Integrated modelling of deformations and stresses in the die casting and heat treatment process chain

Structural high pressure die casting aluminum parts are widely used in the automotive industry. During casting and subsequent heat treatment, the casting experiences thermally induced stress formation and related distortion. The design of the part and the die, together with the process control and the choice of cooling and heat treatment parameters, have a significant impact on how the stresses and deformations evolve during the multiple manufacturing steps. The article presents a fully integrated approach in Magmasoft, to predict casting stresses and distortions for the full manufacturing process chain, which has been applied to different industrial castings. The benefits are significant when dimensional tolerance problems are identified and resolved systematically in the design phase of the component or before tooling is manufactured.

Jesper Thorborg, Jörg Klinkhammer and Heinz-Jürgen Gaspers, Aachen

1 Introduction

Structural aluminum parts used in the automotive industry are widely produced by the High Pressure Die Casting process, HPDC. The process is mainly used because of the high production rate and the possibility to manufacture complex parts with high requirements to shape and tolerances. Due to microstructural requirements and mechanical performance of the aluminum parts, the HPDC process is in many cases followed by a sequence of heat treatment steps, which govern the final properties of the parts before assembling into larger structures.

During casting and heat treatment the cast material is thermally loaded in a wide temperature range, starting from the casting temperature going through the solidification interval and during solid state cooling down to room temperature. Depending on the chosen heat treatment process, the temperature is subsequently changed in several steps by reheating the parts and holding the temperature for some time before finally cooling down to room temperature again. Depending on the design of the part, the process control, and the choice of cooling and quench parameters, the level and change in temperature lead to thermal gradients and conditions which have a high influence on how the stresses and deformations evolve during the multiple manufacturing steps.

To analyze and predict the evolution of stresses and deformations quantitatively, it is important to simulate the full sequence of manufacturing steps in a coherent and consistent way, where the full load history of the material is considered. Today, casting process simulation is widely used and accepted to be an efficient way of optimizing the casting process. Industry is showing an increased interest in extending the simulation capabilities to also analyze the subsequent heat treatment process.

This article presents a state of the art modelling approach where results from the casting process are considered in the subsequent heat treatment calculation. This fully integrated approach in Magmasoft supports the work flow of autonomous engineering, where virtual experiments are used to optimize mechanical properties and performance, to improve quality and to reduce costs and production time. The benefits from analyzing the full manufacturing process chain are significant when dimensional tolerance problems are identified or can be resolved before tooling is manufactured or even in the design phase of the component.

2 Process steps and distortion control of structural parts

In the HPDC process, the majority of the aluminum solidifies inside the die and even cools down below the solidus temperature before it is removed from the die. Therefore a considerable level of stresses due to constrained contraction is formed in the cast material before ejection. The result is a complex interaction between the cast material and the die, i. e. some regions shrink onto the die and other regions open up gaps with no contact, [1]. Depending on the cooling conditions and how long the part stays in the die, the constrained contraction will lead to stresses and permanent deformations in different regions of the part. During the die opening sequence and ejection, some of the stresses will be released due to elastic spring-back, and the part will deform as a consequence of removing the constraints due to the die. The part will freely contract during the final cooling/quenching step until it reaches room temperature. At room temperature, the total amount of deformation is a sum of the full thermal contraction from solidus to room temperature plus the permanent deformations which were mainly generated during cooling in the die. The casting process is schematically shown in **Figure 1**, where the different process steps are indicated by small icons.

Casting of aluminum structural parts for the automotive industry is often followed by a heat treatment process, where the main objective is to improve the mechanical properties by modifying the as-cast microstructure in a sequence of thermal steps. In this way, it is possible to obtain a material with increased ductility and higher strength compared to the as-cast state. The heat treatment steps can also have a significant influence on the stress level and the distortion that builds up during e. g. solution treatment. To predict the final distortion of a structural part, it is necessary to consider all relevant steps of the manufacturing process. This imposes some challenges for the simulation of the integrated process. The importance for having an appropriate simulation technique originates from a relatively new trend in the automotive industry to apply distortion engineering to structural parts. Relevant process stages and the related temperature history imposing stresses and distortion during the heat treatment process are illustrated in **Figure 2**.

The following three alternatives to reduce/avoid possible final distortion of the part are usually pursued in practice:

- Design support frames used during heat treatment to allow the part to distort back to the desired shape.
- Trim or straighten the part after casting or heat treatment.
- Compensate expected as-cast distortion by modifying the die cavity.

3 Simulation approach

Thermo-mechanical modeling of the casting and heat treatment processes is a challenge. The main concern is to model the mechanical response of the material at different temperature levels, on different time scales and sometimes with different strain rates. A unified creep model has been chosen as an appropriate constitutive mode, [2] and [3]; further details can be found in the "Thermo-mechanical constitutive model" box (**Appendix 1**).

The simulated stresses results depend on a prior comprehensive thermal analysis of the entire casting setup, including

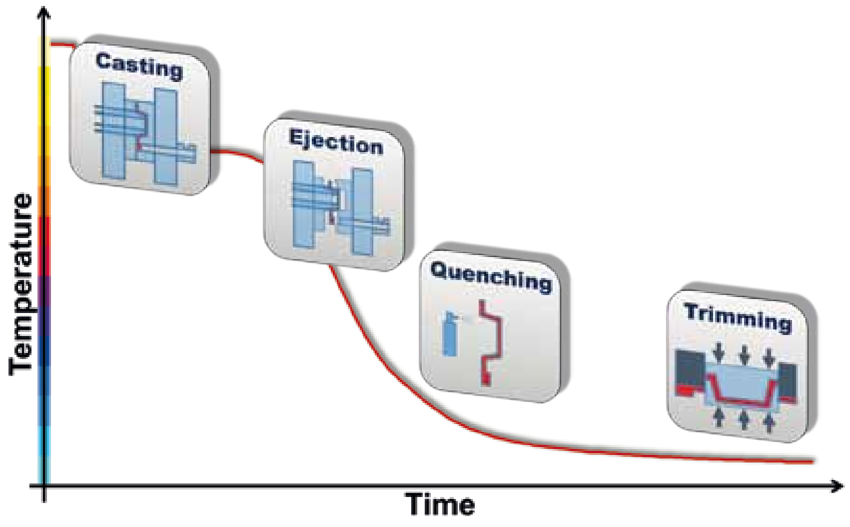

Figure 1: Schematic temperature profile of the HPDC process with illustrations of the associated process events resulting in stress formation.

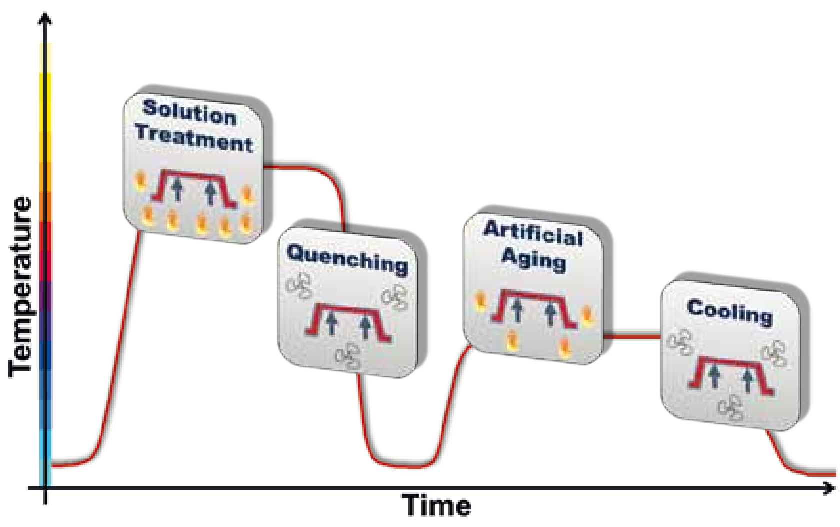

Figure 2: Temperature profile for the different heat treatment steps in a typical T7 treatment after casting of aluminum parts.

SOURCE: MAGMA

filling of the die cavity, cooling and heating of the die, spraying of die lubricants, etc. Furthermore, different process conditions have to be considered such as die open temperatures, die constraints, shake-out conditions and trimming operations. While simulating stresses and distortion for the HPDC process is a rather well known procedure, it is not frequently done for the subsequent heat treatment process. In the integrated approach presented here, parts are placed in the heat treatment support frame after casting. This requires an additional step in the simulation where the already deformed as-cast part is positioned onto a support frame. When the structural part is heated while positioned in the support frame, it can experience a considerable amount of deformation due to gravitational forces and creep in the solution treatment step. During the final artificial aging step, the temperature level is only increased to allow precipitation hardening to take place, [2]. See further comments on the mechanical behavior during casting and heat treatment in **Appendix 2** and **Appendix 3**, respectively. Typical observations in the different process steps are indicated with a small icon of an eye, and interesting behavior/fields to check and validate are indicated by an exclamation mark, !.

