Published in Casting Plant + Technology, Vol. 19, No. 1, March 2003, P. 8-18,

Simulation in modern quality management systems
- Simulation assists the implementation of quality management systems in foundries

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In order to achieve continuous improvements, controlled processes and close customer-supplier relationships foundries have introduced quality management systems which, in particular, enable implementation of the automobile industry quality requirements. Computer-assisted design techniques (CAE) such as Finite Element Analysis (FEA) and simulation of casting techniques are used as effective and reliable tools in order to achieve reliable and calculable product development and production processes. This article will use a practical example to show how the requirements of the QM Standards can be better realized by means of the use of simulation. In so doing, in addition to reliable quality as a contribution to customer satisfaction, it is also mostly to achieve reductions in costs and increases in productivity.

Construction of quality management systems

Contingent upon additional more extensive customer-specific requirements and recommendations of the automobile industry, own branch standards have been introduced on the basis of DIN EN ISO 9000 to 9004, e.g. VDA 6.1 by the Deutschen Verband der Automobilindustrie e.V. and QS 9000 by the US automobile manufacturers. These recommendations have now been harmonized by ISO/TS 16949. In all these standards and recommendations the quality management systems are classified into so-called QM elements. Important requirements for the product and process development are described in the system elements design control, process planning and process control. The following will show how simulation of the casting technique can assist translation of the requirements into concrete measures.

Importance of simulation for the quality management system

Quality management embraces all parts of the company and accompanies a product through all phases of its development and production **(Figure 1)**. One of the most important requirements in the QM system element is the quality planning. Equipment and tool control is one of the most important points, not only for the process planning but also for the design control up to the finished product. In order to be able to plan tools and processes in parallel with the component development within the framework of the quality planning, all participating departments and suppliers must be involved at the earliest possible time. This is an unavoidable pre-requisite in order to realize the ever shorter model cycles through simultaneous engineering. In order that those development stages can proceed simultaneously it is necessary to obtain early information on the effectiveness of the envisaged process and the component itself. Modern simulation techniques take over this task in the development chain. The overriding principles are the avoidance of defects and constant improvement. Techniques such as the evaluation of producibility and FMEA are used in order to already discover potential defects during the planning phase of the component and avoid them through suitable measures.

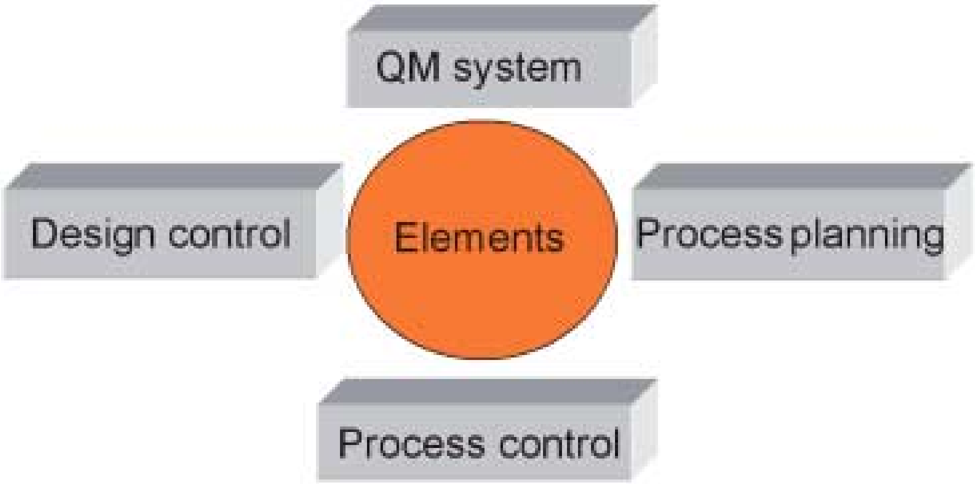


Figure 1: Elements of quality management which contain the requirements and recommendations directly associated with the component development and design of the production process

Simulation-assisted design control

The co-responsibility of the component design for the cost and completion date objectives up to the production of the component is today taken for granted. In order to take over the design responsibility QS 9000 requires special skills such as CAD/CAE, FEA and the use of simulation techniques as well as processes, with which problem areas can be recognized in good time. This means that in addition to the planning of the component function, allowances should also be made for production requirements.

After completion of a design, potential defects are looked for with the aid of design – FMEA. Here, simulation of the casting technique finds its first application. The initial component design is investigated for weak points through calculation of the mold filling, solidification and internal stresses. These can not only be responsible for the origination of various casting defects which influence the function of the part but also cause internal stresses in the casting that can lead to the formation of cracks during production. The calculated internal stresses can flow into the subsequent FE analyses as a pre-stressing factor. During progression of the design, further more detailed simulations enable discovery of newly occurring weak points and the investigation of optimization concepts with regard to their effectiveness, above all also with design changes shortly before the start of and during series production. Modifications to the component with tools already under construction or those already produced can be investigated with regard to their effect on the production process before realization. Tools must not be modified at high cost or prolongation of the development time without knowing whether the modification will achieve the desired optimization.

The following concrete example of a cast motorcycle wheel shows the contribution of simulation in modern quality management systems. Starting from the initial design **(Figure 2)** the first casting and stress simulations were carried out for the cast wheel.

As with the pouring system and the mold the wheel was designed in 3-D-CAD. The first simulation was carried out with casting parameters that were assumed on the basis of values from practical experience. The material is a GK-AlSi7Mg alloy.

Figure 2: Initial design of the motorcycle wheel

Simulation of the mold filling and solidification reveals problem areas in the hub region, namely, a pronounced heat center in the hub caused by accumulation of material. The longest solidification time (5.5 min) is in the hub region, opposed to which the base of the rim already solidifies after 1 min **(Figure 3).** The heat center in the hub is a critical region for feeding. The volume deficit caused by solidification is represented by a feeding criterion **(Figure 4)**; in so doing, allowance is made for the solidification morphology of the alloy with calculation of the magnitude of the volume deficit. These results necessitated modification to the design at the critical positions **(Figure 5)** because it was reckoned that the shrinkage cavity regions would have negative effects on the component function. The solidification time of the hub region could be considerably reduced by design optimization **(Figure 6)**, the regions critical for feeding having become considerably less and smaller **(Figure 7)**.

