Optimized Development for Castings and Casting Processes

Increase in Value by applying an integrated CAE Chain for the Development of Automotive Magnesium Castings

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Summary

Integrated simulation technologies and their simultaneous usage allow shortest development periods, right casting quality “first time” and a reliable production with, on the whole, improved economic efficiency.
The “advanced state of the art” is demonstrated using an example of an automotive wheel, where the simulation result was an optimized casting design with respect to the casting practice, the wheel's behavior under load and the layout of a reliable batch production process. At the same time a detailed documentation of the melt flow and cooling during die filling and solidification process, as well as the residual stress development was taken from simulation. Aspects of construction, tool manufacturing and the foundry process were simultaneously taken into consideration.
The steadily increasing computer performance is an other driving force for the application of CAE tools in casting development: as look into the near future, the potential of computational process optimization is shown. The example is a high pressure die casting process of an aluminum housing, where a closed loop of an optimizer, the casting process simulation on a fast parallel computer, and an automatic evaluation tool for simulation results was used.
Finally, the potential of computational casting design optimization is shown. The example is an aluminum suspension part, where only the allowed assembly space, the mounting conditions and the expected loads were given as initial condition for the casting design. Bionic approaches were used to get the first casting design, which then was reengineered in 3D CAD, counterchecked with casting simulation and FE – analysis and finally manufactured in a RP casting process.

Keywords

Casting Development, Design, Optimization, Modeling, Simulation, FE - Analysis

0. Introduction

"Time to Market" is the slogan by which the competitiveness of developments is judged. The process chain in the development of a magnesium casting consisting of functional design, digital mock up, detailed design, lifetime prediction, casting of prototypes, layout of the series casting process and tools, and the optimization of the series casting process, can be supported by CAE technologies such as CAD, FE analysis and casting simulation. An application of these technologies as distributed solutions does support simultaneous engineering. But, an enormous technical and economic advantage can be gained from the integration of these technologies, meaning the simultaneous exchange and usage of common models.

An optimized development process, which is supported by a completely integrated chain of CAE technologies of 3D CAD, casting simulation and FE analysis, will be demonstrated using the example of a low pressure die cast magnesium wheel. The generation, documentation and interpretation of results gained from FE analysis and casting simulation will be shown, as well as their integration into the development process.

1. State of the art: Simulation in the design process of a magnesium wheel

In the following, the support of the development process of a casting by simulation is documented on the example of an automotive wheel made of the magnesium alloy AM60. The wheel, gating system, casting die and the cooling channels are constructed directly in 3D CAD. The CAD model of the casting is used for mold filling and solidification simulations (based on the Control Volume Method) as well as for the calculation of residual and load stresses (residual stresses can be investigated using the Control Volume or the Finite-Element Method). In this case the calculation of residual stresses has been done with a Finite Element tool by transferring temperatures of the control volume model into to the FE model. This way has been selected to facilitate the information transfer to the subsequent load simulation.

During simulation of the casting processes, mold filling, solidification and microstructure formation are examined as well as the development of residual stresses. Then, the calculated residual stresses are taken as a preliminary load on the wheel in the following FE analysis. During the optimization of the wheel geometry and the casting process, aspects concerning the casting process as well as aspects concerning stresses are taken into account

1.1. Description of the casting process

The wheel is cast using a low pressure die casting process. The elements of a low pressure die casting machine that are most important for the simulation are the movable upper die half (top core), the fixed bottom die half (bottom core), and the slides (side cores), Fig. 1.1. The dies and the slides usually consist of high-alloy tool steels that are coated on the side which is in contact with the casting. The melt enters into the cavity through the ingate which is located on the fixed die half. After die filling and wheel solidification, first the movable die half and then the two slides are opened. The wheel is pushed out of the fixed die half using the ejector pins attached to the fixed die half, which act upon both the wheel horn and the wheel hub.