4 Thermo-mechanical constitutive model

Thermo-mechanical modeling of the casting and heat treatment process has to consider the complex behavior of the material response and the interaction between the casting material and the surrounding dies and support frames. One of the main concerns is to model the response of the material at different temperature levels, on different time scales and sometimes with different strain rates, which is governed by different deformation mechanisms. A unified creep formulation is used as the fundamental constitutive law, [4]. The model is based on Norton's power law and includes by that, strain rate sensitivity and the possibility to describe creep at elevated temperatures:

$$\dot{\varepsilon}^{in} = A \exp\left(\frac{-Q}{RT}\right)\left(\frac{\sigma}{\sigma_{ref}}\right)^{m} \tag{1}$$

and

$$\sigma_{ref} = \sigma_{0,ref}\left(1 + \frac{E\,\varepsilon^{in}}{n\,\sigma_{0,ref}}\right)^{n} \tag{2}$$

The two properties A and m describe the strain rate sensitivity. The Arrhenius expression scales the response according to the temperature dependency and the model is therefore applicable over a wide temperature range. The temperature dependency is governed by the activation energy, Q. The reference stress σ_{ref} describes the isotropic strain hardening by a classical power law, where the inelastic strain, ε^{in}, is used to capture the effect of hardening when e.g. dislocations are piling up and annealing when the temperature is elevated, accounting for diffusion processes.

Calibration of the thermo-mechanical properties is based on a large range of tensile tests and creep tests at different temperature levels. The tensile tests are typically performed at different strain rates at intermediate and high temperatures to get information about the strain rate sensitivity. Creep tests are performed at high temperatures to get information for the heat treatment process and for slow cooling casting processes, where stress relaxation is important.

The hardening response is governed by two temperature dependent properties, the initial reference stress $\sigma_{0,ref}$ and the hardening parameter n. The response of the creep equation and the hardening law can be illustrated by classical creep curves and the strain rate dependent tensile curves, see Appendix 1.

5 Application of the simulation approach

The integrated simulation approach of Magmasoft has been applied to different industrial castings. The primary example is a shock tower, which illustrates how simulated distortion from the casting process is used to design a support frame for subsequent heat treatment. The objective is to reduce the deviations in shape compared to the reference geometry by using the distortion from solution treatment to correct the overall shape of the part. The results are compared to results from a straightening simulation, where corrections are obtained by applying a correctional force at room temperature. The simulated results are compared to measurements.

Secondly, a space frame connection node is simulated and virtually measured distortion after shake-out and cooling is used as information to pre-shape the die cavity dimensions to pre-compensate for and to reduce distortion.

Thirdly, the ejection process is evaluated on the same space frame connection node. Simulated ejection forces are used to evaluate the number and layout of the ejector pins. Based on the results, a reduced number of pins are used for an optimized layout and the ejection forces are compared to the initial layout.

Finally, a virtual Design of Experiments (DOE) has been applied to a third example, which is another space frame connection part. Several layouts of the heat treatment support frame and different process conditions are automatically calculated and evaluated to minimize the distortion during solution treatment.

6 Casting distortion and design strategies for the heat treatment support frame

Significant distortion and unwanted stresses can be a consequence of the casting process. Even though the final distortion is relatively simple to measure, it is very hard to control and tackle in production. Simulation and careful analysis of the conditions after casting can be used as input to design strategies for the support frame, to actively 'correct' deformations during solution treatment.

The front wheel shock tower (**Figure 3**) of a passenger car had initial problems with distortion being out of the allowed tolerances after heat treatment, [5]. Therefore it was decided to analyse the process with Magmasoft.

7 Casting process

The casting process was simulated as a first step, to predict the distortion before heat treatment. **Figure 4** shows the evolution of the stress levels during the casting process and how the displacements build up at the same time. The von Mises stress distribution is shown above the process view and the displacements are shown below the process view. Starting from left, the results show the conditions just before die open, just after ejection, at ambient temperature and finally after trimming.

In the first result the stress level is governed by the constraints from the die and the chosen die open time, Figure 4a. Evaluating this result makes it possible to analyze if critical stress levels are reached, which could promote large permanent deformations or even affect the ejection process. After ejection the stress level is significantly reduced, which is seen in the second result, Figure 4b. During the subsequent cooling step to room temperature moderate stresses are generated due to the thermal gradients, see the third result, Figure 4c and only small changes are seen in the subsequent trimming step Figure 4d.

Evaluating the distortion at the same points in time shows how the main distortion evolves during the cooling step from die open to room temperature. Only a limited amount of distortion is observed just before die open Figure 4a, due to the constraints from the die. Just after the ejection process some distortion is seen, mainly due to elastic spring back when the constraints from the die are removed, Figure 4b. The free thermal contraction from die open to ambient temperature generates a significant amount of distortion, Figure 4c. For this reason it can be useful to make variations in the die open time to investigate how much the free contraction affects the final distortion level. For this example, the final trimming step does

Figure 3: Front wheel shock tower of a passenger car. Initial problems with distortion being out of tolerance after casting and heat treatment were analyzed virtually.

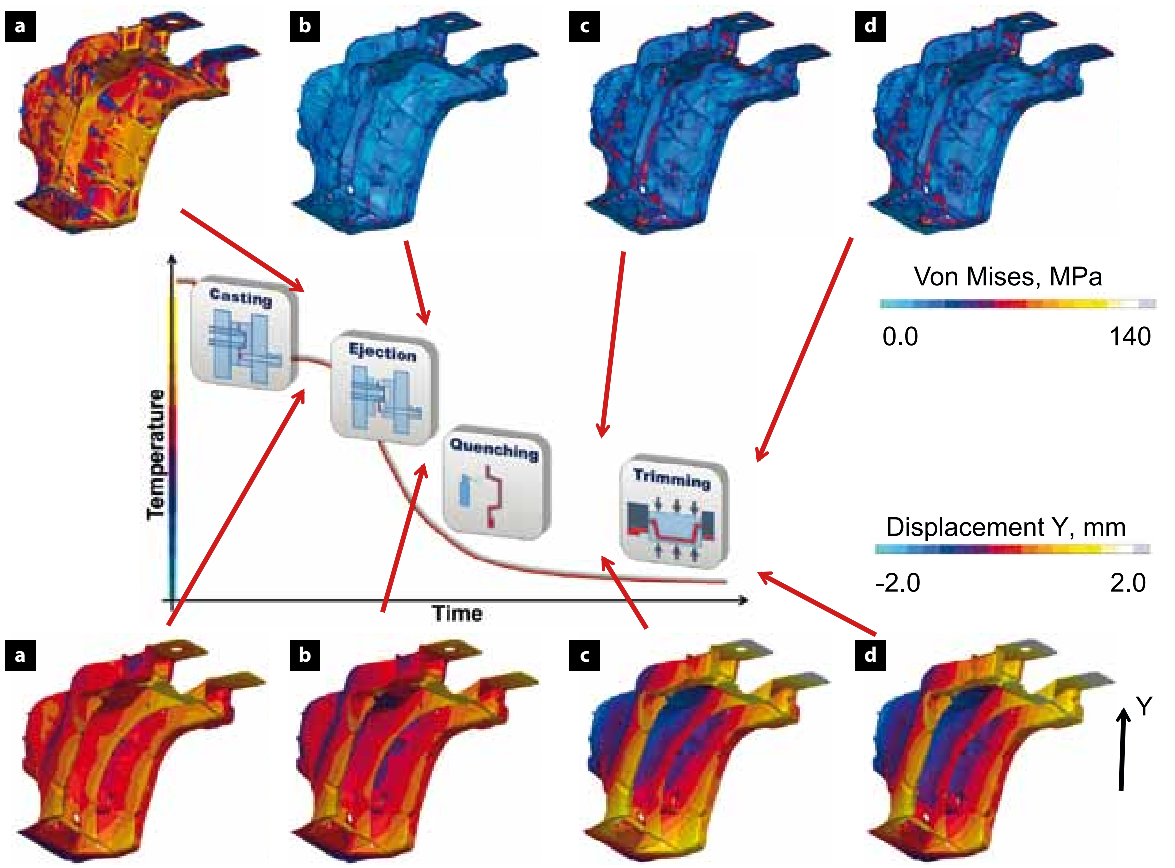

Figure 4: Evolution of von Mises stress (upper row of results) and displacement in Y-direction (lower row of results) during the different HPDC process steps. From left, the results are shown at different process times just before die open (a), just after ejection (b), at ambient temperature (c) and finally after trimming of the gating system (d).

not change the distortion significantly, Figure 4d. However, depending on the gating system and the design of the part, this final step can contribute to the distortion level.

8 Heat treatment and support structure design

The final distortion after casting was used to design the support frame for the subsequent heat treatment steps. It was clear from the calculated distortion, **Figure 5**a, that the upper left corner bends downwards whereas the upper right corner bends upwards compared to the reference geometry. The directions of bending are indicated by the two arrows.

This type of unwanted distortion can in most cases be reduced by allowing the structure to deform in a controlled way during solution treatment. As the temperatures are close to solidus, small forces from gravity promote creep in regions where the support frame does not restrict the deformation. The amount of obtained creep, and by that distortion, in the structure depends on the temperature level and the process time. The temperature must be sufficiently high to activate creep and the frame must be carefully designed to allow wanted distortion and restrict unwanted distortion.

For the considered example the frame was designed as shown in Figure 5b. The zoomed-in view in the box at the right shows how the part initially has a gap between the upper right plate and the bar in the frame just below it. This freedom to deform is designed to allow the two plates to align at the end of solution treatment.