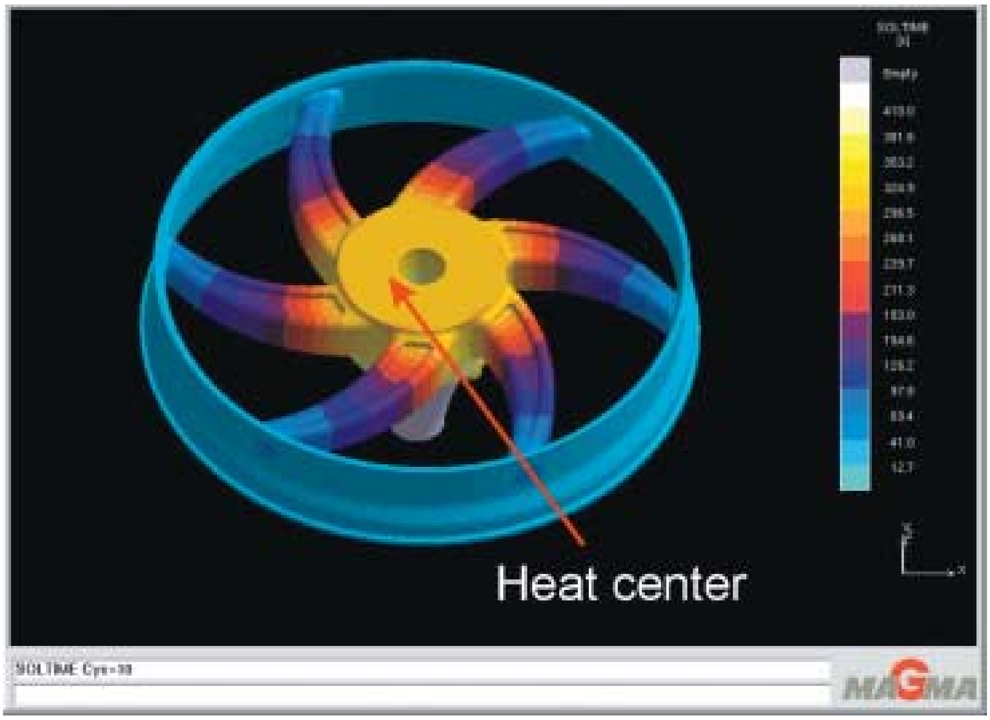


Figure 3: Solidification times within the casting. The longest times of 5.5 min are in the hub region, as against 1 min in the base of the rim

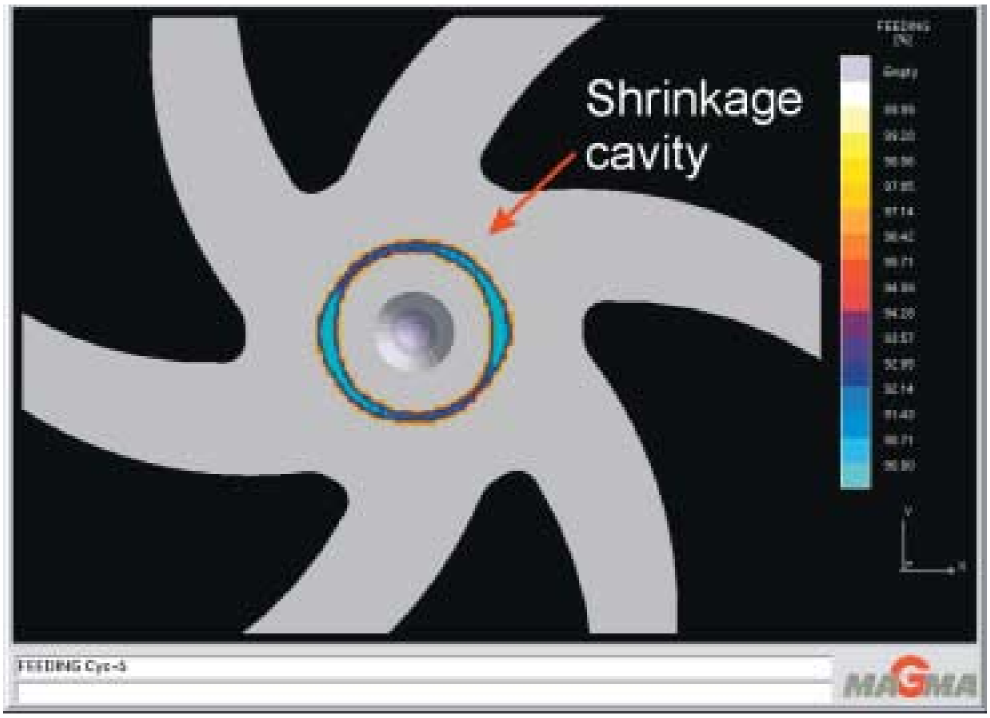


Figure 4: Shrinkage cavities in the hub region. The heat center in the hub is a critical region for feeding. The volumetric deficit caused by solidification is represented by a feeding criterion

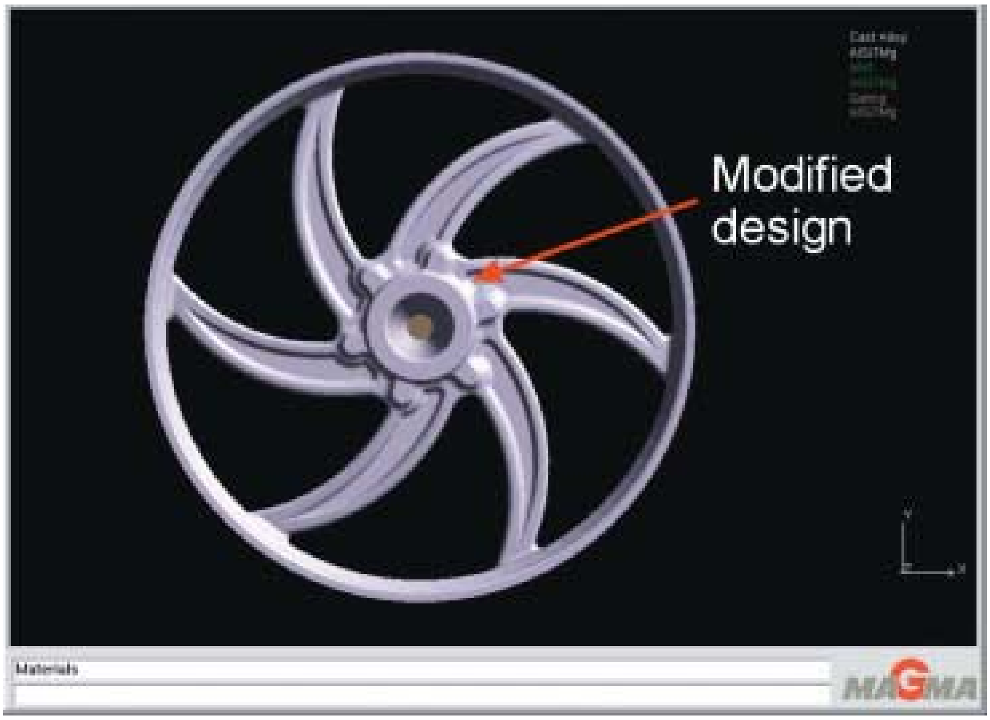


Figure 5: New component design in which the material accumulations in the hub region have been optimized

