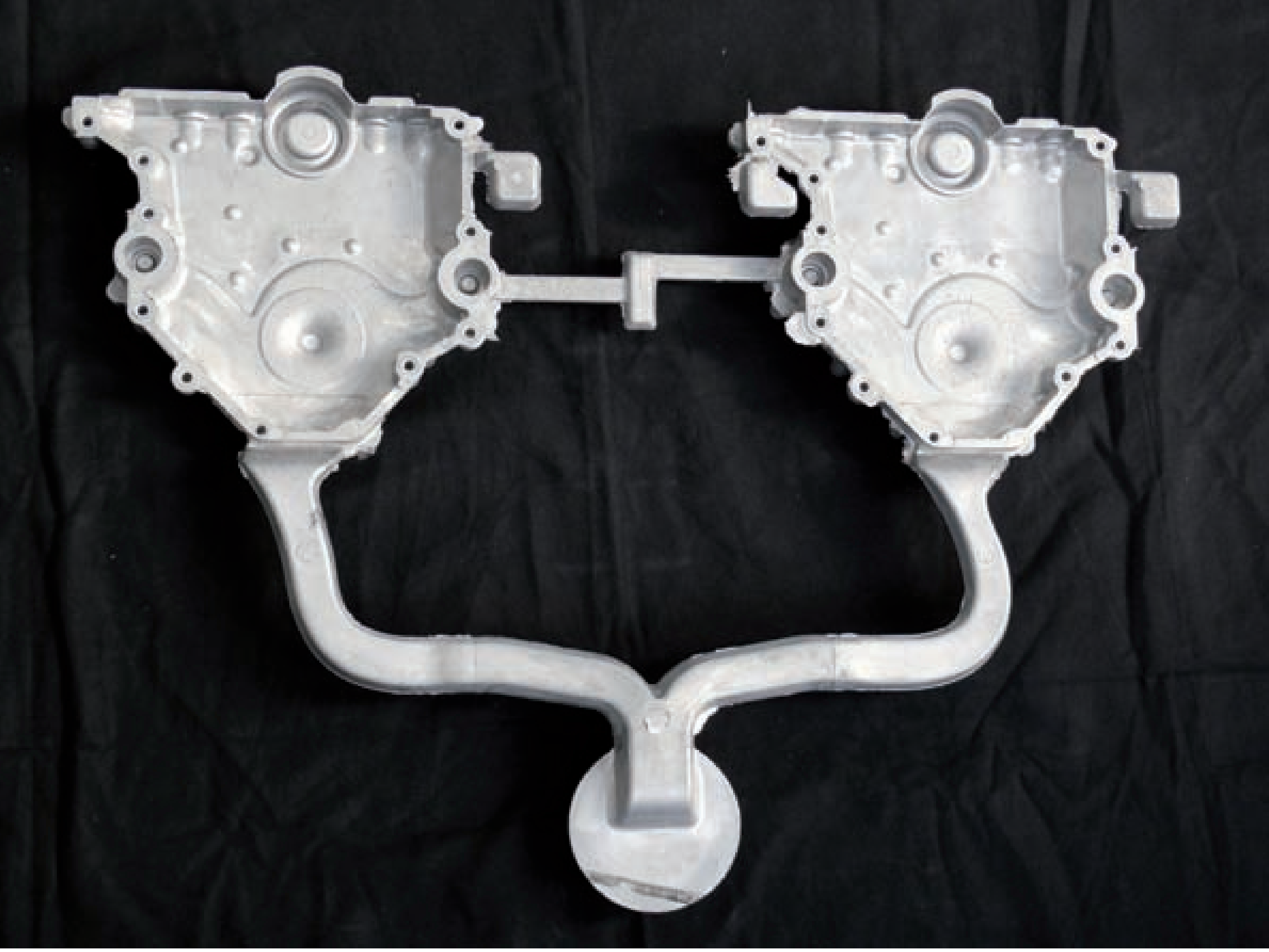

Two for One – transferring proven filling characteristics from a single to a two cavity die casting die

The demands on the productivity and robustness on the high pressure die casting process for high quality components are continuously rising. At the same time, financial considerations mean that an exact and reliable planning of the die layout and production process is required. Today, experience from previous projects as well as the modeling of the casting process using physical principles provides a basis for a dependable production planning. With the ever-increasing complexity of die castings, however, the application of experience from previous projects to new castings is increasingly difficult and questionable.