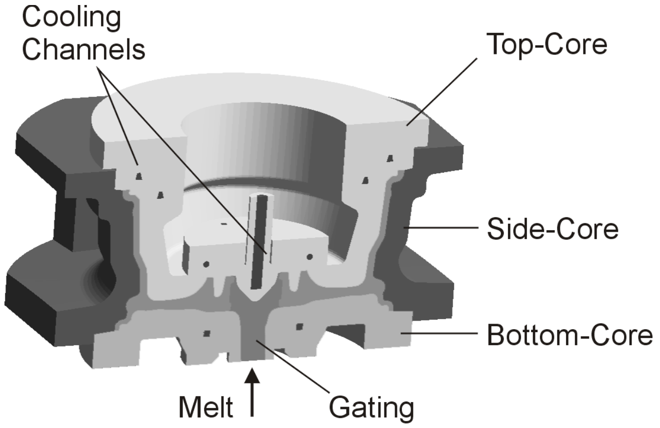


Figure 1.1: Geometry of the casting system which is enmeshed using control volumes for the simulation of die filling, solidification and microstructure formation within the casting. Mold and casting are displayed in cross-section.

1.2. Simulation of the initial design

The die filling via the spokes causes a turbulent flow between the spokes, Fig. 1.2. This is why the coldest melt is between the spokes. Later during die filling, the melt calms down and the die is filled evenly.

The solidification simulation shows areas that are critical for feeding at the transition between the spokes and the well of the wheel and in the rim flange, Fig. 1.3. The feeding problems are caused by a solidification which is not adequately directional, and by the hot spot at the transition between the spokes and the well of the wheel. Due to the early freezing of the spokes, the hot spot can no longer be fed adequately.

Figure 1.2: Temperature distribution during the filling of the wheel. Unfilled areas are shown transparent.

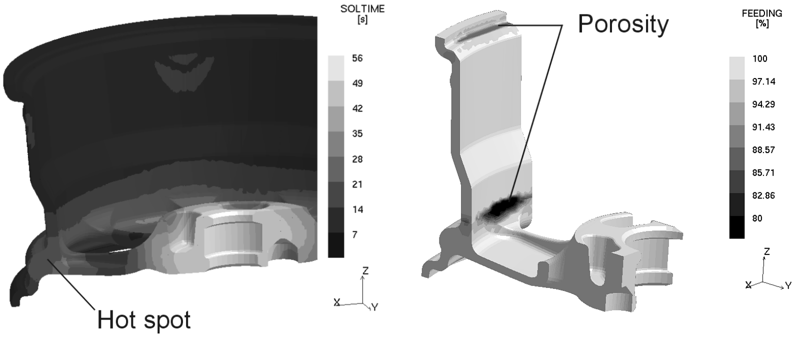


Figure 1.3: Critical areas for feeding due to isolated hot spots.

To calculate the residual stresses, the temperatures calculated during the solidification simulation are transferred fully automatically from the Finite Volume Model to the Finite Element Model. Then, the temperatures are gradually deposited onto the wheel as external loads. The calculation results show maximum residual stresses of approximately 45 MPa on the back side of the spokes. The residual stresses are caused by the hot spot in the wheel hub. In the FE-analysis, a rotating bending test is carried out on with the wheel, a test force of 3500 N is applied at an axial distance of 600 mm from the hub, Fig. 1.4.

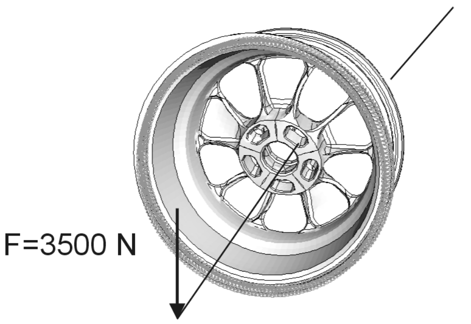


Figure 1.4: Boundary conditions for the load stress analysis (rotating bending test)

The test force introduce a bending moment onto the wheel. This leads to tensile stresses within the upper spokes and to compressive stresses within the lower spokes. Therefore, the tensile residual stresses are increased in the upper spokes, and, on the opposite side, the compressive stresses caused by load are reduced by the tensile residual stresses, Fig. 1.5. The resulting stress at the most loaded spoke is approximately 150Mpa and therefore clearly lies above the fatigue strength under reversed bending stresses of approximately 80 MPa.