Figure 6: Substantial reduction of material accumulations has enabled reduction in the solidification times in the hub

Figure 7: Modification of the hub region and the associated change in the solidification behavior resulted in substantial reduction of the shrinkage cavities

During further optimization the internal stresses were calculated, this having been based on the results of the solidification simulation and simulation of the further cooling to ambient temperature. Inhomogeneous temperature distribution in different thicknesses in the casting during solidification and cooling is one of the main causes for the occurrence of internal stresses that would amount to 120 MPa in the cast wheel (effective stress according to von Mises) **(Figure 8).**

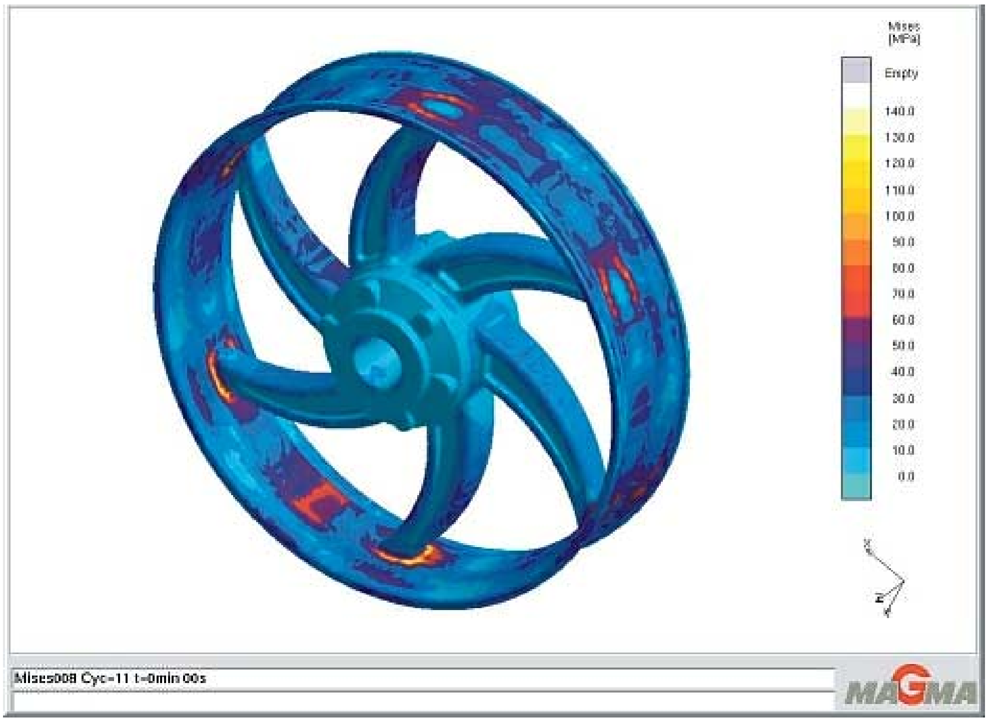


Figure 8: Effective stress according to von Mises: calculation of the internal stresses results in spoke values up to 120 MPa.

The to be expected distortion of the wheel caused by stresses imposed by the spokes on the base of the rim are clear to see through the 40 times enlargement **(Figure 9).** In order to avoid such high stresses the spoke geometry was modified **(Figures 10** and **11),** the new simulation then showing lower stress values **(Figure 12)** and also less deformation in the base of the rim **(Figure 13).** The still remaining stress peaks in the transition from the spokes to the base of the rim can be reduced by a change in the radius **(Figure 14).** Further calculations of the stresses for different load cases with the inclusion of the internal stresses resulted in the fact that it is not possible to reduce the still existing material accumulations on account of the component strength. The hub regions still remaining critical for feeding after the design optimization are counteracted within the framework of the simultaneously occurring process planning through the optimization of the thermal balance of the mold.

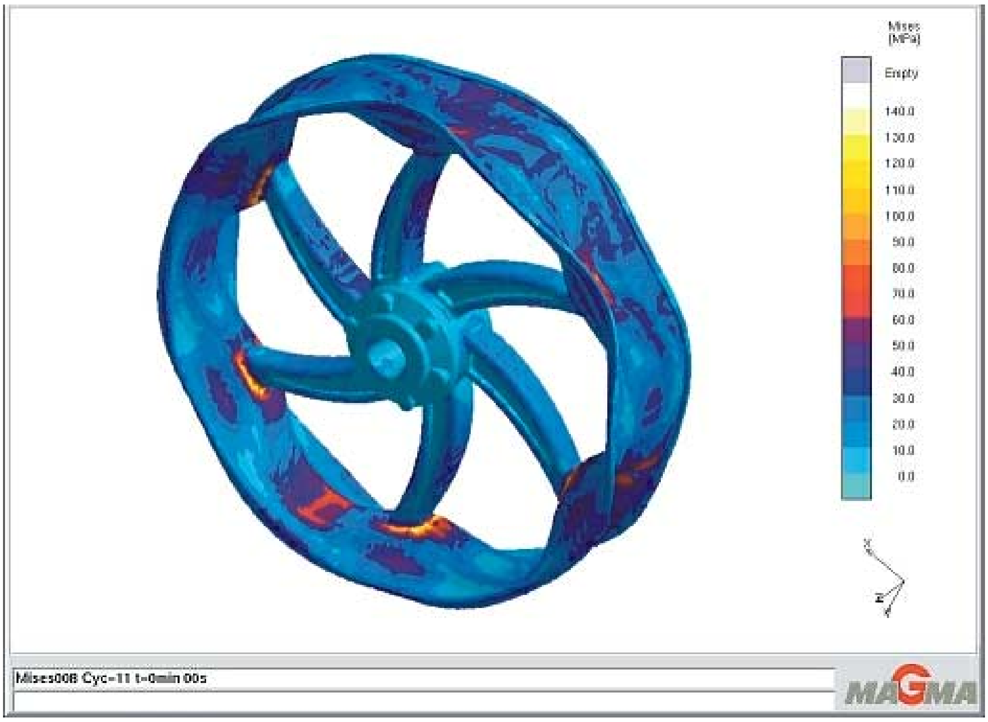


Figure 9: The effects that the internal stresses in the spokes have on the base of the rim are shown by the deformations of the first casting design (40 times enlargement)