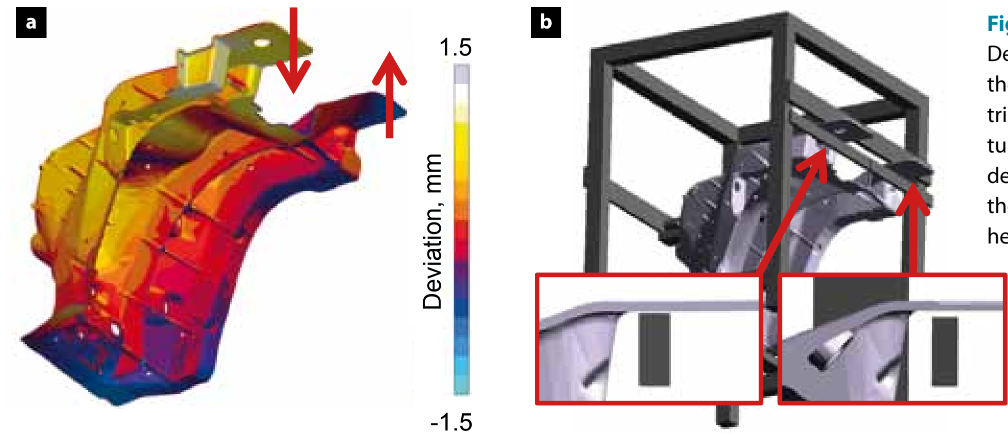

Figure 5:
Deviation of the casting from the reference geometry after trimming at room temperature (a) and support frame designed to compensate for the casting distortion during heat treatment (b).

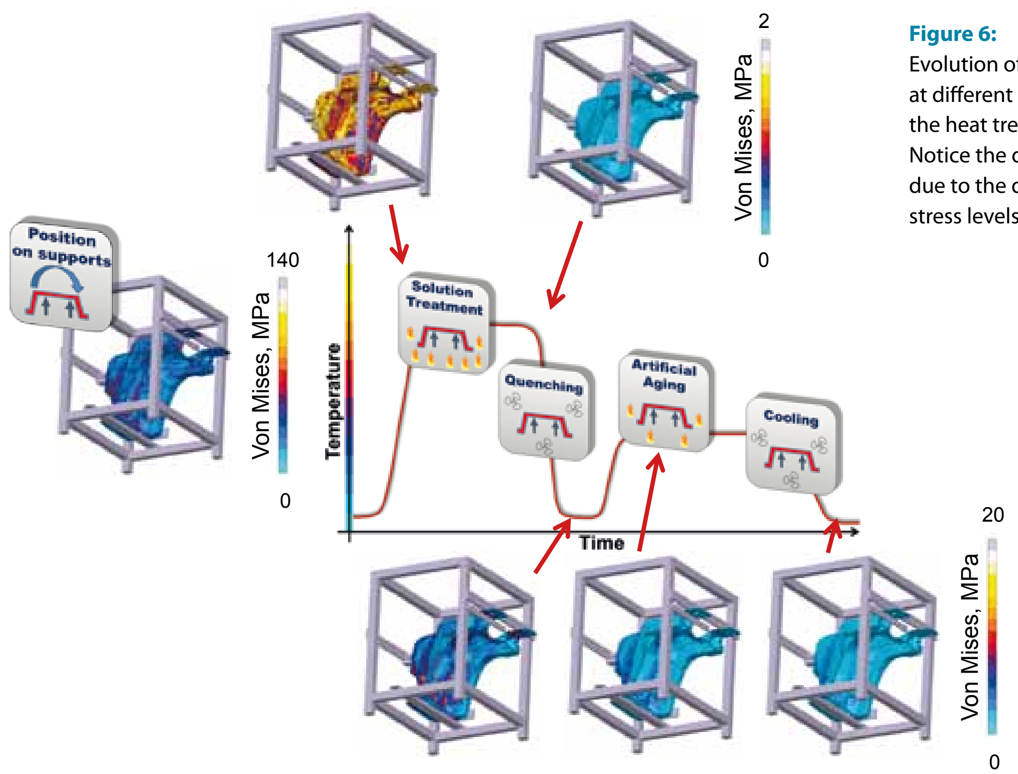

Figure 6:
Evolution of von Mises stress at different points in time during the heat treatment process. Notice the different stress scales due to the different ranges of the stress levels.

Results from the casting process are mapped to the position of the part in the support frame, Figure 5b. This step is done automatically in Magmasoft, i. e. all relevant mechanical fields are transferred from the orientation in the casting process to the orientation in the heat treatment process.

9 Stress development during heat treatment

During the heat treatment process, the stress level in the part significantly changes due to the elevated temperature levels and the cooling conditions. To illustrate the influence on the considered part, several von Mises stress results are shown in **Figure 6**, where the initial stress level is based on the mapped results from the casting simulation. As expected, the stresses are relaxed to almost zero during solution treatment, where the temperature level is approximately 460 °C. The subsequent cooling only leads to a small increase in the stress level, and in the final aging step, at approximately 220 °C, the stresses are again relaxed to an even lower level at the end of the entire heat treatment process.

10 Distortion evaluation after heat treatment

The results in **Figure 7** show the obtained distortion after heat treatment and the deviation from the reference geometry after casting and after heat treatment. The designed gap in the support frame clearly allows the wanted deformation to develop during solution treatment and by that to actively compensate for the casting distortion. The level in deviation from the reference geometry was reduced by approximately 1.5 mm, see Figure 7 below.

11 Validation of results using optical measurements

The obtained correction to the casting distortion was compared to measurements. **Figure 8** shows the distortion of the cast part after the full process chain of casting and heat treatment. The curves show the deviation at multiple measurement points from the reference geometry. The red curve shows the Magmasoft-simulation result, where the blue, yellow and green curve show measurement results for 3 different specimens of the part.

The predicted results show a very good agreement to the measurements in almost all areas. Differences mainly appear in the red marked areas, where the measurement points are located very close to the outer bounds of the geometry. In these outer regions, mechanical influences from e. g. handling and trimming are very likely to have influenced the measured results. In one case (detail on the right) an artificial indentation in the imported stl-geometry, containing the measured shape, is responsible for the shown deviation to the simulation result.

Overall, the agreement between simulation and measurements is very good and the applied simulation approach has been useful to analyze the distortion problem during casting and the subsequent heat treatment processes.

12 Straightening and the risk of deforming the part at room temperature

Distortion after casting and heat treatment is typically corrected by different types of straightening processes. The needed corrections to get sufficient accuracy in the final shape are obtained by applying high mechanical loading to produce localized permanent deformation in different regions of the struc-

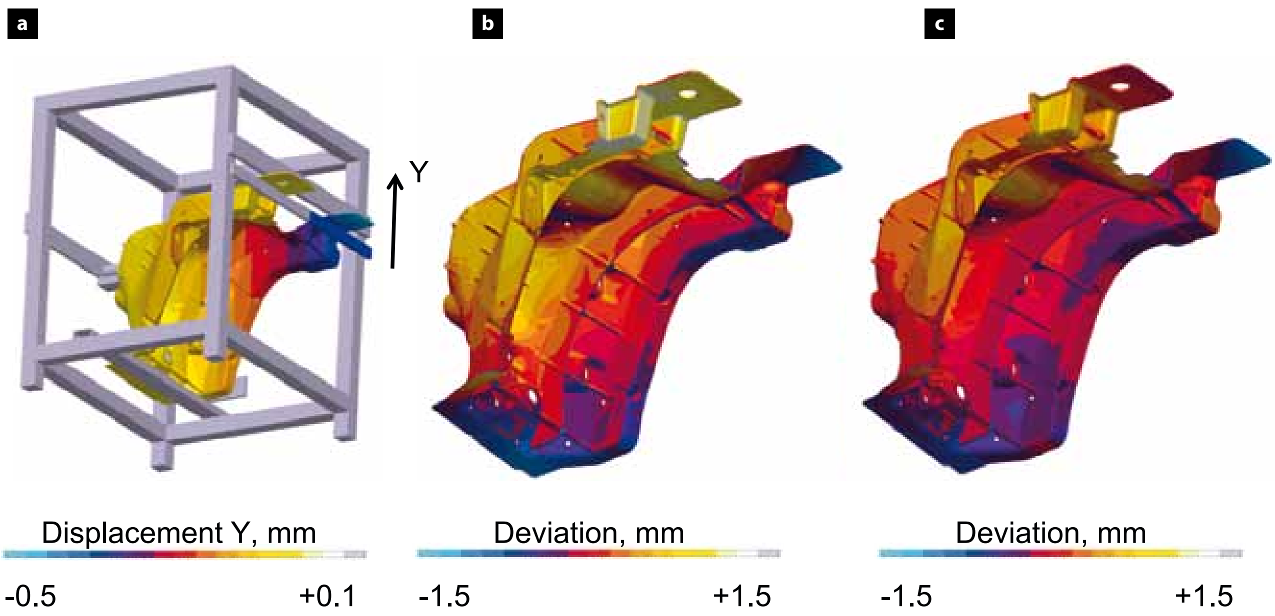

Figure 7: Distortion in the direction of gravity (a), deviation from the reference geometry after casting (b) and deviation from the reference geometry after heat treatment (c).