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A new and novel approach using autonomous optimization makes it possible to use information gained from an existing casting process with a good component quality and to use this information as the target to be achieved in the optimization of the layout of a new die. In doing so, a virtual test program for the die layout is carried out using casting process simulation. The program learns on a stand-alone basis, through trial and error, and searches for the best concepts for runner and gate design or shot conditions in order to reproduce previously effective conditions in the new casting.

The economic potential of die casting

To illustrate the methodology described above, the transition from a single-cavity to a two-cavity die for the production of a head cap casting can be used. Here, the tried and tested filling characteristics present in the single cavity die should be reproduced during filling of the two-cavity tool. This example is particularly significant in foundry practice, because substantial cost savings are possible through the change from a single- to a multiple-cavity die. Classical methods of process optimization using the single-cavity die can by no means reach a comparable jump in productivity. A pilot project carried out using this new optimization methodology shows the enormous potential for cost savings. For instance, when a two-cavity is used in place of a single-cavity die, cost savings between 20 and 40% can be achieved, dependent on the cost category considered **(Figure 1)**.

If savings are related to one casting, the highest savings potential can be reached in the contribution from maintenance, followed by savings in the energy needed for equipment operation and the reduced requirements for wear parts, such as shot chamber and plunger **(Figure 2)**. At the same time, the risks in manufacturing rise considerably with an increasing number of castings per die. Consequently, process reliability for each die-casting cell (machine, de-flashing press, robot and furnace) must be ensured. The conversion from a single to a multiple-cavity die requires that the runner design be modified, which often leads to quality differences between the castings from one and the same tool. Quality problems often occur in asymmetrical castings, where the die cavities have an identical orientation in the tool and are each filled through a separate runner. In such cases, quality problems can be reduced by applying the methodology of autonomous optimization as described in the following.

Autonomous optimization

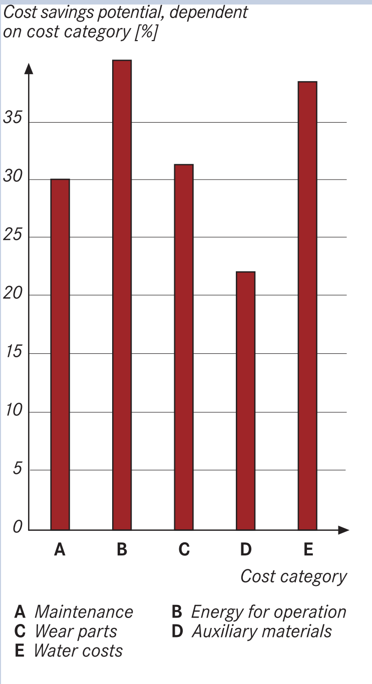
Autonomous optimization with the MAGMAfrontier program provides a novel approach for the solution of complex production problems. MAGMASOFT casting process simulations with varying process and design conditions are used as a test field. The optimization process runs on its own, without requiring any external intervention. Several goals (e. g. casting quality, productivity, material consumption) can be followed simultaneously during the optimization. To move in the direction of the desired targets of the optimization, the manufacturing parameters (such as shot conditions, materials, or die temperature control) and geometries (e. g. runner design, gate dimensions, position and dimension of cooling lines) can be varied. Moreover, production constraints (e.g. cycle times, spray conditions, die concept) can also be taken into consideration.

Figure 3 illustrates the design optimization process with MAGMAfrontier schematically. The starting point for the optimization is a sequence of varying designs selected using methods based on a statistical design of experiments. In the following, casting simulations are carried out for a defined number of generations, each with a given number of designs. Following each simulation, the results are evaluated, and genetic principles are used to define new designs based on these results [2]. After a sufficient number of simulated designs, a good compromise between the different optimization goals can typically be found [3]. Experience has shown that geometrical changes often have the largest influence in reaching the desired optimization objectives.

