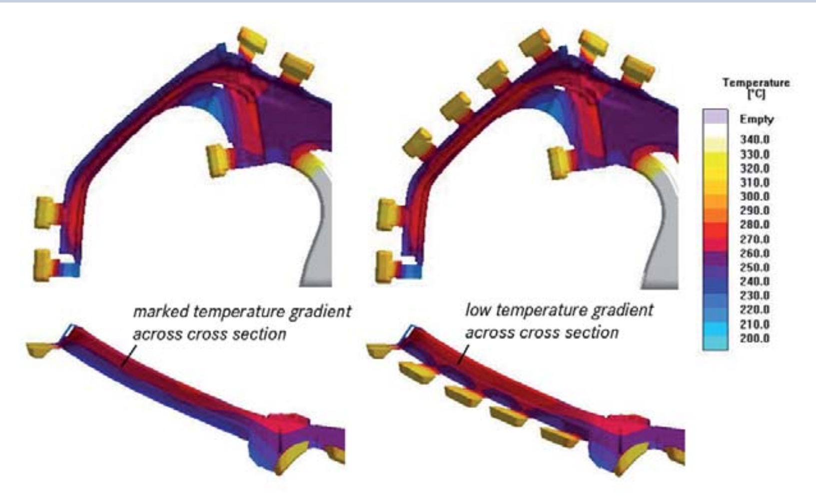
Calculated versus measured distortion after clipping

Figure 10



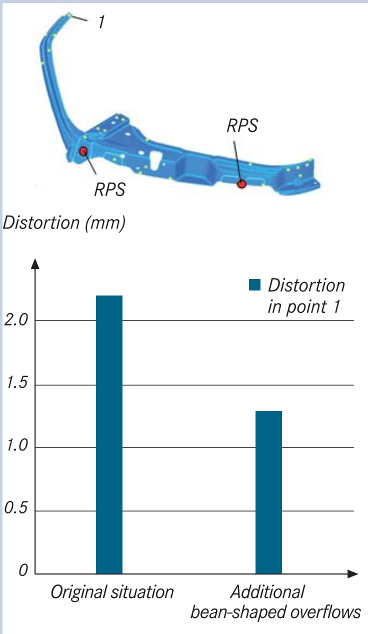
Parameter sensitivity of distortion calculated for the measuring points 1 and 21

Figure 11



Effect of additional overflows on the temperature distribution in the "swan neck"

Figure 12



Effect of changed temperature distribution on the distortion of the "swan neck" after casting

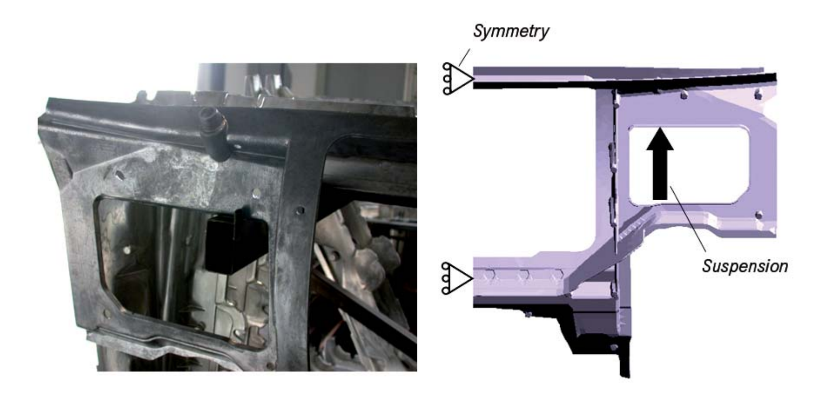
process is the key factor for the casting's overall distortion.

For the heat treatment the bulk head is suspended on both sides, as illustrated in **Figure 13**. The simulation takes into account the symmetry of the casting geometry and the suspension situation.

Figure 14 shows the stress and deformation condition after solution annealing. Whereas the maximum stresses reach only 0.9 MPa, the maximal displacements are about 4.6 mm.