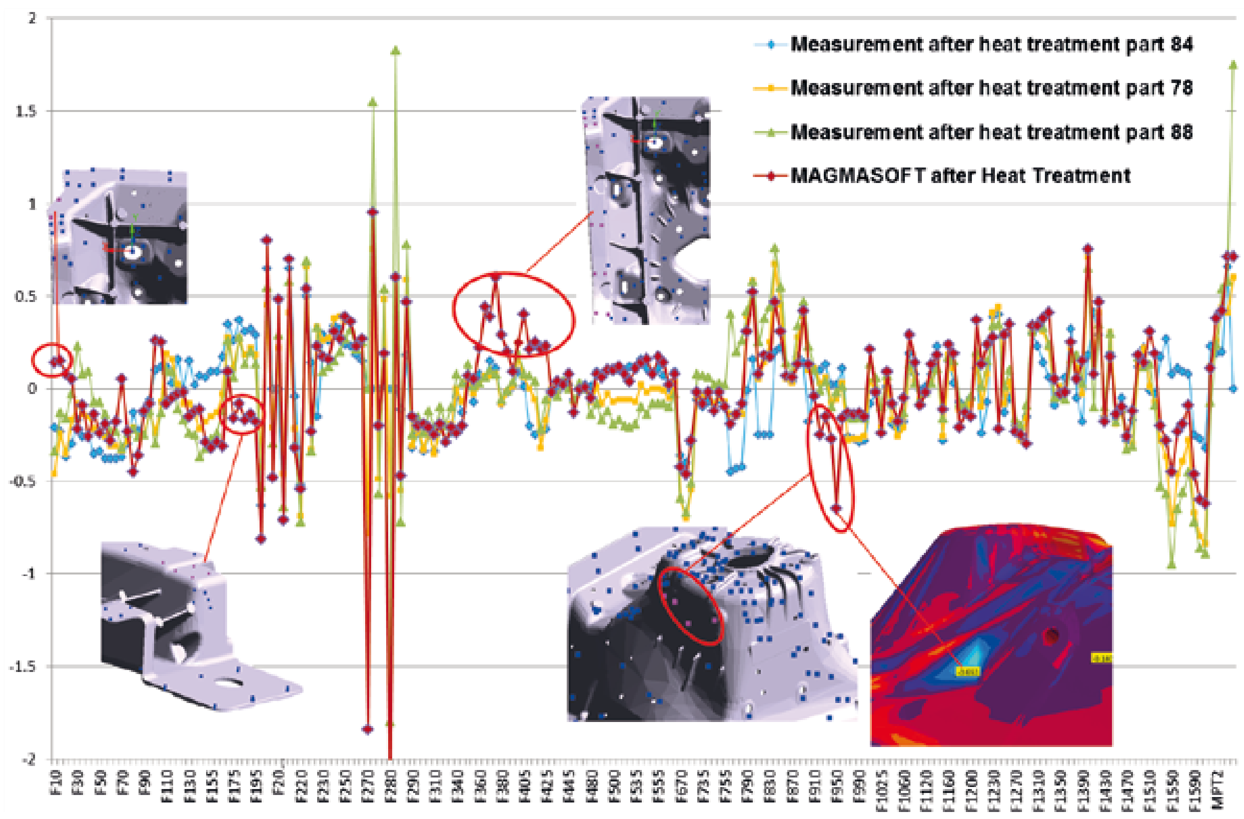

Figure 8: Measurements compared to results of the simulated deviation from the reference geometry for more than 50 measurement positions. Notice the measurements contain a spread in the level for the three considered parts.

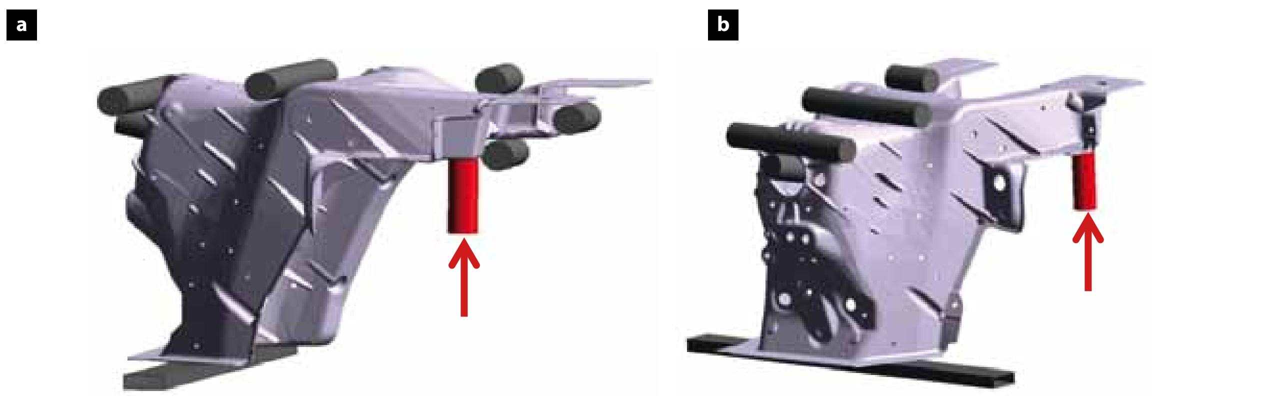

Figure 9: Setup for modeling the straightening process. The dark gray cylinders are constraints and the red cylinder indicates the location and direction of the applied load.

ture. Today, state-of-the art straightening is done in a fully automatic process where several steps of pushing, pulling and twisting can be applied to the part in different directions. The most advanced systems are based on self-learning algorithms to reduce and optimize the required number of correction steps. The straightening process provides a high level of freedom to correct the part, but the mechanism behind the process is to plastically deform the material at room temperature, which in the worst case can influence the mechanical performance during service loading. Especially if several big correction steps are needed to obtain the required tolerances, the risk of provoking cracks and defects increases.

To illustrate the impact of the straightening process, a force is applied to the shock-tower to compensate for the uneven bending of the two upper plates. The setup is illustrated in Appendix 2 and 3 and **Figure 9**, where the dark gray cylin-

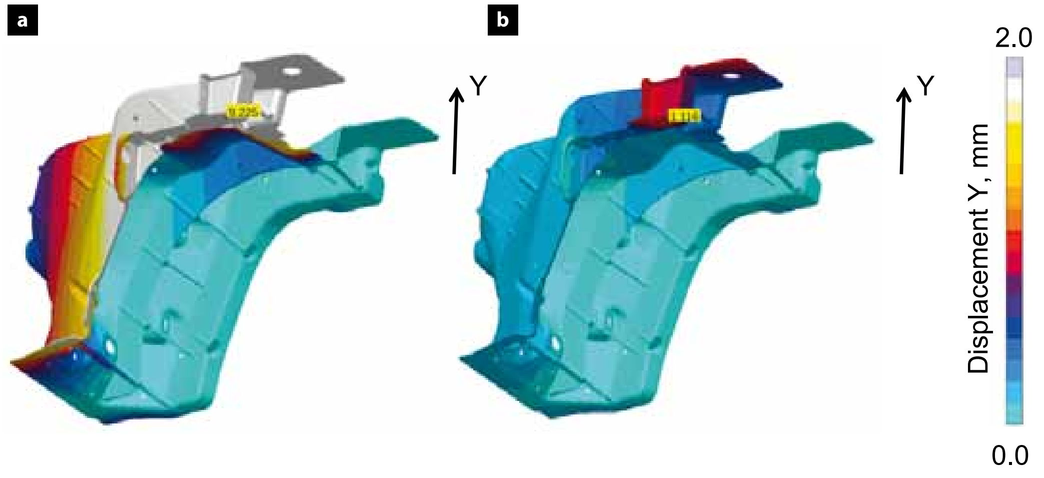

Figure 10: Deformation during straightening (a), obtained deformation after straightening (b).

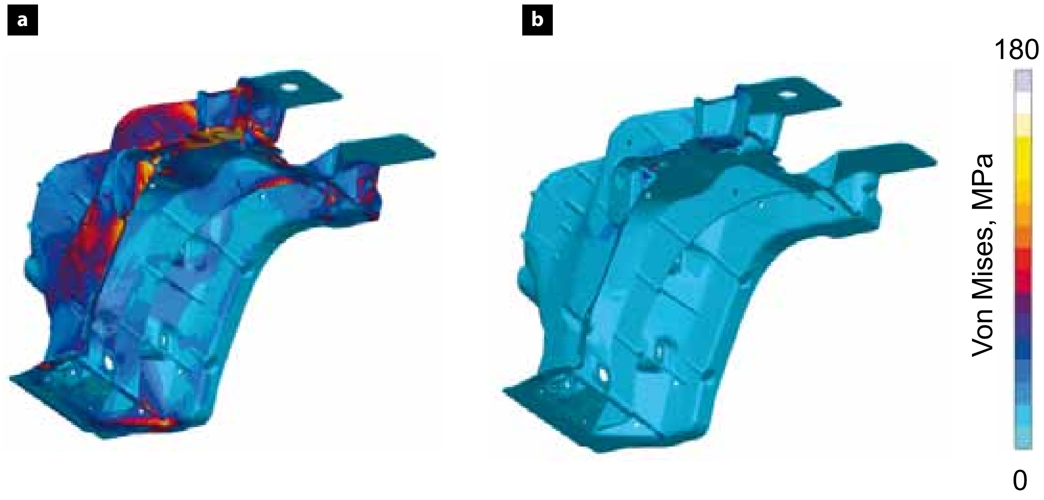

Figure 11: Von Mises stress during straightening (a), von Mises stress after straightening (b).

ders are mechanical constraints and the red cylinder indicates the location of the applied load.