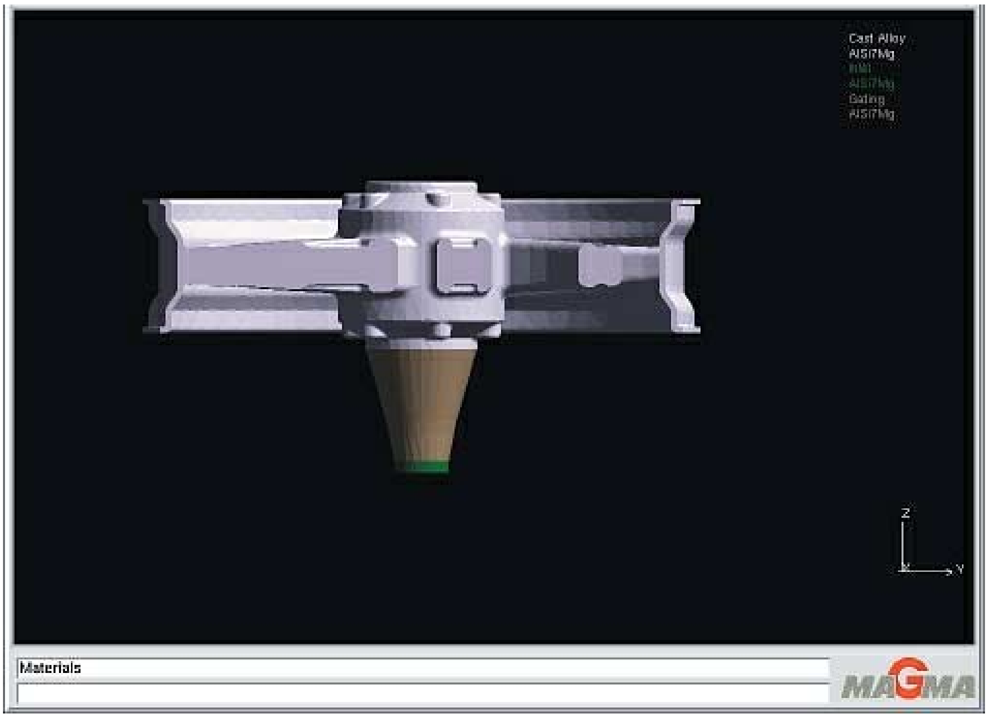


Figure 10: The first component geometry shows pronounced thick walled regions in the spokes

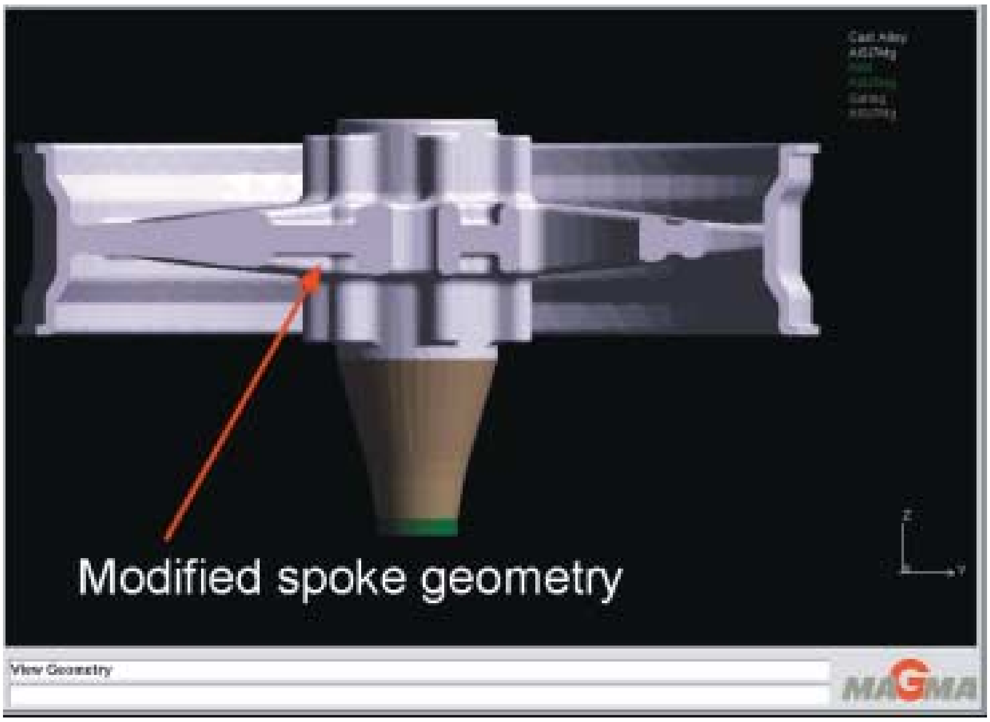


Figure 11: Modification of the spoke geometry has reduced the material accumulations

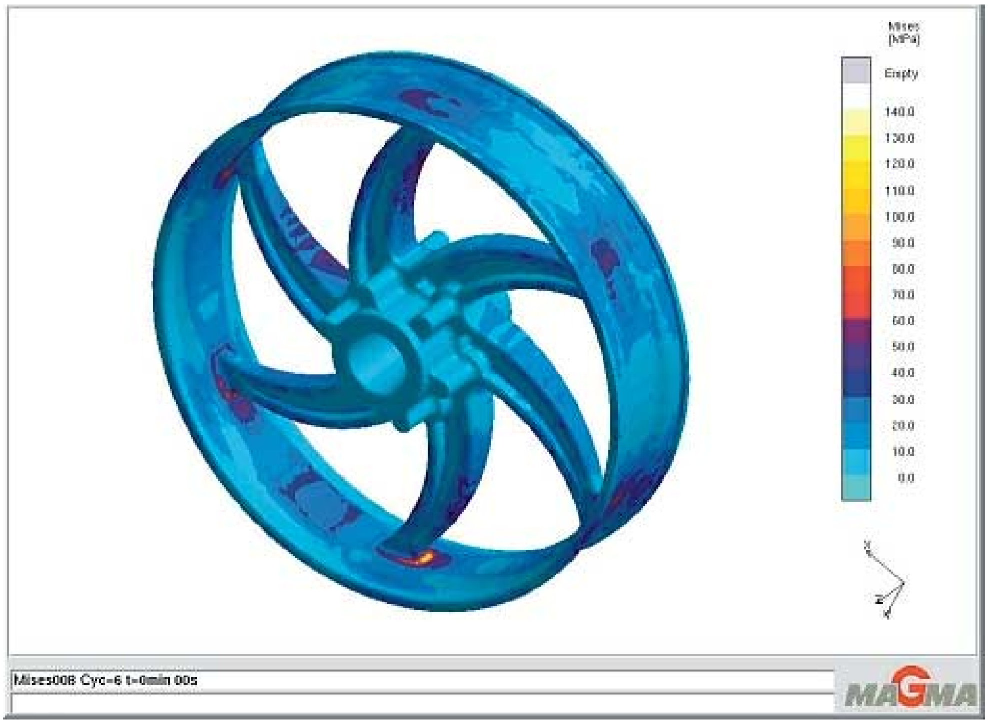


Figure 12: Effective stresses according to von Mises. The internal stresses have been reduced by modification of the spoke geometry