When defining an optimization task, the most important step is the definition of the quality criteria which are used to describe the targets of the optimization. Alone for the design of a runner, the foundry engineer can typically name a number of optimization targets off the top of his head, all of which he wants to fulfill simultaneously:

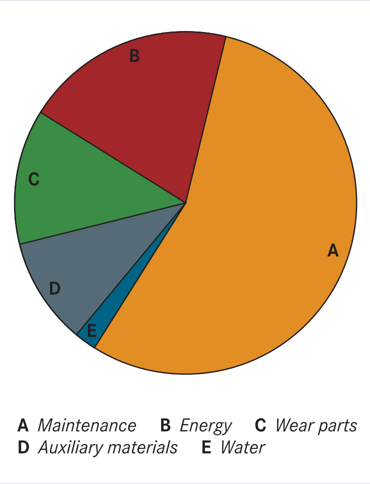
- Transfer of the filling characteristics from a successfully running single-cavity die to a multiple cavity die;
- Achieving a homogeneous and simultaneous filling of all of the cavities in a multiple cavity die, dependent on their position, the runner system and the casting parameters;
- Avoiding the separation of the melt from the cavity wall in the gating system as well as gas inclusions in the casting;
- Optimization of the runner cross-sections to ensure an effective feeding;
- Minimization of the runner volume to increase casting yield;
- Avoiding cold shuts in the casting;

Figure 1



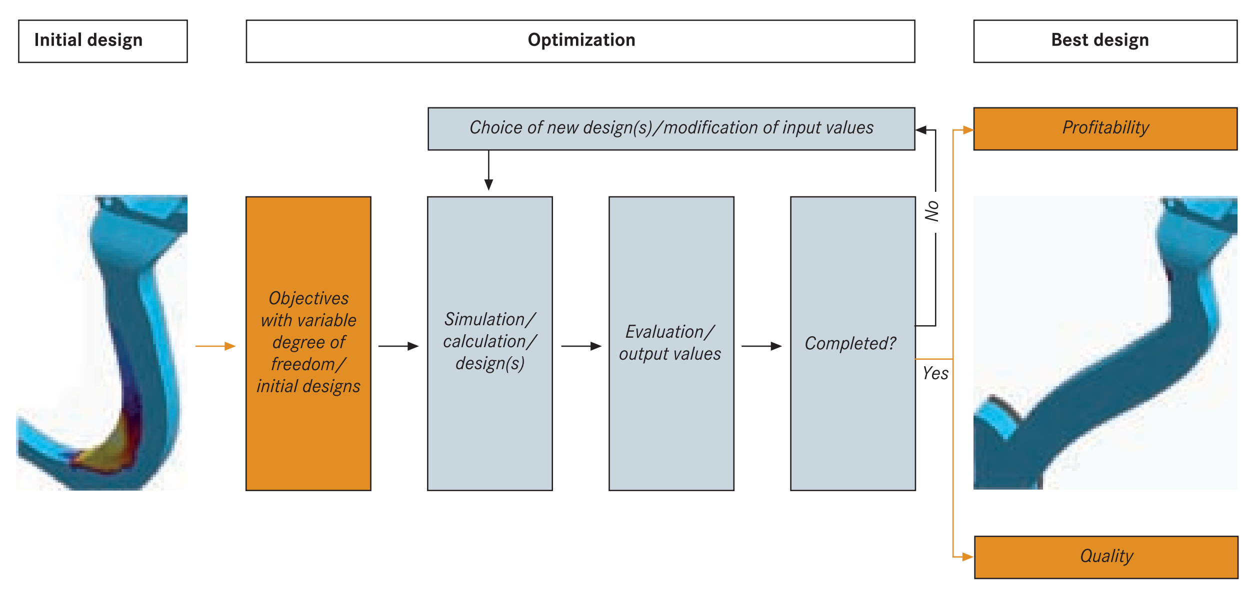
The potential for savings lies between 20 and 40 % when converting from a single cavity to a two-cavity die, depending on the cost category [1].

Figure 2



Weighting of the cost savings per casting [1].