The displacement result in **Figure 10**a shows the distortion during loading, which is approximately 9 mm in the area close to the applied load. The obtained distortion after unloading is shown in Figure 10b and is approximately 1.1 mm. During loading significant stresses build up in the part, which can be seen in **Figure 11**. Stress results during and after loading are shown in Figure 11a and Figure 11b, respectively. As a consequence of the high loading, localized permanent deformation is generated inside the part, which can clearly be seen in the highlighted regions in **Figure 12**.

The initial deviation to the reference geometry after casting is shown in **Figure 13**a. The deviation which was possible to obtain by designing the support frame for heat treatment is shown in Figure 13b, and the deviation obtained from the straightening process is shown in Figure 13c. The deviation in the two results Figure 13b and Figure 13c are to a large extent in the same range.

The example shows how simulated distortion can be used in the design strategy of the heat treatment support frame to promote distortion during solution treatment, which actively compensate for casting distortion. This approach can be used to reduce the required amount of straightening steps at the end of the process chain, which reduces costs and the risk of generating defects and increased residual stresses in the final part.

13 Pre-shaping the die to compensate for as-cast distortion

In addition to the different correction methods, which are applied to the part as shown in the previous sections, it is of course vital to use a reasonable shrinkage factor in the design of the die and when possible pre-shape the die to reduce the as-cast distortion. The procedure for using simulation to pre-shape the die is illustrated in **Figure 14**.

To generate the red pre-shaped die cavity in Figure 14f the procedure is as follows:

– The blue reference geometry Figure 14a is scaled up according to the shrinkage factor of the aluminum alloy, red rectangle in Figure 14b. This is a standard procedure to account

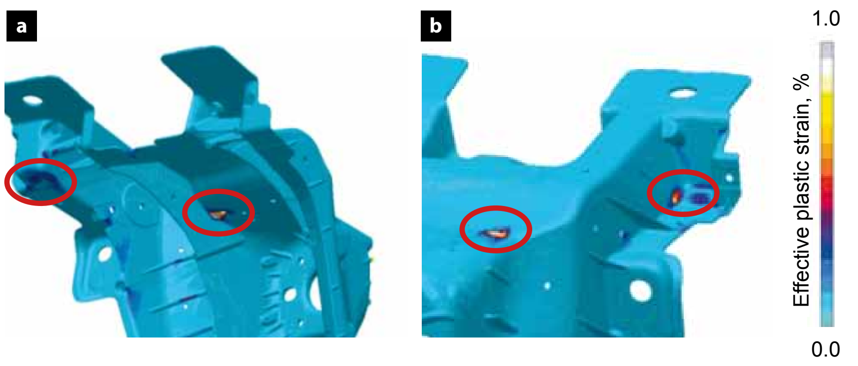

Figure 12: Effective plastic strain on the inner side (a), effective plastic strain on the outer side (b), both after straightening. The results show the localized permanent deformation which was generated during straightening.

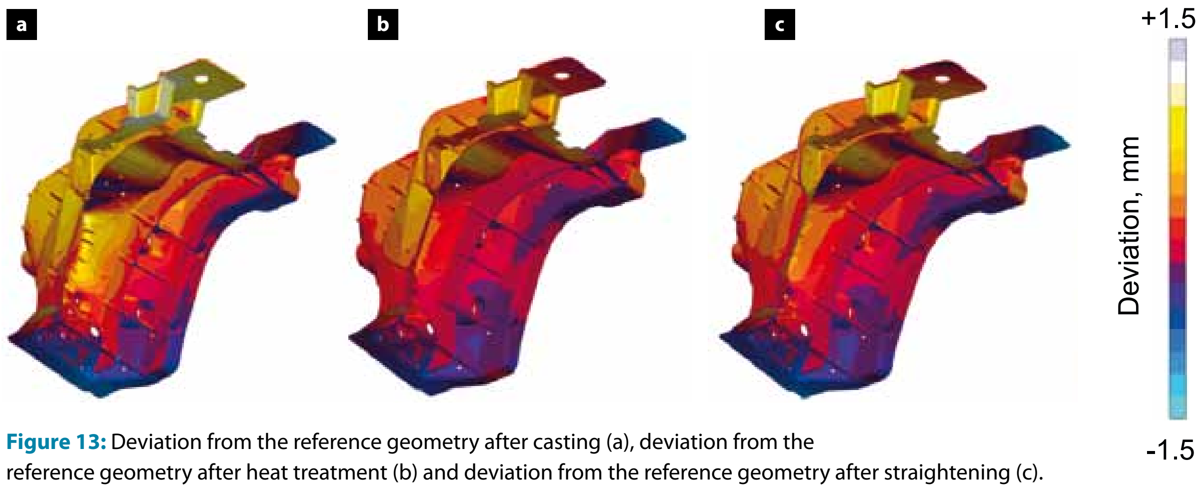

Figure 13: Deviation from the reference geometry after casting (a), deviation from the reference geometry after heat treatment (b) and deviation from the reference geometry after straightening (c).

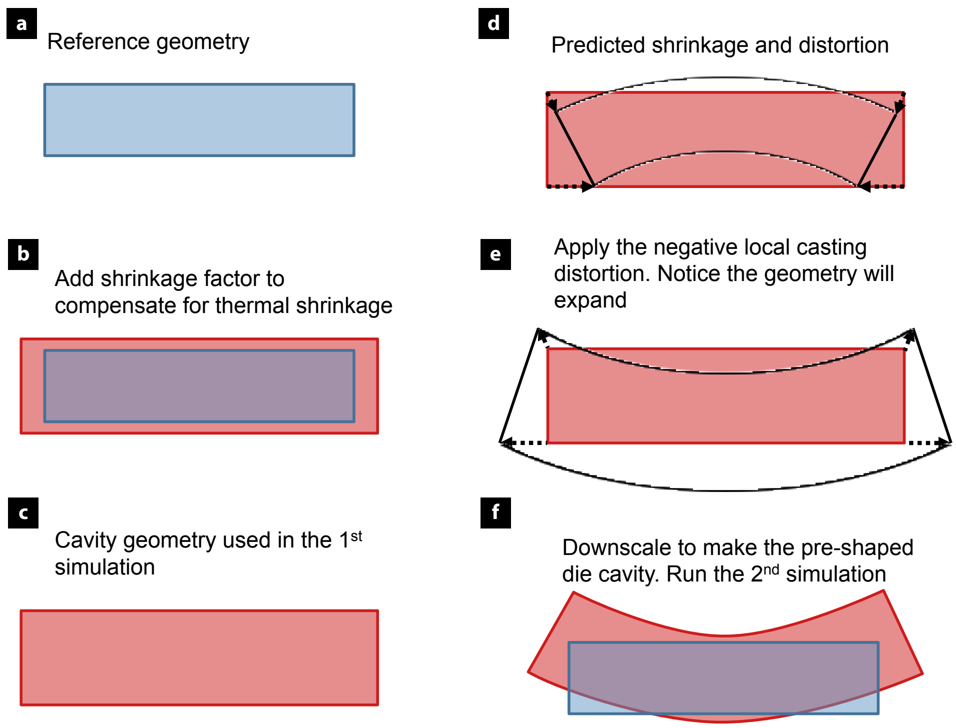

Figure 14: Procedure for pre-shaping the die. Reference geometry (a), enlarged geometry to compensate for thermal shrinkage (b), cavity geometry for the first calculation (c), predicted shrinkage and distortion (d), applied local negative casting distortion (e) and pre-shaped die cavity for second simulation (f).

for the thermal contraction of the casting during solidification and cooling.

- The first simulation is based on the up-scaled die cavity in shown red in Figure 14c and the results are indicated by the black line geometry in Figure 14d. The four small arrows in the corners of the two geometries in Figure 14d indicate the predicted distortion.
- This result is multiplied by a negative scale below -1.0 and applied as a correction factor to the die cavity shown by the black line geometry in Figure 14e. The correction is indicated by the four arrows. The negatively deformed geometry is scaled down and used as the new cavity shape, red shape in Figure 14f.
- The applied negative correction expands the geometry and a last down scale is applied to predict the new pre-shaped cavity.
- A second simulation is used to check to which extend the pre-compensation corrects the original distortion.

Depending on the complexity of the geometry, it can be difficult to correct distortion in all regions of the part even if the steps above are repeated several times. However, compared to making changes to the real die, the above simulation approach is a very attractive way of evaluating how far as-cast distortions can be reduced by pre-shaping the die.
To illustrate the die pre-shaping procedure, a space frame connection node is used as an example. The considered connection node is shown in **Figure 15**. The deviation from the reference geometry after casting using the original cavity dimensions is in the range of 0.9-1.0 mm as shown in Figure 15a. The negative of the casting distortion shown in Figure 15a was used to correct the dimensions of the die. In Figure 15c the grey colored part illustrates the dimensions for the original cavity geometry, and the purple color indicates the modified cavity geometry using the predicted distortion shown in Figure 15a. After compensating the distortion by pre-shaping the die, the level of deviation from the desired geometry is reduced to be less than 0.3 mm as shown in Figure 15b.