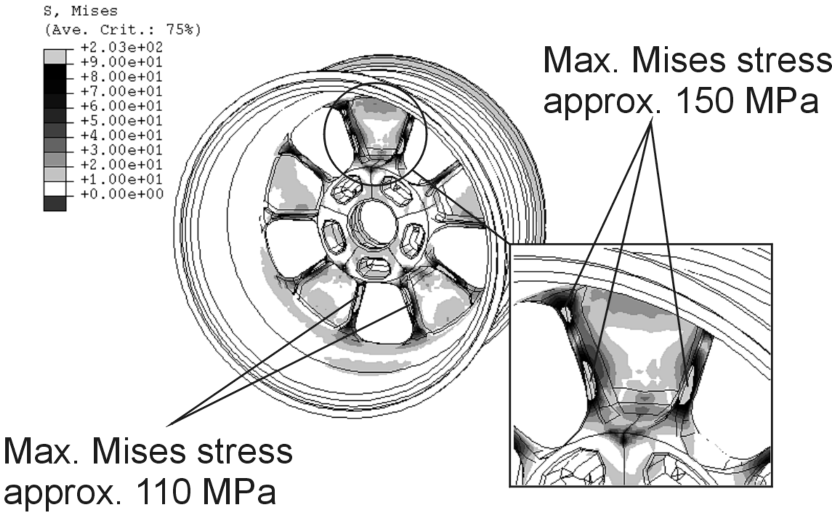


Figure 1.5: Stress distribution in the wheel under the testing load (original geometry). During the stress calculation, the residual stresses were taken into account as a preliminary load of the wheel.

1.3. *Optimization of casting design and casting process*

Taking the simulation results as a basis, the spokes of the wheel are reinforced in their cross section, and the base of the wheel is thickened continually towards the spokes. In the transition area between bottom core and slides, the tool is additionally cooled with air from the outside. An additional cooling is also placed in the area of the wheel horn, and cooling is increased in the area of the hub after die filling. On the one hand, the objective of these measures is to improve the directional solidification and thus the feeding possibilities in critical areas. On the other hand, the reinforcement of the spokes supports the reduction of stresses under load. The temperature differences between the base and the hub during casting ejection are reduced by increased cooling of the hub. In this way, the residual stresses within the spokes are also reduced.

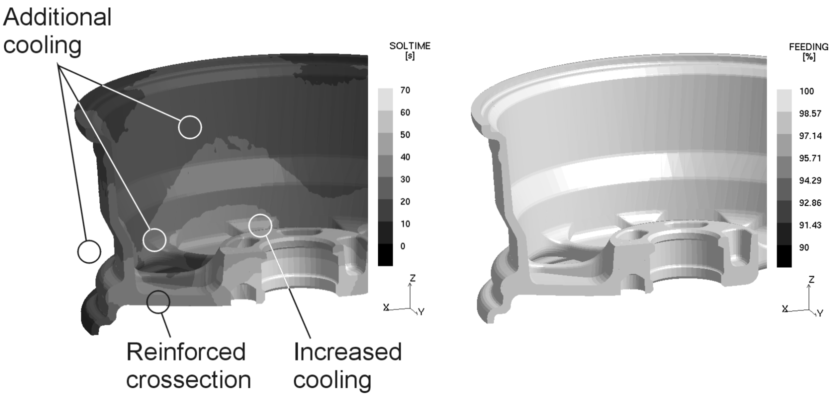
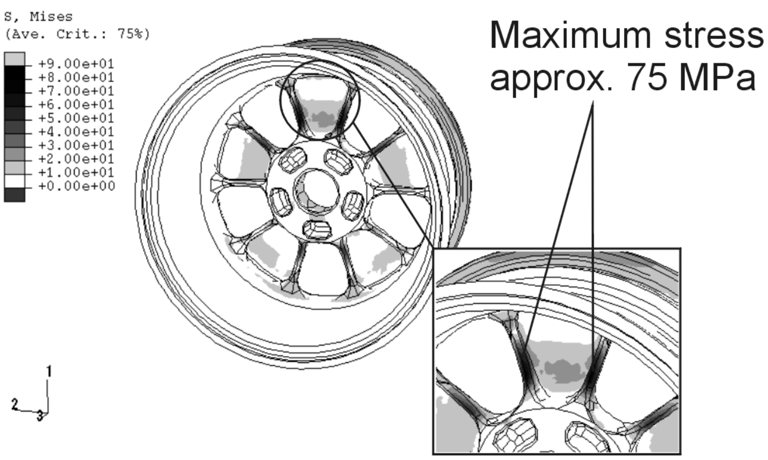