Figure 3



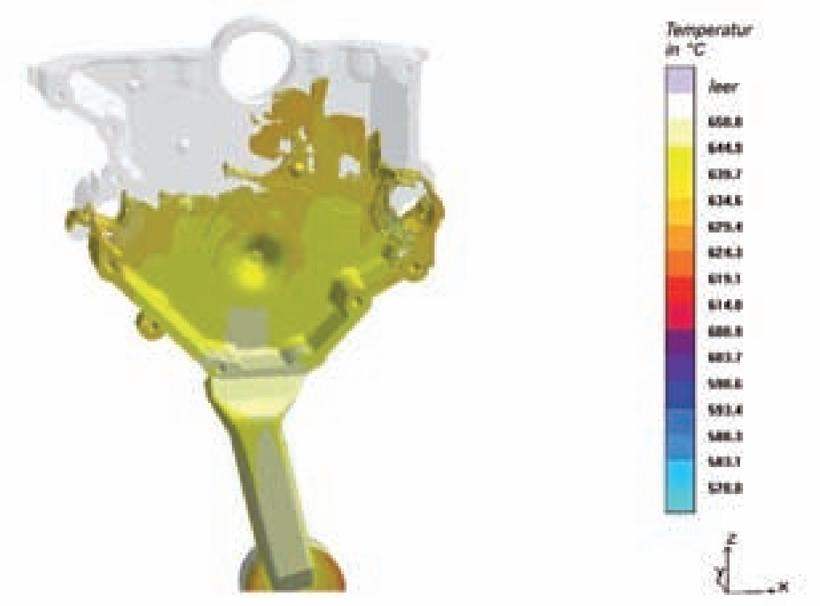
Schematic illustrating the design optimization process with MAGMAfrontier [2].

- Layout of cooling lines to reduce the solidification time of the runner or to reduce cycle times.

In practice, even though the tooling design takes many of these targets into consideration in a qualitative sense, it is necessary to focus on a few primary goals in the optimization process. This means that this type of optimization often ends once the primary issues have been satisfactorily solved. Improvements in those areas that have not been adequately addressed can only be reached through process optimization in production or have to be considered in the design of a successor tool.

Simulation-based autonomous casting optimization supports this approach and has the potential to systematically consider and pursue many of these objectives simultaneously, even though they are often in conflict with one another. The key advantage of this procedure is that quantitative information about the effects of variations of the manufacturing conditions is provided, which may also be used to carry out sensitivity studies. In this way, the expert also learns from the optimization results and can use this knowledge for future components. This will be illustrated in the following example.

Figure 4



Die filling behavior in the single cavity die – a successful filling of the head cap is achieved through a specially designed gate and a slightly slanted runner.

Transfer of the filling characteristics from a single cavity to multiple cavities

The manufacture of a head cap with a single-cavity die had shown that the quality of the resulting component was mainly dependent on the form of the runner and ingate. The high level of quality of castings from the single-cavity die used in production resulted from the use of a slightly slanted runner and a specially designed gate, which were designed using practical experience over several iterations **(Figure 4)**. For this reason, it was especially desirable to try to reproduce the filling pattern from the single-cavity as closely as possible in both impressions of a two-cavity die.

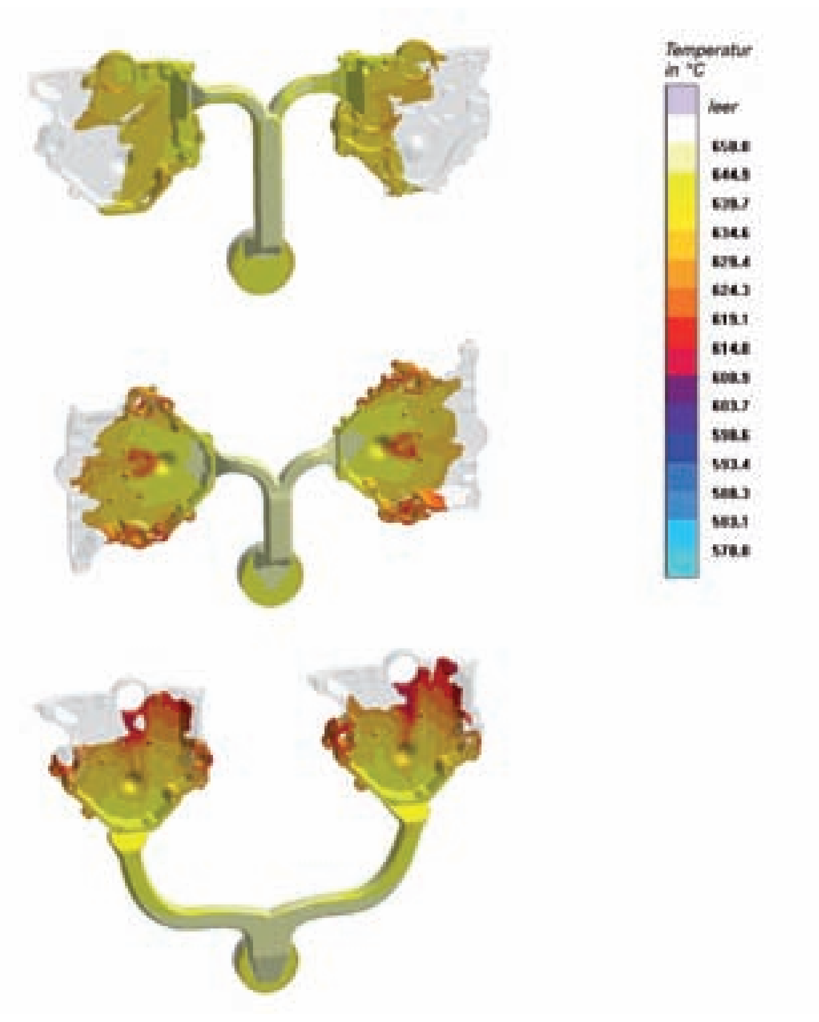
The conversion from a single cavity to a two cavity die, however, required a modified runner design. A study carried out to examine various casting orientations and differently designed runner systems **(Figure 5)** shows varying filling patterns for each cavity. This is due to the different flow lengths of the melt and/or the orientation of the metal stream when leaving the gate. Thus, each cavity has its own unique filling characteristic. The filling of the individual cavities does not correspond to the filling process of the single-cavity die.