14 Analyzing the ejection process

The location and number of ejection pins governs the stability of the ejection process of the cast part from the die. It is important to design a layout which distributes the required ejection forces in a way that the part does not stick to the die or deform the part. Simulation can be used to evaluate different layouts, and by that add pins where ejection forces reach a critical level and remove pins where they have little or no effect. Design constraints from e. g. the cooling system and die inserts can, of course, be considered when the locations are evaluated.

The ejection process is evaluated for a space frame connection node, where the initial layout of 12 ejector pins was simulated and the results were used to check the force level on the different ejector pins. Based on the results, four pins were removed from the layout and results from a new simulation were compared to the original layout **Figure 16**.

The ejection process for the initial layout is visualized in **Figure 17**. The three snapshots show the deformed part during ejection with a magnification factor of 5.

The ejector pins are controlled by a time dependent displacement input and the pins will force the part out of the die as function of time. The interface between the part and the ejector die is described by a Coulomb friction model, which governs the reaction forces depending on the shrinkage induced clamping.

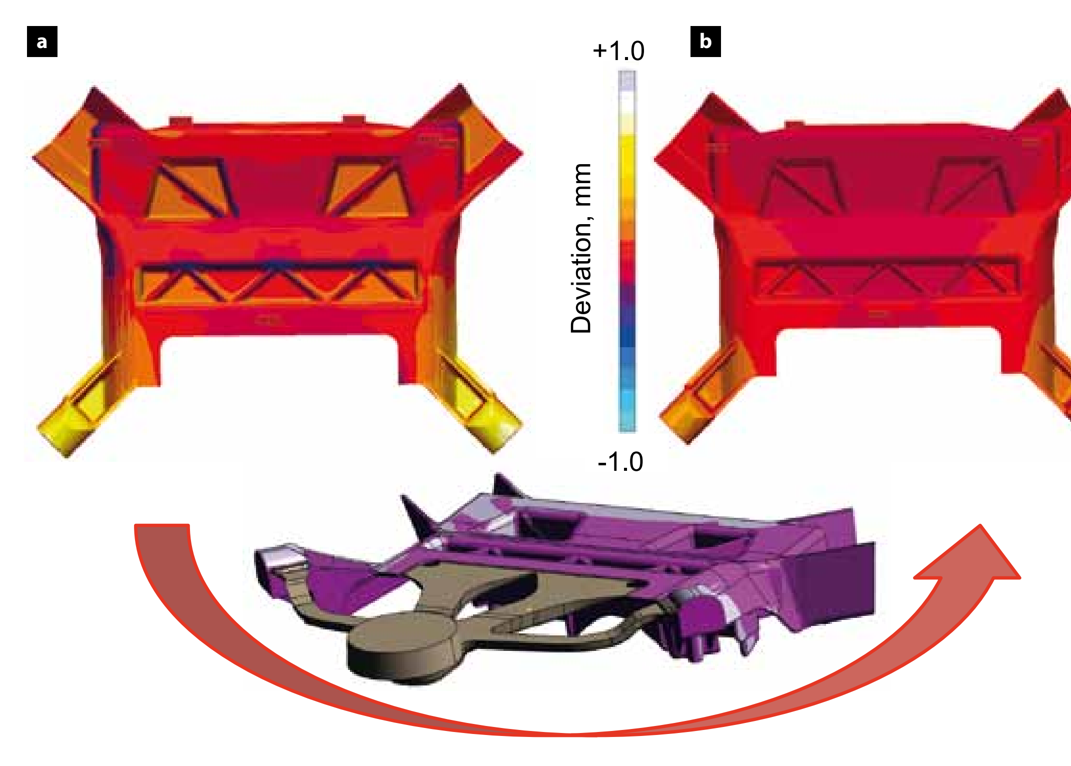

Figure 15: Pre-shaping of the die. Deviation from the reference geometry after the first simulation (a) and deviation after the second calculation where the pre-shaped cavity is used (b).

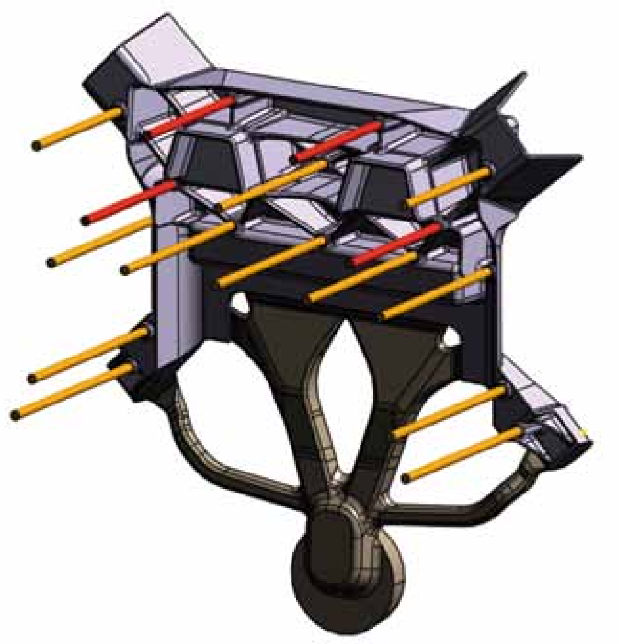

Figure 16: Layout of the ejector pins, where the red pins are not active in the second simulation.

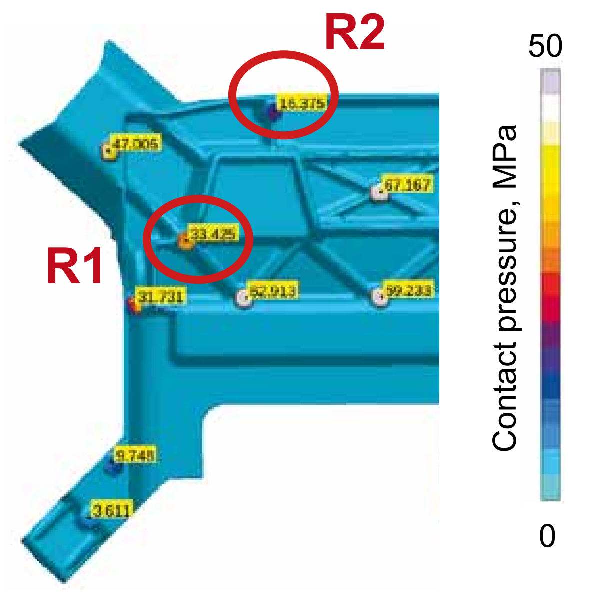

Figure 18: Contact pressure in the interface zones between the part and the ejector pins. The contact pressure is shown after approximately 1 second. Due to symmetry, only half of the part is shown.

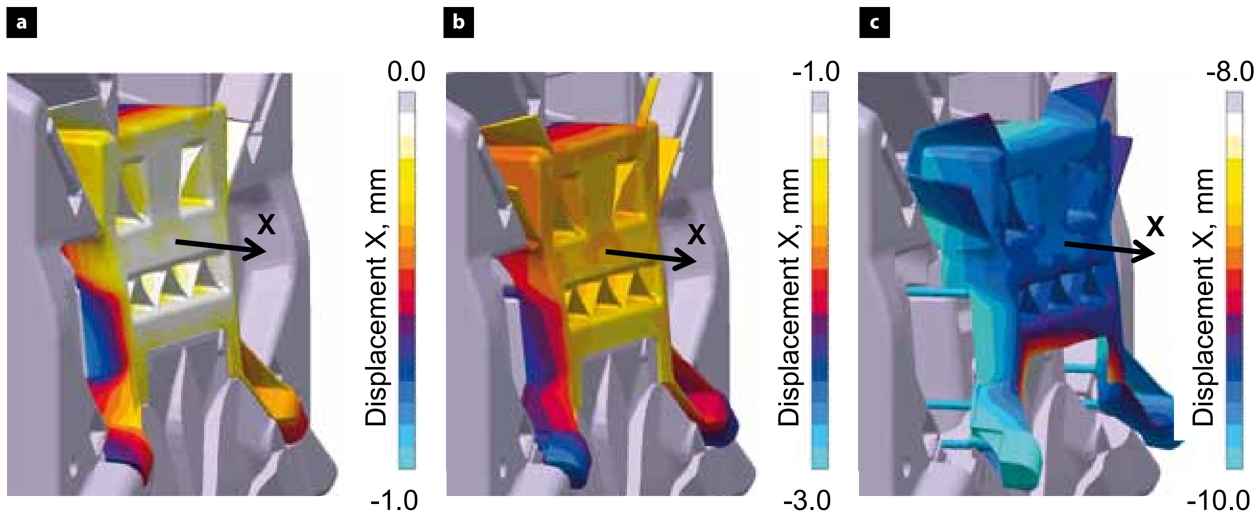

Figure 17: Deformation of the part during the ejection process (5x magnification). The snapshots show from the left: The beginning of ejection (a), the time where the forces are highest (b) and the end of the ejection (c).