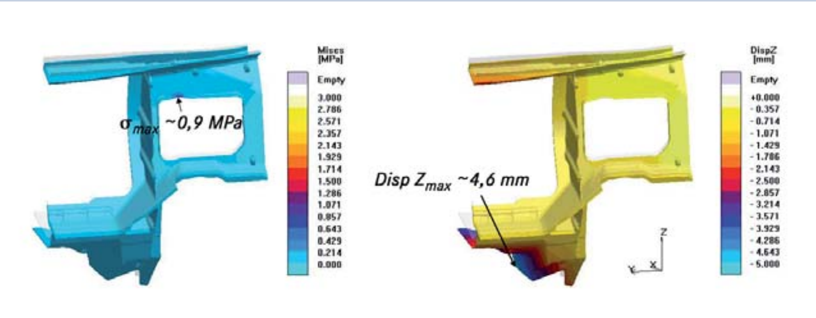
The calculated dimensional deviations as well as the mean, maximum, and minimum measured values are plot-

Figure 13



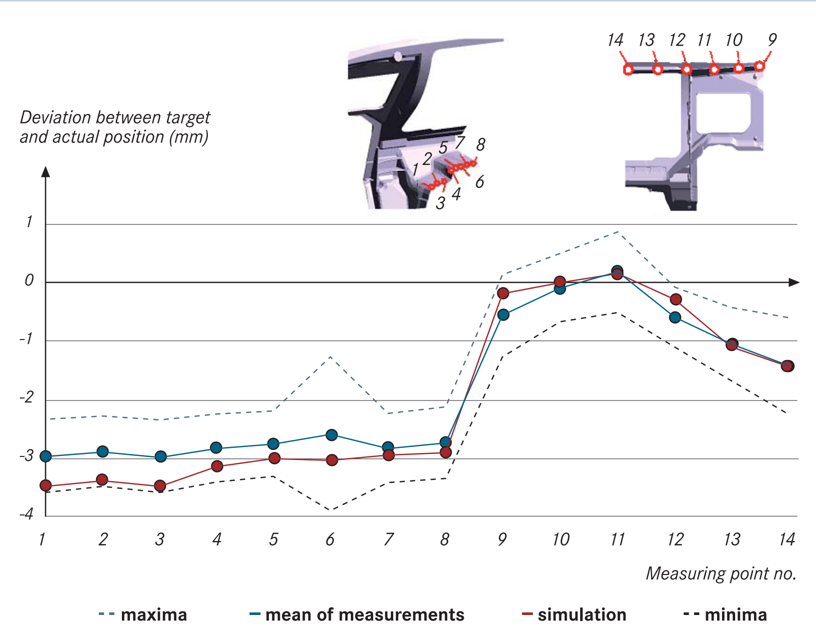
Suspension of the bulk head during heat treatment

Figure 14



Stress distribution and deformation of the bulk head after solution annealing. The non-deformed bulk head geometry is shown transparent.

Figure 15



Calculated and measured distortion of the bulk head after heat treatment

ted in **Figure 15**. The calculated distortion values for the bulk head are very close to the mean of the measurements.

Summary

The capability of controlling distortion of thin-walled structural castings is a highly challenging manufacturing task that can only be solved if the mechanisms of distortion development and its specific effects on the casting are well understood. Modern simulation techniques nowadays enable precise prediction of distortion caused by the casting process, clipping, or heat treatment. Based on the obtained results it is possible to derive suitable optimization measures, which might be geared towards the manufacturing process or the design of the casting. Typical casting process related measures include an optimized design of the runner system (to minimize contraction towards the runner), the optimization of the time until casting removal or of the thermal conditions and pre-correction of distortion in the tooling. Distortion during heat treatment can be minimized by appropriate holding frames, the development of which should be supported by modern simulation techniques.

Simulation using the described innovative computation solutions supports the die caster in manufacturing high-quality thin-walled structural castings.

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