In order to achieve a consistent casting quality, however, a homogeneous filling behavior in both cavities is crucial and it should correspond to the filling characteristics of the single cavity die. To achieve this, autonomous optimization was used to design a runner and gating system for a two-cavity die that reproduced the filling pattern from the single-cavity die. To start, the filling behavior in the single cavity was characterized by a precise analysis of the current production process and subsequent casting process simulation.

To characterize the die filling process, information about melt speed and direction was gathered and assessed in three adjacent evaluation areas defined in the simulation model at the end of the runner (marked in green in **Figure 6**). These characterizing parameters could later be used at the same locations as quality criteria for the autonomous optimization of the runner geometry for the two-cavity die. In mathematical terms, the objective was to minimize the deviations of the melt speed and direction at the end of the runner ascertained from the single cavity to those in both impressions of the two cavity die.

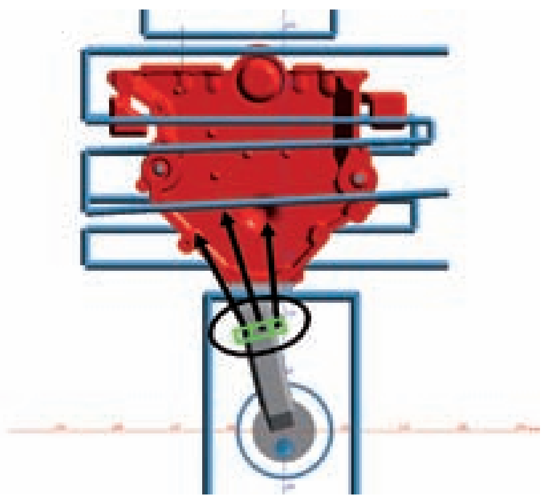
In the two-cavity die, both cavities were placed next to each other in the same orientation as in the single cavity die. **Figure 7** shows a parameterized section of one of the runners (marked in violet). Above this section, the specially designed gate plus a piece of the adjacent runner are visible, which have

Figure 5



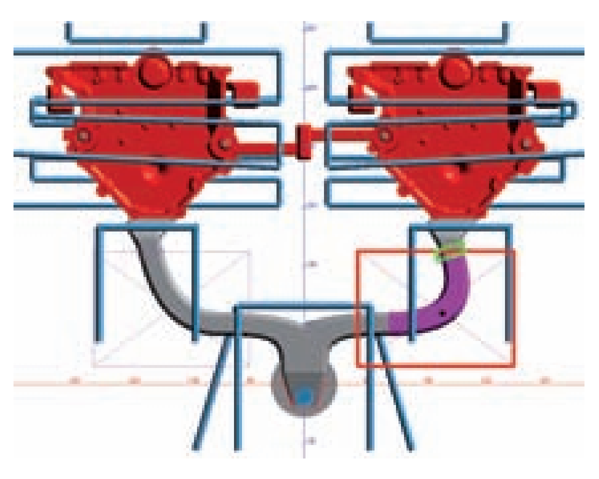
Comparison of various layouts for a two-cavity die with regards to the filling behavior.