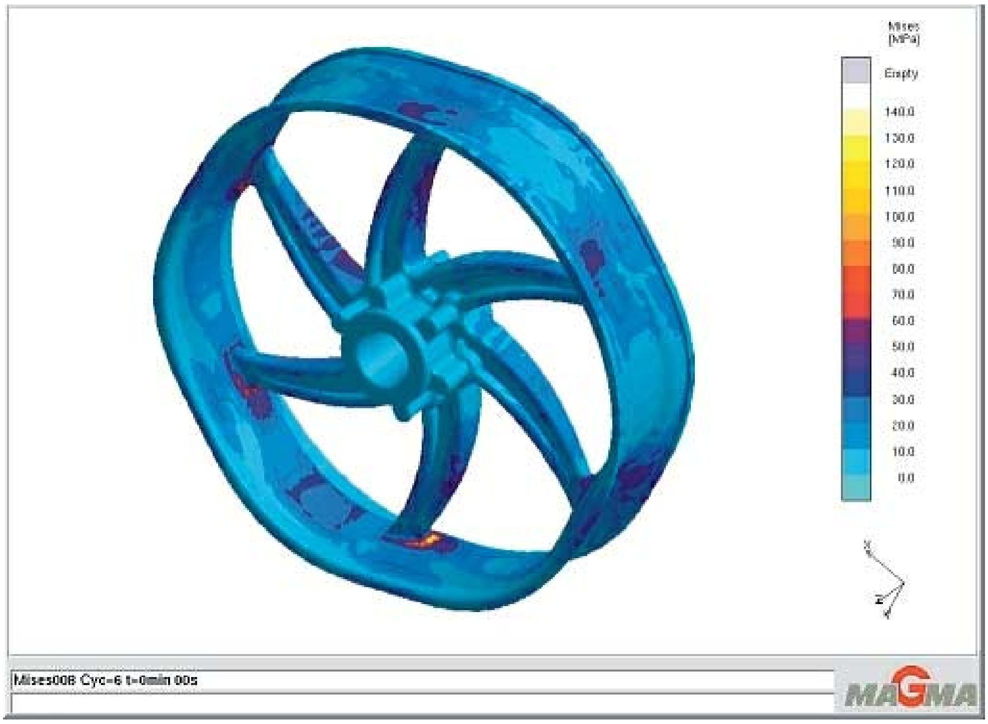


Figure 13: After optimization of the spoke design the distortion is strongly reduced on account of the effect of the internal stresses in the spokes

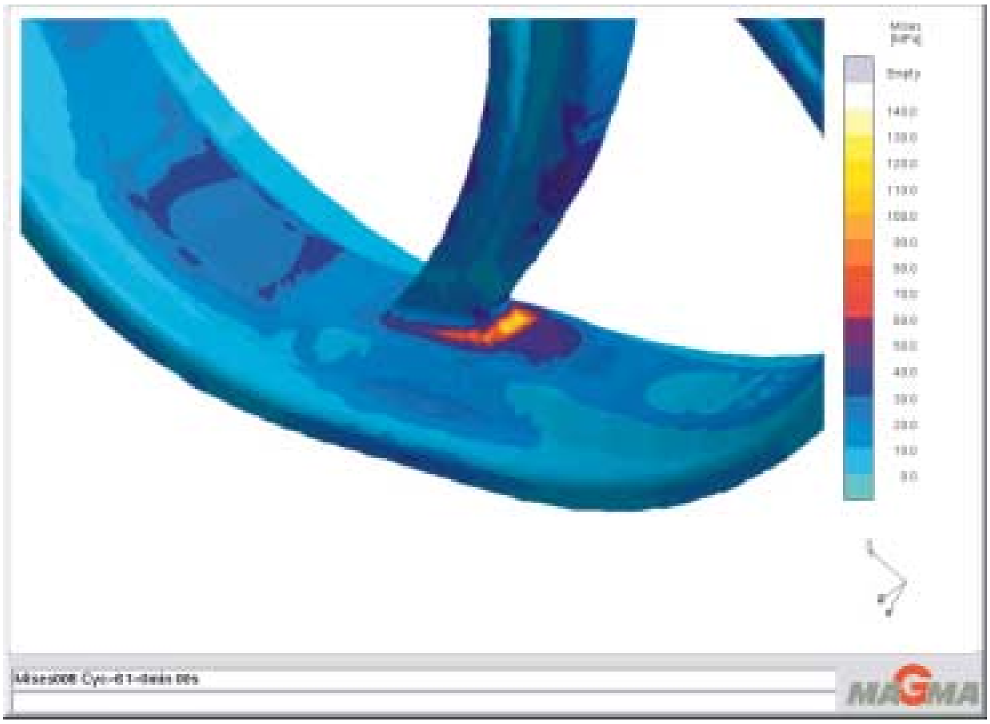


Figure 14: Effective stresses according to von Mises. The still existing stress peaks in the transition from the spokes to the base of the rim can be reduced by a change in radius

Simulation in process planning

The objective of every process planning operation is production of the components with assured and stable results. For this purpose it is necessary to already recognize problem areas by means of suitable methods and to introduce measures for their avoidance. With casting processes with permanent molds the quality of the process is not only dependent on the pouring parameters but also to a considerable extent on the casting tool (die).

The process and tool planning is almost simultaneously carried out with the product development or, if this has already been completed, it must be finished in good time before manufacture of the tool and the detailed design of the process. If the component was not developed by the foundry, it is subjected to an evaluation of its producibility before signing of the contract. At this point the foundry evaluates the results of the simulations already carried out during development of the component and, with the initial fundamental consideration of the tool and casting technique, can carry out a further simulation to ensure the producibility of the casting.