Figure 1.6: Optimization measures and their influence on the feeding result. There is no more porosity detected.

The result is the almost complete elimination of pores, Fig 1.6. At the same time, the total load on the wheel under the combination of residual stresses and the bending load is reduced to less than 75 MPa, Fig. 1.7.



Maximum stress approx. 75 MPa

Figure 1.7: Stress in the optimized wheel under the test load. During the stress calculation, the residual stresses were taken into account as a preliminary load on the wheel.

2. Automatic optimization of casting processes

The faster hardware and modeling algorithms become, the more optimization potential can be gained from casting simulation. Parallel computation techniques lead to calculation times in the range of minutes, where actual single processor CPU’s still need days for the computation of, for example, complex mold filling and solidification processes. This automatically creates a bottleneck in post processing, or, looking from another angle, creates the opportunity to apply algorithms and techniques for an automatic optimization of the casting process.

An example is the high pressure die casting process, where the tool steel die is exposed to dramatic temperature changes from cycle to cycle, Fig. 2.1 which leads to substantial thermal stress **[1].**

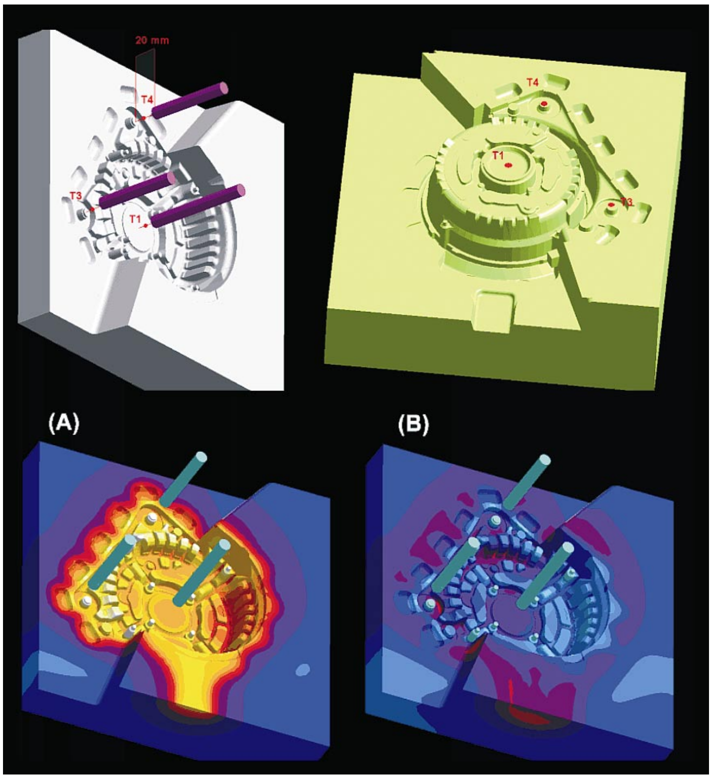


Figure 2.1: Above left and right are views on a tool steel die for an aluminum housing. Below are graphs showing the simulated temperature distribution in one die segment right before the casting is removed (A) and right after a coating was sprayed onto the die surface (B). Additionally the cooling cycles are shown