Figure 6



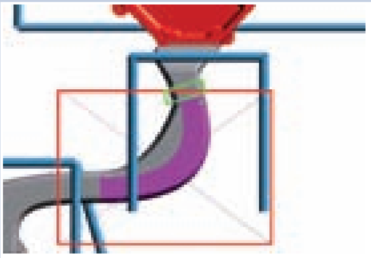
Evaluation of characteristics of the filling behavior of the single cavity die using three evaluation areas (green).

Figure 7



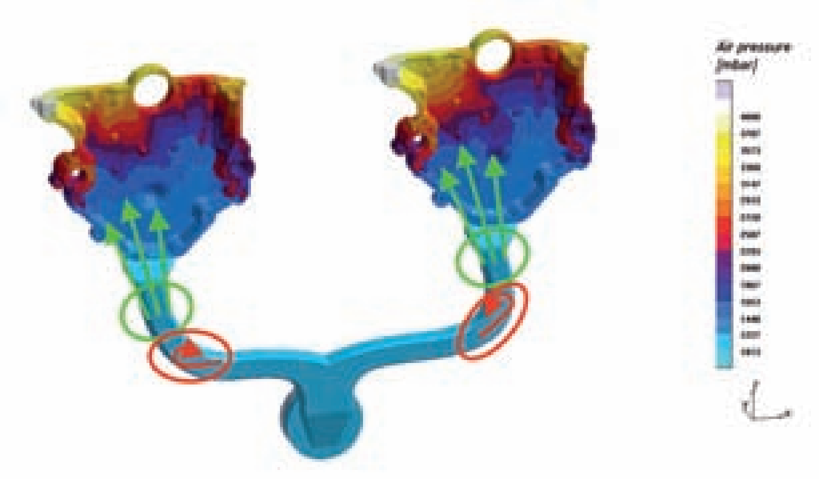
Geometry of the two-cavity die with a parameterized runner section (violet), evaluation area for the determination of melt separation from the die wall (red), and evaluation areas for the analysis of melt velocities and directions (green).

Figure 8



The shape of the parameterized section of the runner can be modified with the help of two independent and two dependent parameters. To illustrate the effect of parameterization, two different runner variations are shown on top of each other.

Figure 9



Optimization targets for the runner design. The values for velocity and flow direction taken from the single cavity (green) constitute the optimization targets for the two-cavity die; a third criterion minimizes the separation of melt from the die wall in the runner (red), which is related to recirculation of the melt.

been taken directly from the end of the single-cavity runner and used for both impressions in the two-cavity die. This automatically results in different shapes for the two runners from the shot chamber to the gate as well as in differing flow patterns. In an evaluation area (marked in red), separation of the melt from the die wall is monitored in both runners. The evaluation areas where velocities and directions are analyzed are marked in green.

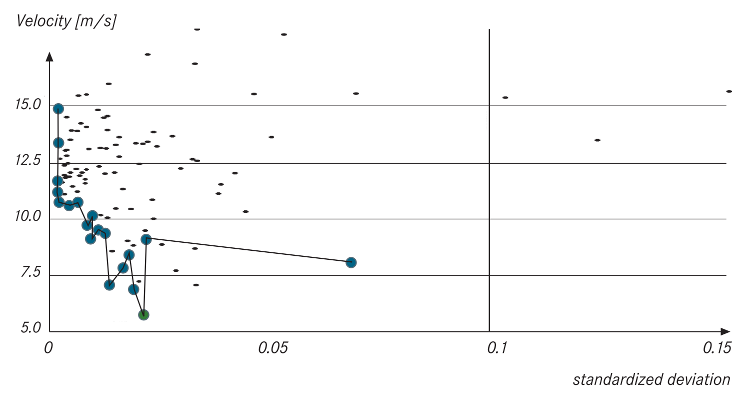
To change the die filling pattern, the runner between the shot chamber and the gate segment was modeled parametrically. Its shape could be significantly modified over a wide range by the optimization program using two independent and two dependent parameters (Figure 8).

Autonomous optimization requires a significant number of individual simulations so that the optimization algorithm can generate new sets of design variables (in this case, runner geometries) with the help of statistical methods. To speed up calculation times, the size of the models should be held to the minimum required for a reliable simulation. In the case of the head cap, an easily recognizable solution was to divide the project into two separate models. In other words, separate optimizations of the left and right runners were carried out. In addition, only the area of the casting closest to the gate was considered in the simulation. This is sufficient for capturing the significant characteristics of the filling of the cavity.