The analysis of the defect possibilities during production is continued with the process-FMEA, the decisive factors being the design of the mold, filling of the mold with the preplanned parameters and solidification of the component in the mold with regard to the quality of the casting. Simulation of the casting technique also here enables an effective analysis. The thermal balance and temperature control are important criteria in the design of the mold. The 3-D-CAD model of the mold is included in the simulation calculations. The temperature distribution in the mold is calculated for the complete casting cycle. This is an important prerequisite for the accurate calculation of the temperature distribution in the melt during mold filling and with the solidification. Different coating thicknesses are allowed for through different temperature-dependent heat transfer coefficients. Tempering of the mold can only be optimized with the information regarding the temperature distribution at various times during the casting cycle. **Figures 15** and **16** show the mold tempering system after the initial design, which was the basis for the simulation of the optimized component design. Cooling of the hub region took place through central point cooling and annular cooling. **Figures 17** and **18** show the temperature distribution of the mold top core at the end of the cycle. The highest temperature is in the hub region.

Figure 15: First tempering system proposal in the bottom core with annular cooling as well as point cooling in the hub region

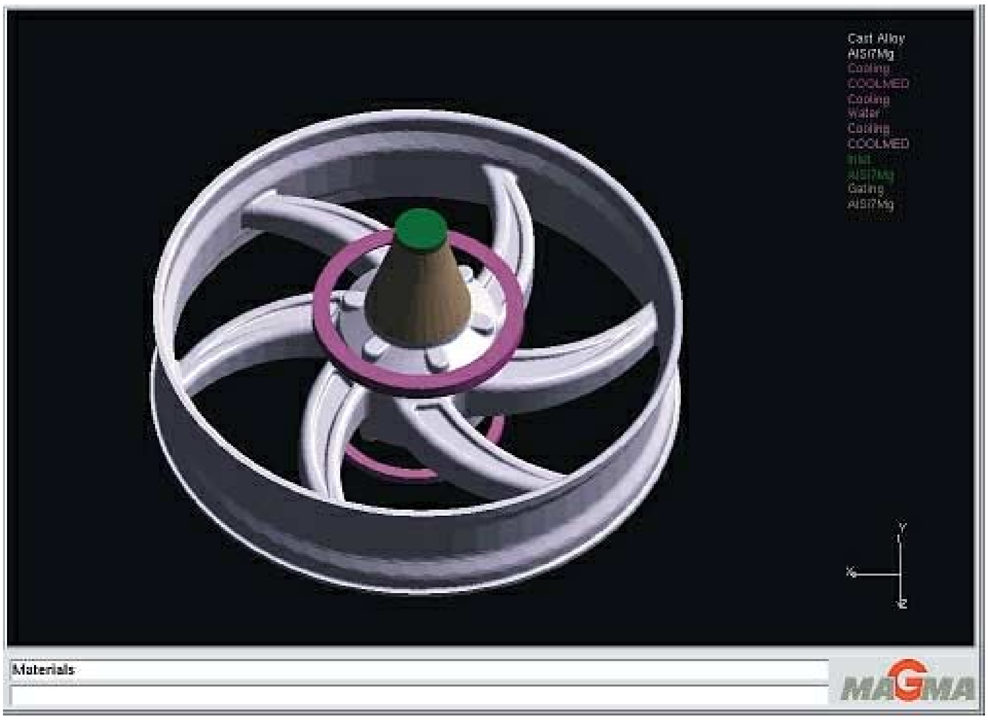


Figure 16: First tempering system proposal in the top core with annular cooling in the gate region

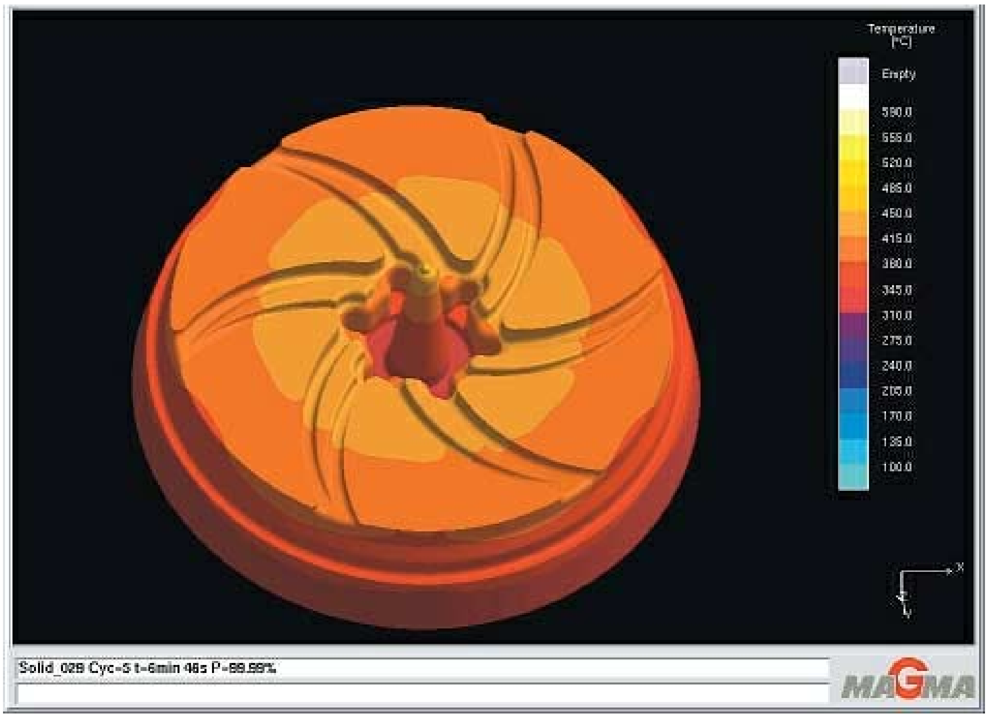


Figure 17: Top core rotated by 180°, temperature distribution at the end of the cycle. The highest temperature is in the hub region.