For this reason, the die lifetime depends particularly on smooth temperature gradients and moderate quenching or heating rates. In praxis the thermal balance is adjusted by an optimized lay-out of the cooling and tempering. Automatic optimization means, that simulation results are evaluated automatically, and an optimizer proposes the process variables for the next simulation loop (here modified cooling power and media), which again is started automatically, Fig.2.2

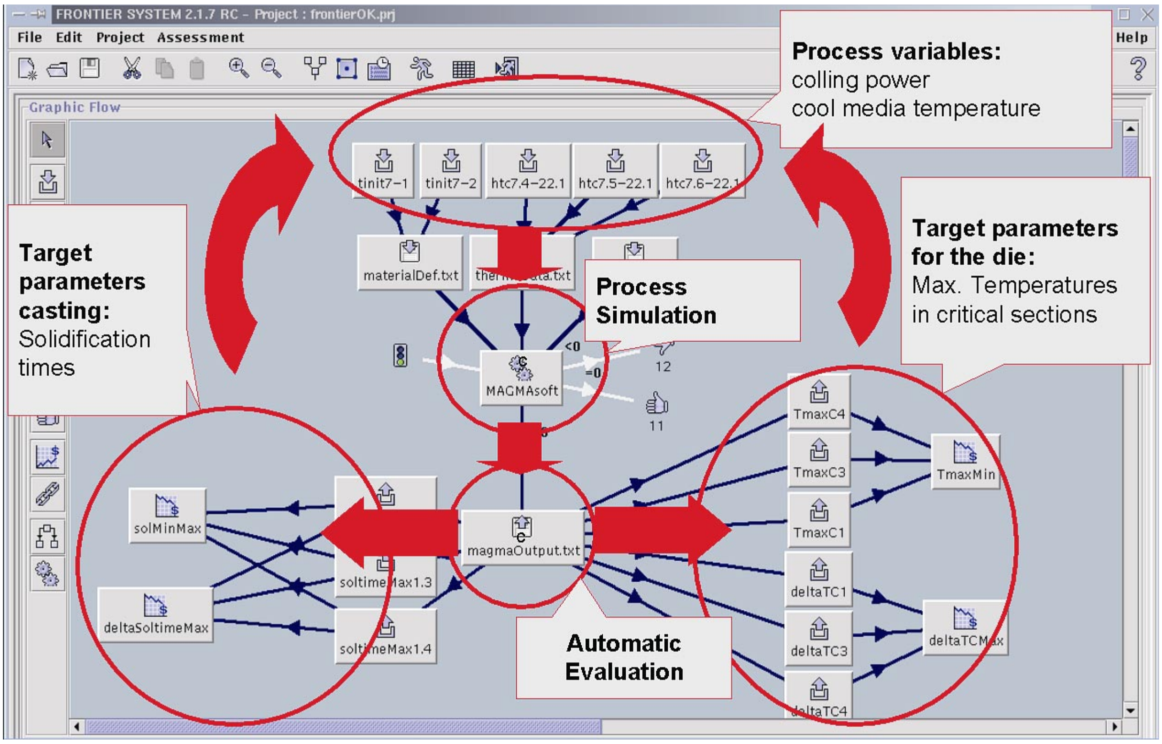


Figure 2.2: Closed optimization loop for an automatic casting process optimization, consisting of the simulation engine, an automatic simulation result evaluation and an optimizer making the decisions for parameter variations.

The results of this procedure are very valuable: The cycle times were cut by reducing the overall solidification time of the casting, Fig.2.3, this making a substantial positive economical contribution to the production. At the same time the die temperatures were homogenized by reducing the maximum die temperatures and its variation, Fig. 2.4, hence, increasing the die life. Finally the casting quality was increased by reducing the porosity, Fig.2.5.