An optimization was carried out for each of the separate models. In each case, the objective in the optimization was to match the melt velocities and directions determined for the single-cavity die. In addition, another quality criterion was used to recognize areas of melt separation or recirculation in the runner. For this purpose, the simulation program provides a special criterion for the identification of areas of entrapped air. The optimization process aimed at minimizing the areas where the criterion showed entrapped air (Figure 9) by changing the runner geometry [4, 5].

The results of autonomous optimization runs can be assessed with the help of various evaluation tools. The socalled Pareto set shows those simulations that were better than all others with regards to all of the optimization targets. In this respect, these designs constitute the best compromise in attempting to fulfill each of the optimization objectives. A graphical evaluation shows the relative position of the various designs with respect to the different optimization targets **(Figure 10)**. It can be used to find the best solution amongst the good designs in different situations.

Figure 10



Evaluation of the runner optimization process – Results for two objectives for the optimization of the right-hand runner. The Pareto set (blue dots) is situated in the left-most position and/or at the bottom, because a minimum is aimed at for both optimization targets. For the design marked in green, all optimization targets are met equally well.

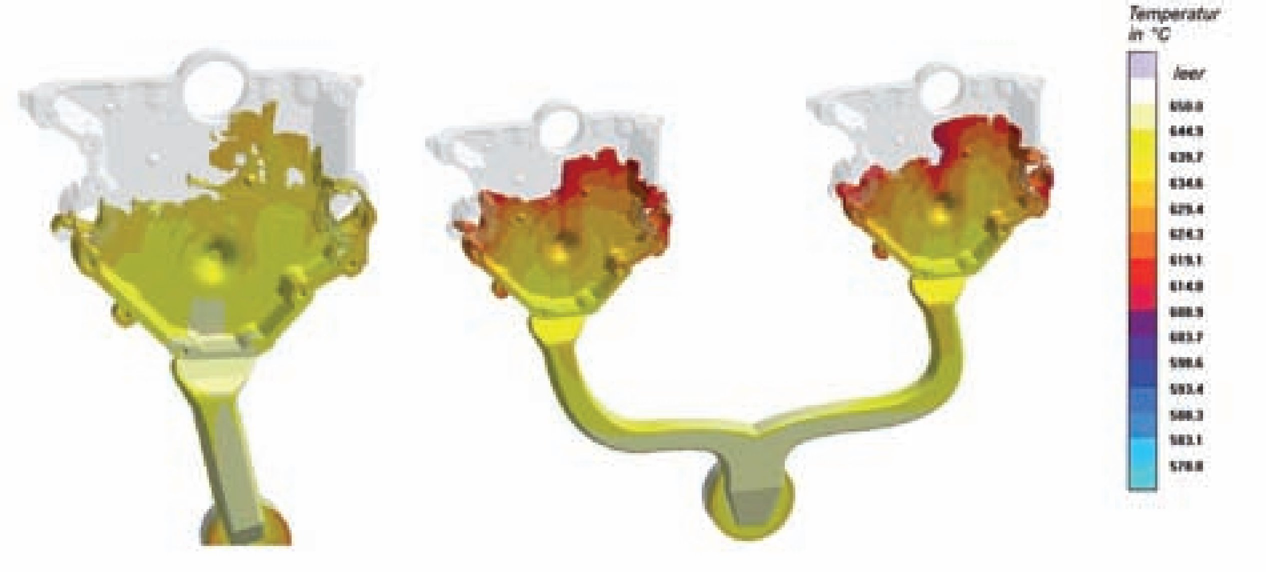
For the right-hand runner, 106 different alternatives were evaluated, and for the left-hand runner, 97 variations were simulated in approx. 39 h and 36 h, respectively. 19 designs which were good compromises between the objectives were found for the right-hand runner, as well as one runner design fulfilling all optimization targets equally well. For the left-hand runner, 14 designs with good compromises between objectives and two designs where the optimization criteria are met equally well were determined. All simulations were carried out on a commercially available two-processor workstation.

The complete model of the head cap die was obtained by combining the two runner designs selected from the optimization of the left and right runners. A final simulation of the complete model was carried out to verify the optimization results, because interactions can occur when the runner geometries are substantially different. The aim was to confirm that a separate optimization of the two runner sections is possible.

The simulation of the entire system shows a filling pattern comparable to the single cavity for both impressions in the two-cavity die **(Figure 11)**. It clearly shows the asymmetric runner design which resulted solely from the optimization calculations.