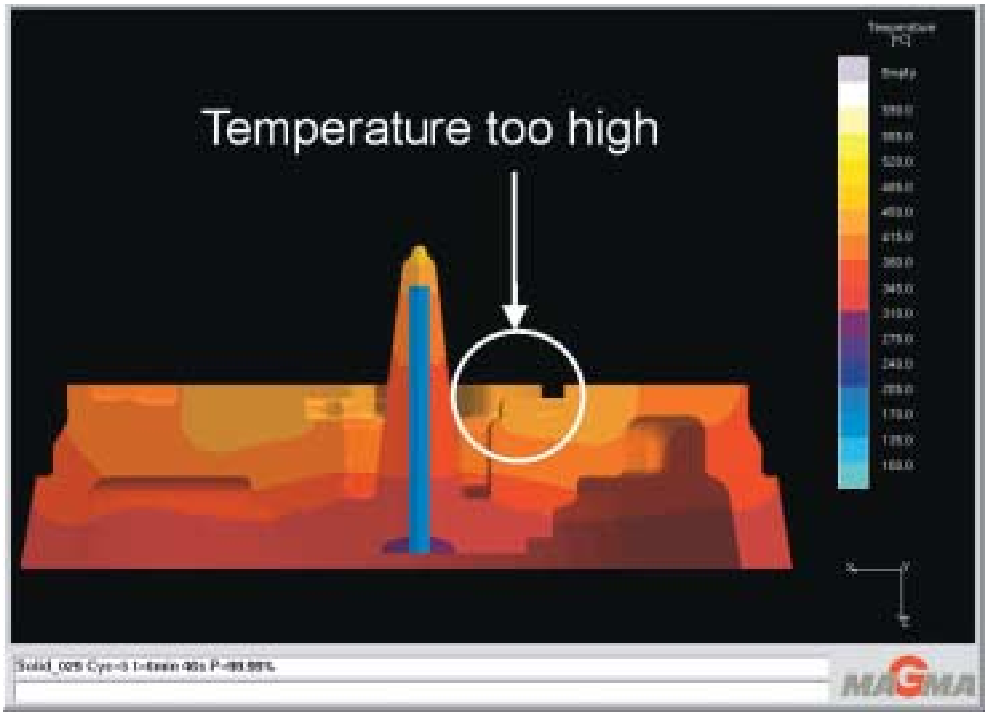


Figure 18: Top core rotated by 180°. The section shows the temperature distribution in the mold at the end of the cycle. The high temperature on the surface continues into the interior

Changing of the cooling should reduce this temperature and thus influence the solidification behaviour of the casting. For this purpose additional point coolings were introduced into the tool model and a further simulation calculation carried out

(Figures 19 and **20).** These measures enabled considerable reduction of the temperature in the hub region **(Figures 21** and **22).** The additional point coolings enable reduction of the mold temperature. The solidification behaviour of the casting is so influenced by this that there is no longer any indication of critical feeding situations in the hub region **(Figure 23).** At the same time, the reduction in the solidification in the hub region results in the possibility of reducing the process time and thus increasing productivity.

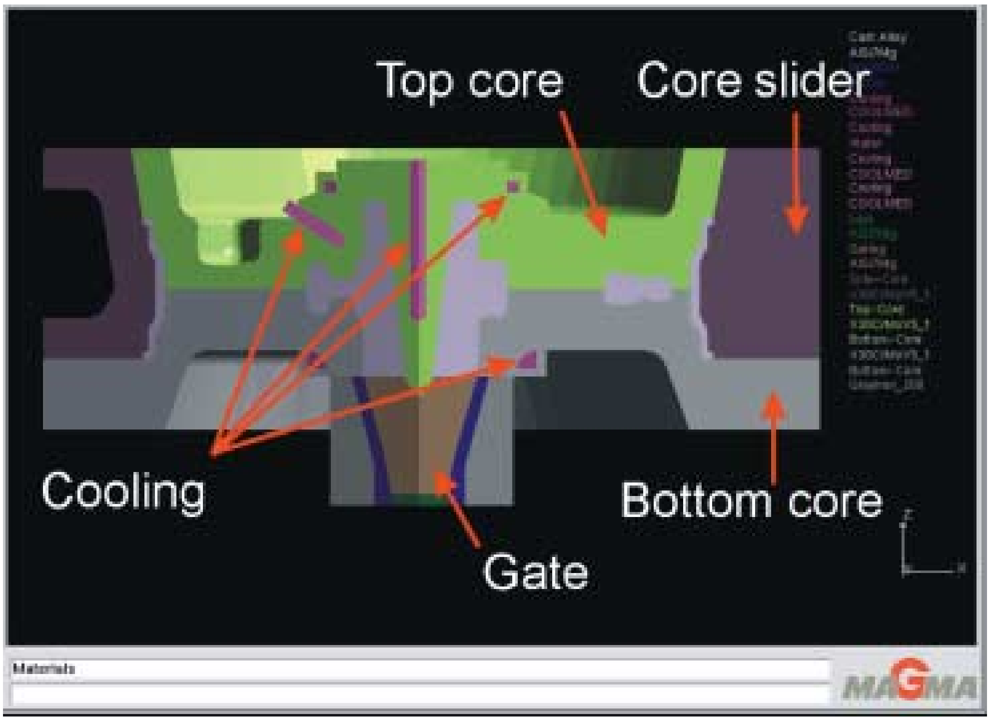


Figure 19: The section through the tool and the casting shows the mold construction with the modified tempering system. Additional point cooling have been introduced