The contact pressures between the ejector pins and the part are evaluated for the initial case where all pins are active. It is possible to visualize the pressure directly on the part, which is shown as an example in **Figure 18** after approximately 1 second. Only half of the part is shown due to the symmetry.

Two points are identified as having a relatively low contact pressure and hence used as candidates for being removed (four points in total – only two are shown due to symmetry). They are highlighted as R1 and R2 in Figure 18. The two points in the lower left corner of the part also show relatively low contact pressures. However, they are kept in the layout due to their location, since removing them could increase the risk of the part tilting and sticking during the real ejection process.

The two identified pins, R1 and R2, were removed and the second reduced layout was simulated. To evaluate the consequences of removing the two pins, the contact pressure in three of the remaining points were compared to the results from the first calculation. The results are compared in **Figure 19**, where the normalized contact pressure is shown as a function of time at the three points. The full lines show

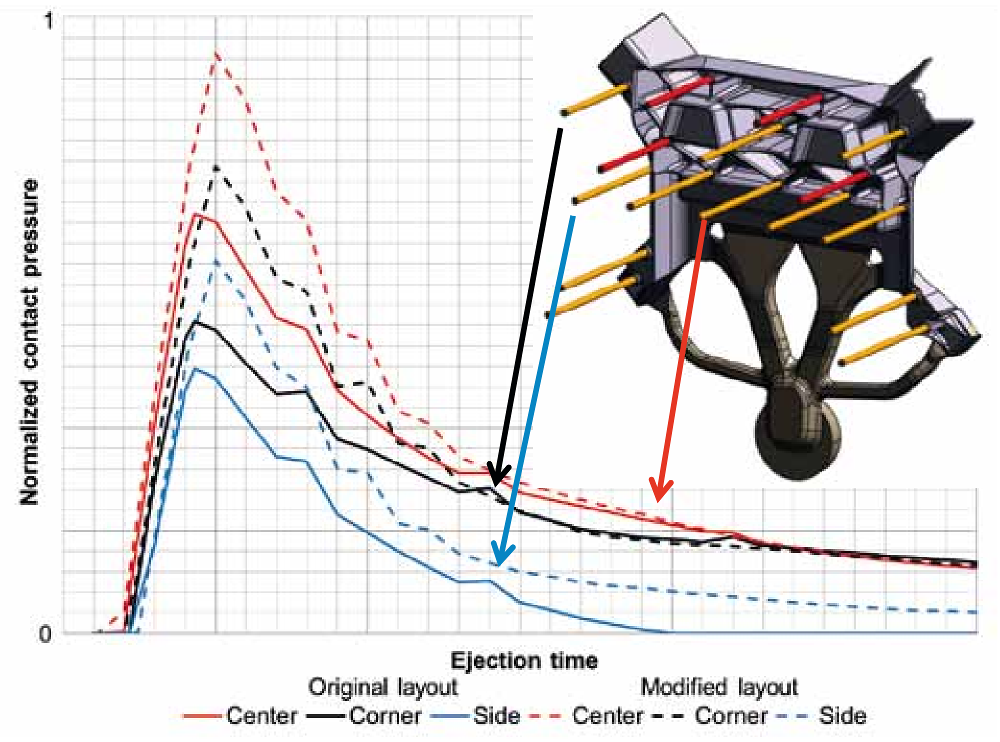

Figure 19: Contact pressure as a function of time in the 3 indicated ejector pins. Full lines are the original layout and the dashed lines are the reduced layout without the red pins.

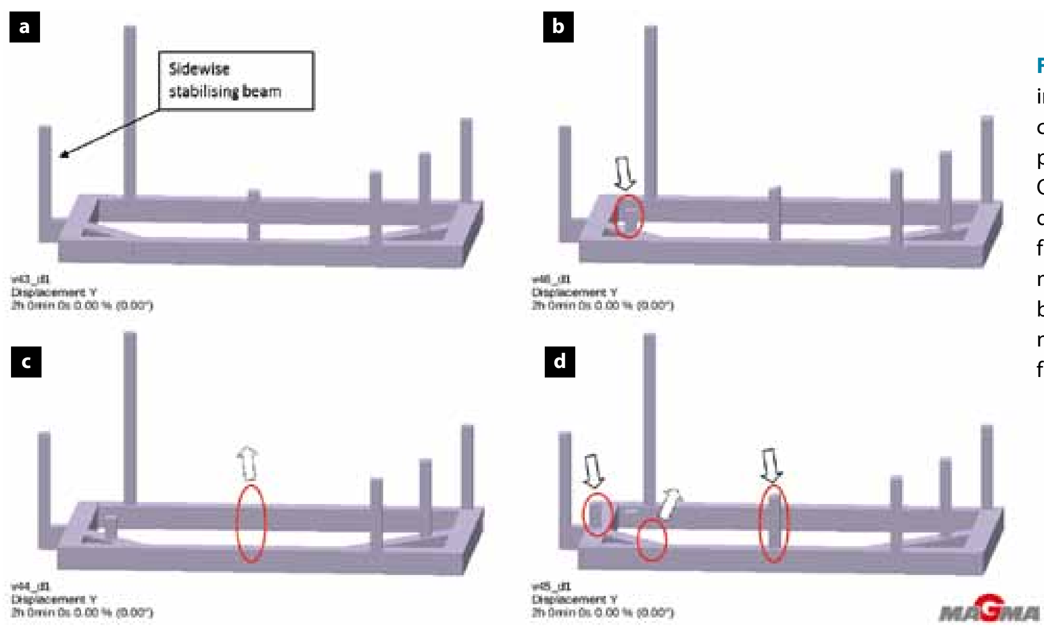

Figure 20: Variations in the number and location of the front support frame beams. Original layout (a), adding a beam in the front left corner (b), removing a front center beam (c) and repositioning the pins in the front (d).

the results for the first case with all pins active and the dashed lines show the results for the second case where four pins are removed from the layout. The contact pressure is generally increased in all three points, but a further evaluation of the general stress state in the part during ejection did not show critical stress levels and no significant permanent deformation was detected due to the change in the number of pins. The reduced number of ejection pins in the second case therefore seems to be reasonable to ensure a stable ejection process.

15 Design of virtual experiments for support frame optimization

The final example is another space frame connecting node located in the rear part of the chassis. The design of the heat treatment support frame was evaluated by performing a virtual DOE varying the number and location of the applied front supporting beams in the frame; see **Figure 20**. The presented results are from the research project "ProGRes", [6, 7]. The objective was to minimize the deformation of the part by changing the layout of the support frame, while keeping the solution treatment parameters fixed at 2 hours and 485 °C.

The results of the DOE simulations are shown in **Figure 21**. For the frame in Figure 21a, 3.2 mm is predicted in the direction of gravity in the left front area of the part. Using an additional support in the front left corner of the frame, the deformation is significantly reduced, Figure 21b. The next variation is done by taking away one of the front support beams. This variation has only a minor effect on the deformation of the part Figure 21c. Moving the front left support beam further left and to the back of the geometry seems to lead to the best result of the performed variations, with the lowest displacements in the gravity direction, Figure 21d.

The results from the DOE made it possible to select a design of the support frame that could significantly reduce the distortion of the part. The changes in design were automatically generated and simulated.

The sensitivity to oven temperature and treatment time was evaluated in a separate DOE and the overview of the results is shown in **Figure 22**. On the x-axis the holding time of the solution treatment is plotted, and the y-axis shows the maximum difference of deformation in the part compared to the reference geometry. The green colored dots show the simulation results for the solution treatment temperature of 485 °C, red dots show the results for 535 °C and the blue ones show the results for 465 °C.

The diagram clarifies that for the same holding time (e.g. 2 hours) the solution treatment with the highest temperature shows the highest deformations of the treated part. At the same time the diagram illustrates the clear tendency towards higher deformations for longer treatment times for the same temperature levels. The tendencies of different colored dots in the diagram show that the values on the y-axis increase analogous to the x-values.

16 Summary

Integrated modeling of casting and heat treatment processes provides a powerful tool for an upfront assessment of critical material conditions and the influence of changing process parameters. Using virtual DOE in the design phase and during process optimization provides a unique possibility to

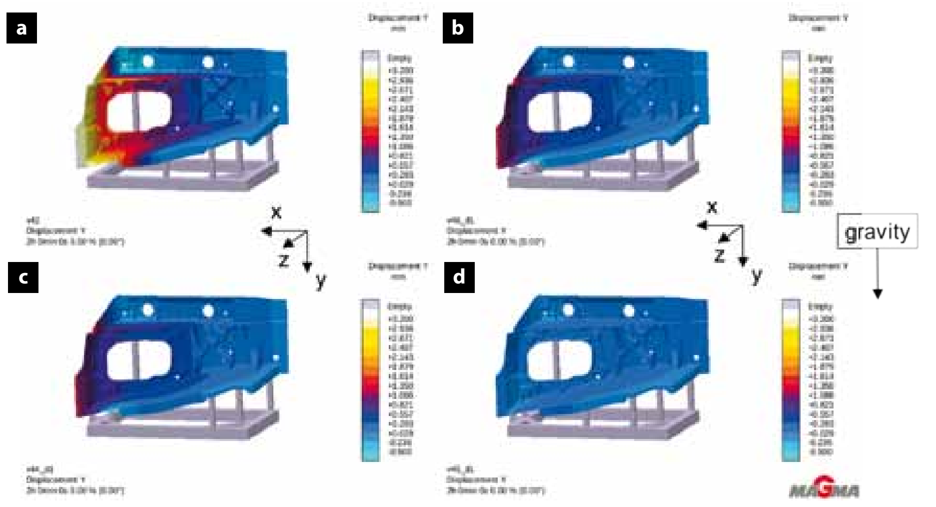

Figure 21: Predicted distortion in the part for different support frame configurations.