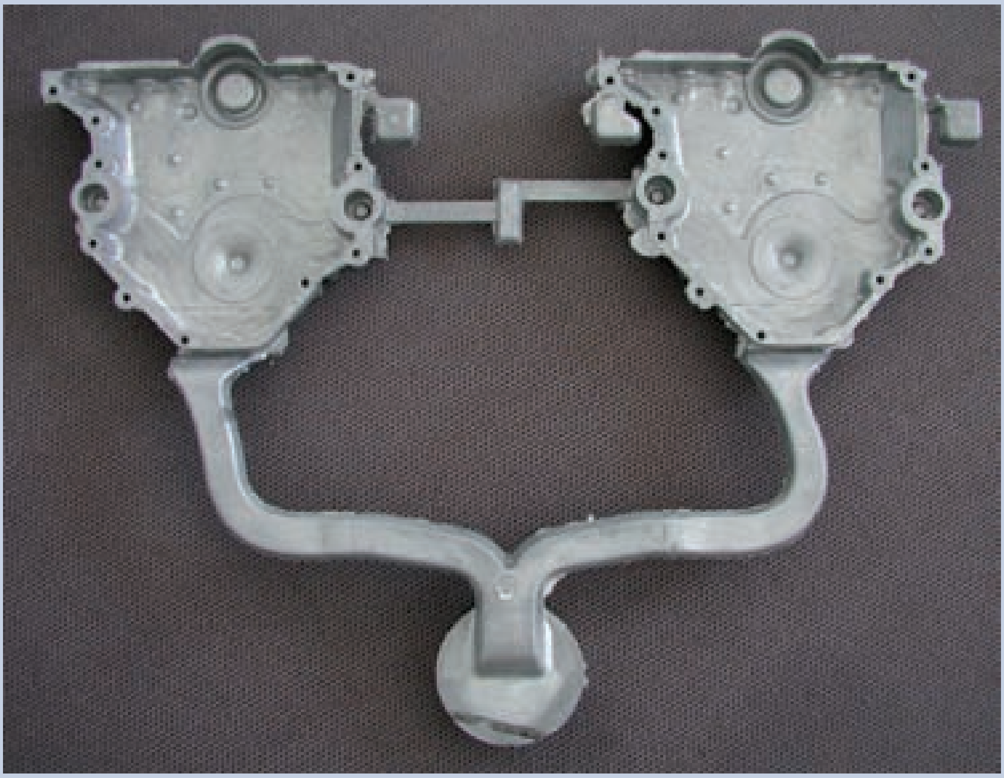
The runner design was put into practice **(Figure 12)**. From the very beginning, the castings manufactured with the two-cavity die showed the excellent quality of the single-cavity components.

Figure 11



The runner system geometry realized in the two-cavity die leads to a flow pattern that is almost identical to that in the single-cavity.

Figure 12



Implementation of the optimized runner for a two-cavity die – the runners selected with the mathematical model were used.

Practical experiences

The method described here for the conversion from a single cavity to a multiple-cavity die was implemented successfully in the die casting foundry of Ford-Werke GmbH, Cologne, Germany. Although a pilot project, a suitable tool design and significant cost savings were reached in a single step with the help of autonomous optimization. The time required for the entire optimization process was approximately two weeks. This is significantly lower than the time required for any other kind of modifications or casting trials which are state-of-the-art today. Time-consuming, iterative fine-tuning of the head cap gate and runner geometries was not necessary due to the precise simulation results, so that the start-up phase was much shorter compared to the single cavity die. There were no costs at all for modifications to the tooling. The high level of quality present with the single cavity die was reached with the two-cavity die. This objective was achieved by the successful transfer of the filling characteristics present in the single-cavity die using autonomous optimization, and the quality could even be improved by combined further measures. Risks in production were avoided by using casting process simulation.

Conclusion

The competitive situation continuously forces foundries to reduce their costs. The highest degree of cost savings can be achieved by increasing the number of castings produced per die. Developing a new layout with conventional methods, however, the risks in production also increase. If a reliable casting layout is already available, the “experiences” gained can be captured by casing process simulation and used as optimization targets for the autonomous optimization of the multiple-cavity layout.

The example of the head cap shows how this innovative methodology can be used to transfer the filling characteristics of a die casting from a single cavity to a two cavity die successfully and without taking any risks. The autonomous optimization of tool design using simulation has emerged to be a powerful tool for the foundry engineer.

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