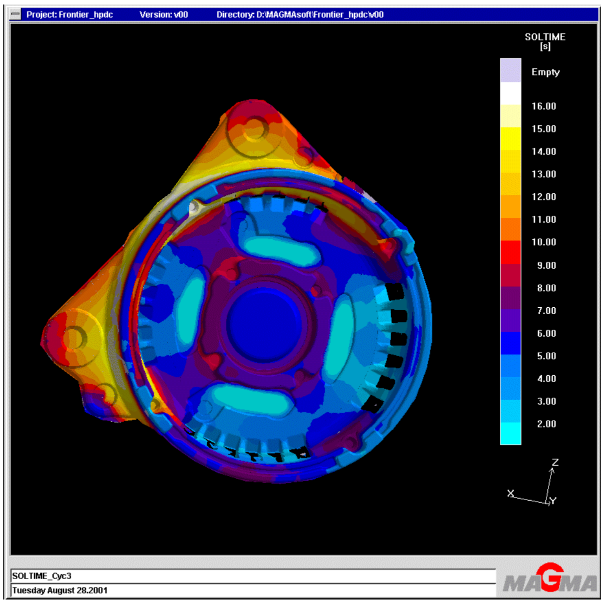


Figure 2.3: the local solidification times in the casting were reduced so that the overall cycle time could also be reduced.

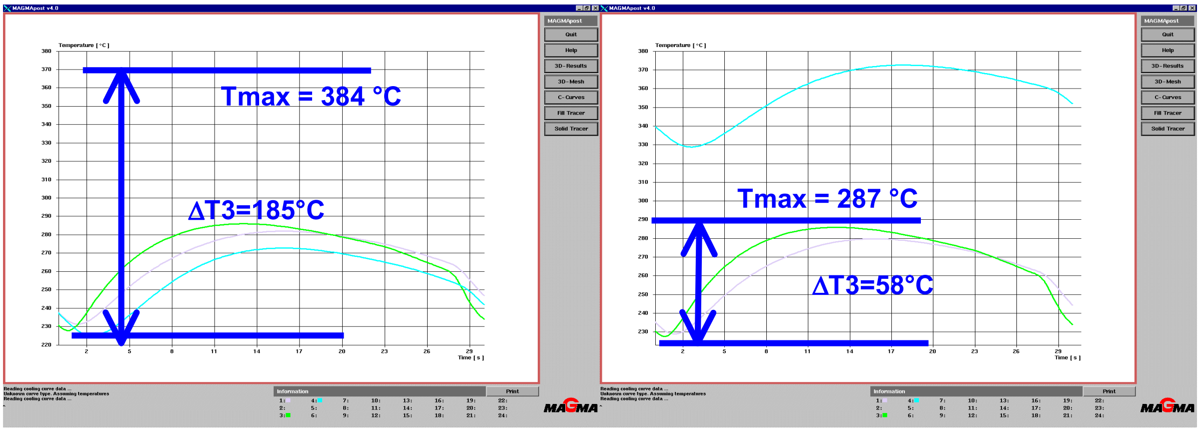


Figure 2.4: To the left are die temperature plots over one cycle before the optimization, to the right after the optimization. The maximum die temperatures could be reduced by about 100°C and its variation during the casting cycle has been cut down to 58°C starting from initial 185°C, both reducing temperature gradients and temperature shock at the die coating procedure.