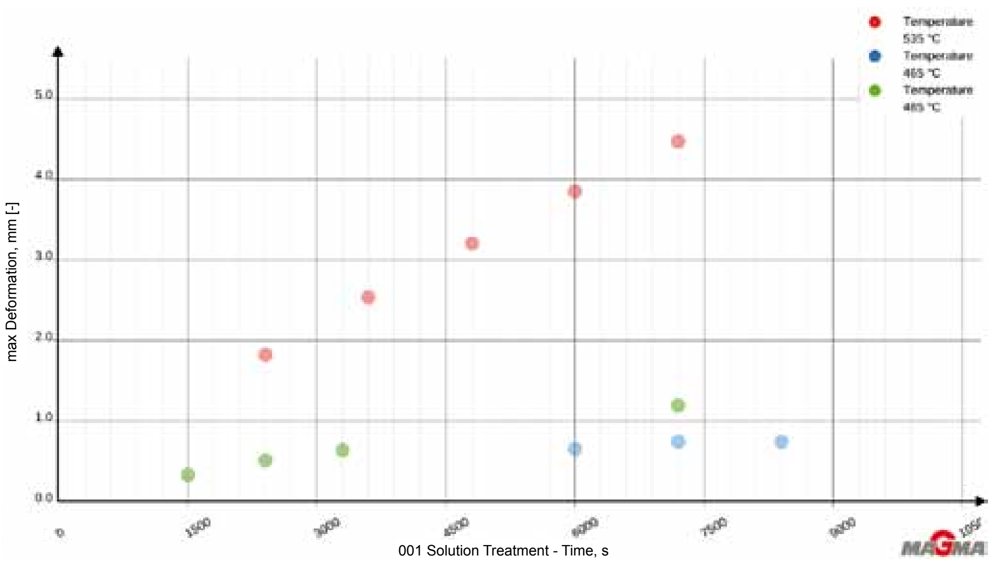

Figure 22: Results of a virtual Design of Experiments. Maximum part deformation during heat treatment for different solution treatment temperatures and times.

control distortion and meet tight tolerance requirements. Detailed simulations of specific process steps and the integration of results from the different manufacturing processes provide a fundamental understanding of the complex conditions in the casting and heat treatment processes. As this virtual approach can be applied already during casting and process design, it offers the opportunity to avoid most of the currently performed experiments and measurements from production, where expensive changes to the process or design delay the production significantly. It also helps reduce costly and time consuming tool changes or modifications of heat treatment supports. The systematic implementation of virtual Design of Experiments into the product and process development chain is a powerful methodology to establish robust process conditions before the first casting is made.

Dr. Jesper Thorborg, Dr. Jörg Klinkhammer und Dipl.-Ing. Heinz-Jürgen Gaspers, MAGMA Gießereitechnologie GmbH, Aachen

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Appendix 1: Thermo-mechanical constitutive model.

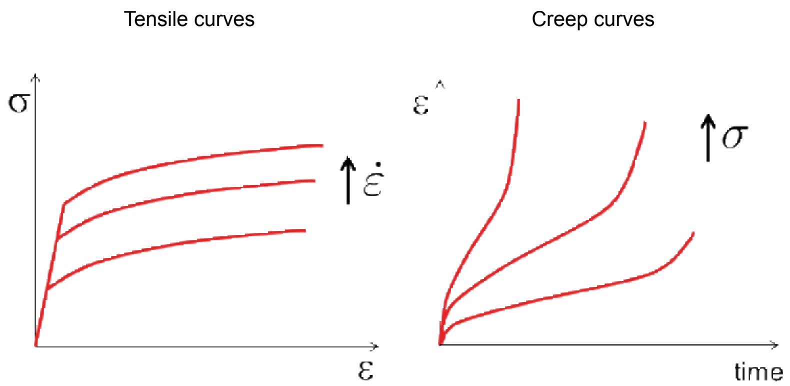
Thermo-mechanical constitutive model

Thermo-mechanical modeling of the casting and heat treatment process has to consider the complex behavior of the material response and the interaction between the casting material and the surrounding dies and support frames. One of the main concerns is to model the response of the material at different temperature levels, on different time scales and sometimes with different strain rates, which is governed by different deformation mechanisms. A unified creep formulation is used as the fundamental constitutive law, [4]. The model is based on Norton's power law and includes by that, strain rate sensitivity and the possibility to describe creep at elevated temperatures:

$$\dot{\varepsilon}^{in} = A\, exp\left(\frac{-Q}{RT}\right)\left(\frac{\sigma}{\sigma_{ref}}\right)^{m} \quad \text{and} \quad \sigma_{ref} = \sigma_{0,ref}\left(1 + \frac{E\,\varepsilon^{in}}{n\,\sigma_{0,ref}}\right)^{n}.$$

The two properties A and m describe the strain rate sensitivity. The Arrhenius expression scales the response according to the temperature dependency and the model is therefore applicable over a wide temperature range. The temperature dependency is governed by the activation energy, Q. The reference stress σ_{ref} describes the isotropic strain hardening by a classical power law, where the inelastic strain, ε^{in}, is used to capture the effect of hardening when e.g. dislocations are piling up and annealing when the temperature is elevated, accounting for diffusion processes.

The hardening response is governed by two temperature dependent properties, the initial reference stress $\sigma_{0,ref}$ and the hardening parameter n. The response of the creep equation and the hardening law can be illustrated by classical creep curves and the strain rate dependent tensile curves, see Figure.



Calibration of the thermo-mechanical properties is based on a large range of tensile tests and creep tests at different temperature levels. The tensile tests are typically performed at different strain rates at intermediate and high temperatures to get information about the strain rate sensitivity. Creep tests are performed at high temperatures to get information for the heat treatment process and for slow cooling casting processes, where stress relaxation is important.

Appendix 2: Casting process overview. Summary of the different process steps during casting and the typical observed behavior of the mechanical fields.

Casting Process Overview

Thermo-mechanical modeling of the casting and heat treatment process has to consider the complex behavior of the material response and the interaction between the casting material and the surrounding dies and support frames. One of the main concerns is to model the response of the material at different temperature levels, on different time scales and sometimes with different strain rates, which is

Solidification and cooling inside the die

- Stresses build up during cooling due to constraints from the die
- Plastic strain is generated due to the constrained deformation

! Check temperature level to evaluate when the die should be opened

! Evaluate the level of the shrinkage factor applied to the die

Ejection process

- Stresses are relaxed
- Distortion builds up during die open and ejection

! Check if the force levels on the pins are similar or if some pins experience less or higher forces than others

! Compare the contact pressure when the number of pins and the location of the pins are changed

! Enlarge the design space for the cooling system

Cooling/Quenching outside the die

- Thermal contraction governs the final size and shape of the part
- Stresses build up for high thermal gradients

! Evaluate how the die open temperature affects the final size due to different levels of free thermal contraction

! Check how different cooling histories affect the level of the stresses

Trimming step

- Stresses are redistributed when the gating and other materials are removed from part

! Check if high stresses build up when load carrying material is removed

Appendix 3: **Heat treatment overview. Summary of the different heat treatment steps and how the thermal load influences the mechanical behavior.**

Heat treatment overview

Thermo-mechanical modeling of the casting and heat treatment process has to consider the complex behavior of the material response and the interaction between the casting material and the surrounding dies and support frames. One of the main concerns is to model the response of the material at different temperature levels, on different time scales and sometimes with different strain rates, which is

Positioning on support frame and mapping results

- ! Designing an appropriate support frame for the heat treatment process, e.g. to compensate for casting distortions during solution treatment
- ! Positioning of the deformed part
- ! Optimize the support frame to meet the requirements of the reference/target geometry

Solution treatment

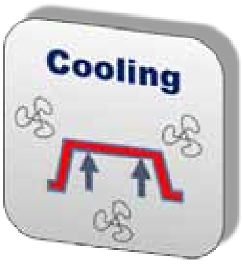
- Initial conditions from the casting process, i.e. stresses and deformations
- Relaxation of the stresses during heating and solution treatment process, rotation and translation of mechanical fields
- ! Deformations due to gravity and the influence of the location of the support frame
- ! Check if stresses are relaxed at the end of the process step and the deformation level is acceptable

Quenching

- Stresses build up during quenching, depending on the cooling rates and thermal gradients
- Thermal contraction reduce the size of the part
- ! Check if the cooling conditions promote unwanted stresses due to the thermal gradients

Artificial ageing

- Moderate stress relaxation due to the elevated temperature level
- ! The influence of the temperature level on final stress level could be checked



Cooling

- Thermal contraction reduces the size of the part
- ! The final shape of the part can be evaluated and compared to the reference geometry and measurements if available