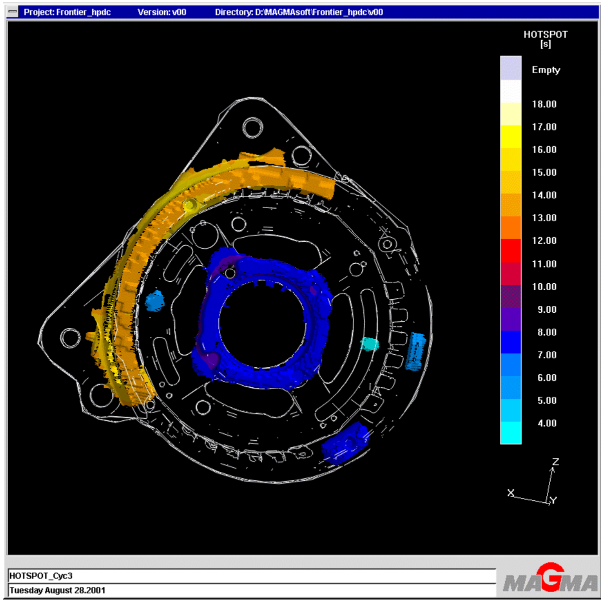


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Figure 2.5: This simulation result indicates sections, where porosity has to be expected within the casting. By automatic optimization these sections could be reduced substantially.

3. Automatic optimization of casting design

Generally, casting is a manufacturing process what allows total design flexibility. This is only limited by restrictions from large series casting processes, particularly the removability of the casting or the model from the mold. Few designers really use this potential, most castings are designed applying standard rules, which then are proved by FE analysis. Within the last years, the potential of automatic shape optimization has been discussed, and today we can see the first casting designs retrieved from automatic, computational shape optimization.

In the automotive sector, this technology seems quite promising for the optimization of suspension parts design. A simple rear suspension arm has been selected as a test case. The input for the optimization are the mounting dimensions and the mechanical loads on the component, Fig. 3.1. The target was to minimize the casting weight and to fulfil the specifications for distortion under load. The part was enmeshed, and the optimization was done with OPTISTRUCT®. The basic optimization rule is to remove material sections from the part, which are below a certain stress level when applying the test load. The result of the optimization is a quite filigree part, Fig. 3.1. The optimized structure, available as an FE-mesh, was then reengineered in 3D CAD, Fig. 3.2, so that parameterized data for further design changes are available.

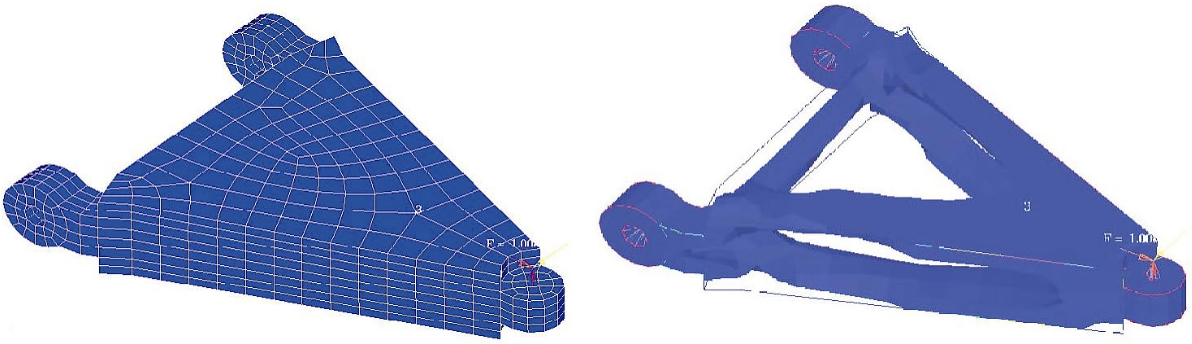

Figure 3.1: Initial FE-mesh as starting condition for the optimization (to the left) and optimized structure of the part after some simulation / optimization loops (to the right).

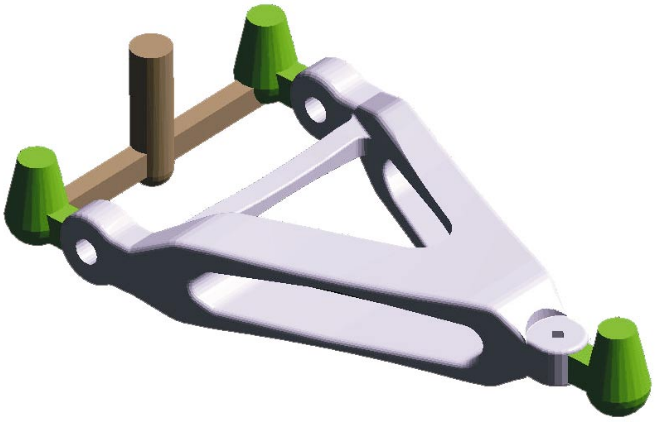

Figure 3.2: Based on the optimized part structure the design of the casting was reengineered in 3D CAD. The necessary set up for performing the casting simulation and manufacturing a mold was completed in 3D CAD.

After counter checking the reengineered design with FE-analysis, a casting simulation has to be done to gain information about possible casting defects, the microstructure and residual stress which have to be expected, Fig. 3.3. These parameters have some influence on the mechanical behavior under load, as shown above with the example of the wheel.

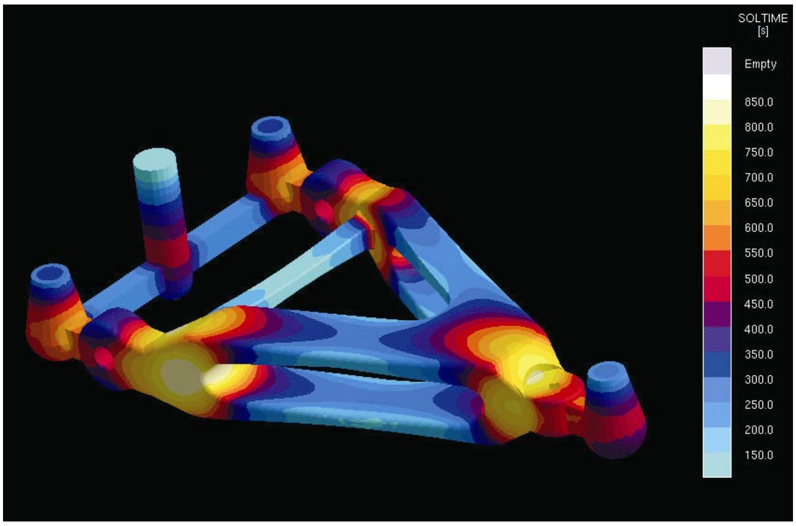

Figure 3.3: The optimized casting design has to be checked for eventual casting defects. The distribution of the local solidification time here give hints on microstructure and porosity, which has to be expected.

Conclusions

The examples which were discussed here show clearly the reasons, why several CAE technologies, particularly including CAD, FE-analysis and casting simulation have to be used simultaneously and integrated at the automotive casting design. The reasons are:

Most castings appear with residual stresses. The initial conditions for the FE-analysis are then very much different from the assumption of a residual stress free situation. Neglecting such residual stresses, might result in a completely wrong FE-analysis.
Castings always have a non uniform microstructure distribution, and might show defects such as porosity no matter whether they are raw components (straight from the casting process), machined and/or heat treated. This leads always to non uniform distributions of mechanical properties.

Additionally, the computational optimization of casting shape and casting process parameters was discussed. Particularly the optimization of casting process parameters has big potential for the following reasons:

The permanent improvement of computer performance, particularly the parallel processing, leads to dramatically shortened calculation times for one simulation loop.
It is possible to fully exploit this using automatic result evaluation methods together with a parameter optimizer.

Summarizing, it could be stated that the world of automotive casting development is actually faced with the most challenging changes since the introduction of CAD technologies in the eighties. The actually available computer based technologies such as casting simulation, as well as the upcoming technologies of computational optimization of casting design and casting processes will change the development environment dramatically. The co-operation of casting consumer and the foundry will be facilitated. Casting designers will have the chance to consider the process conditions in early stages of their design work and take full potential of the materials potential. The foundrymen will be strengthened since casting designs will adequate to the process demands. All this contributes to the continuous demands of the automotive market to guarantee shortest times to market and deliver optimal products.

References

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