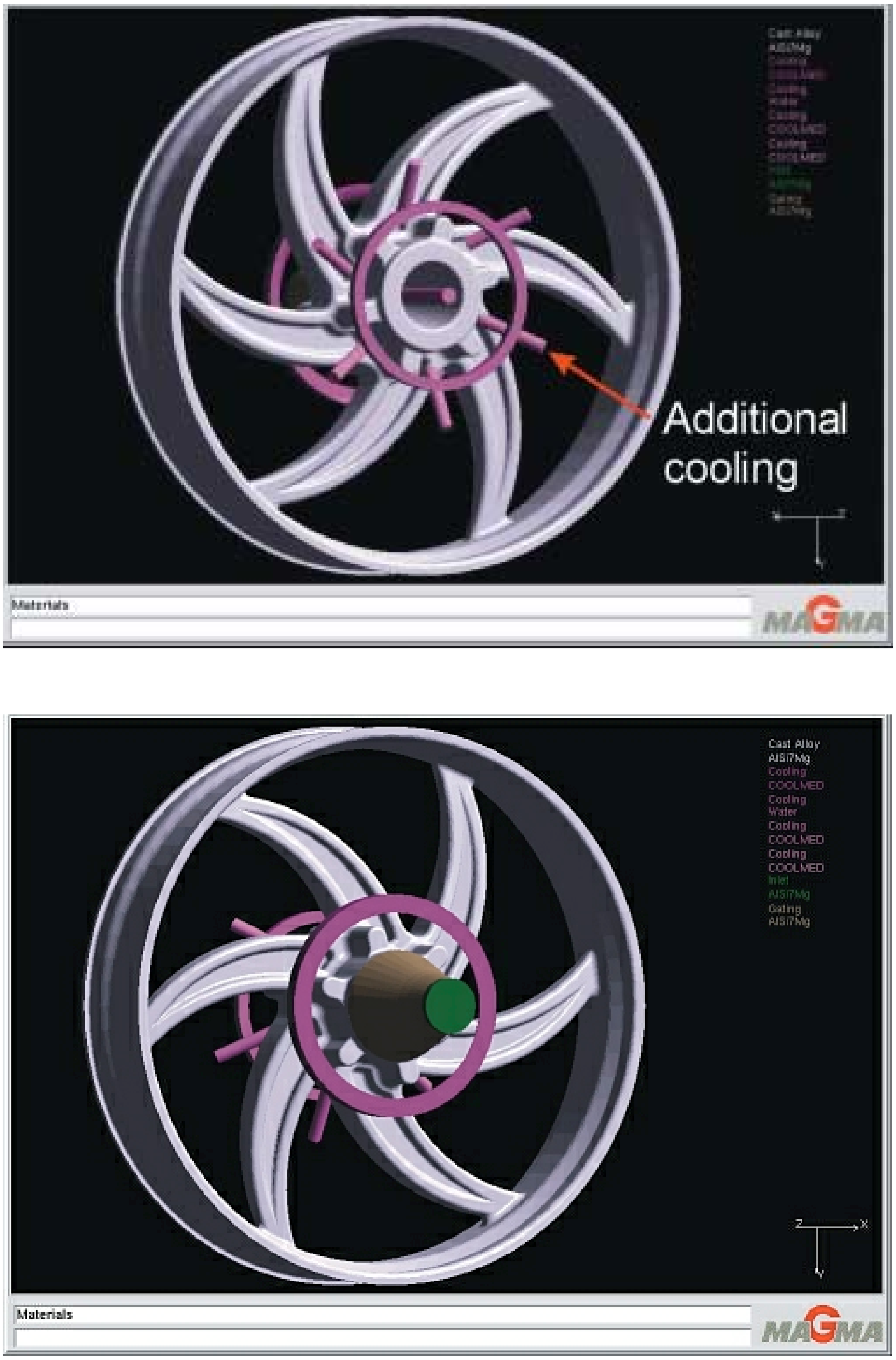


Figure 20: Optimized tempering system with additional point coolings for reduction of the temperature in the hub region in order to influence the solidification behavior

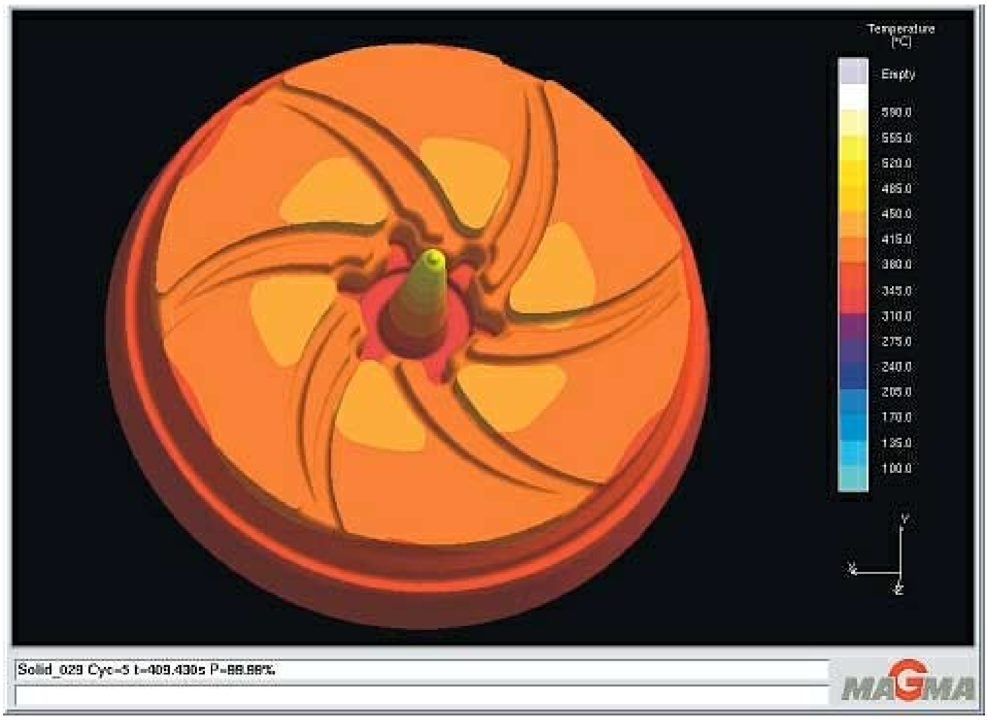
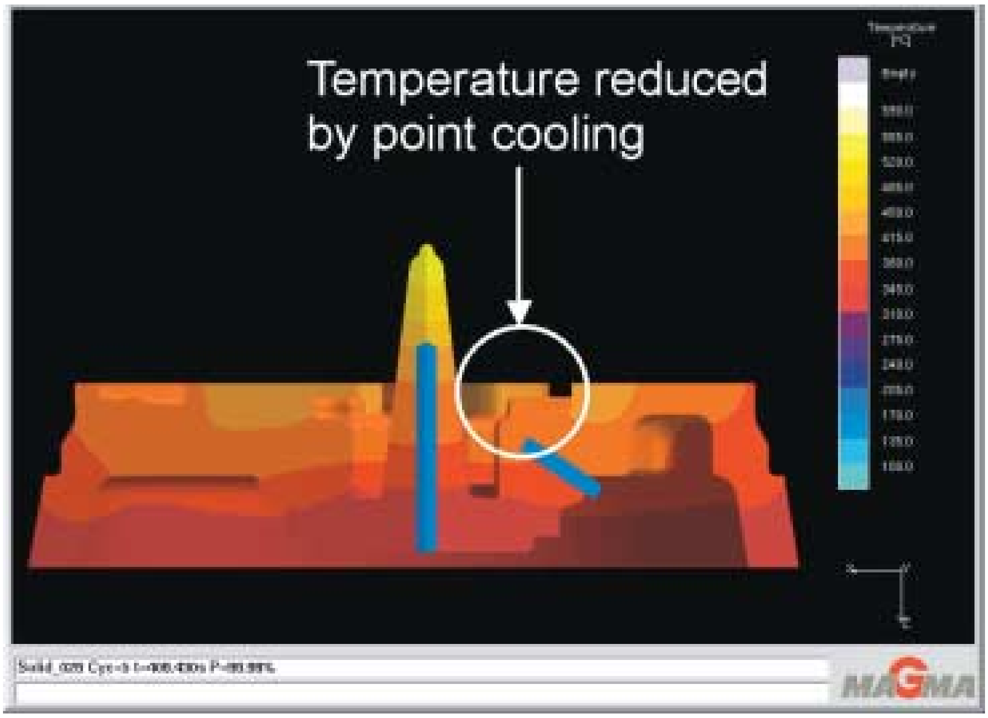


Figure 21: Temperature distribution in the top core after optimization of the cooling with a lower temperature on the surface



Temperature reduced by point cooling

Figure 22: Top core rotated by 180°. The section shows the temperature reduction in the inside of the mold through improved cooling

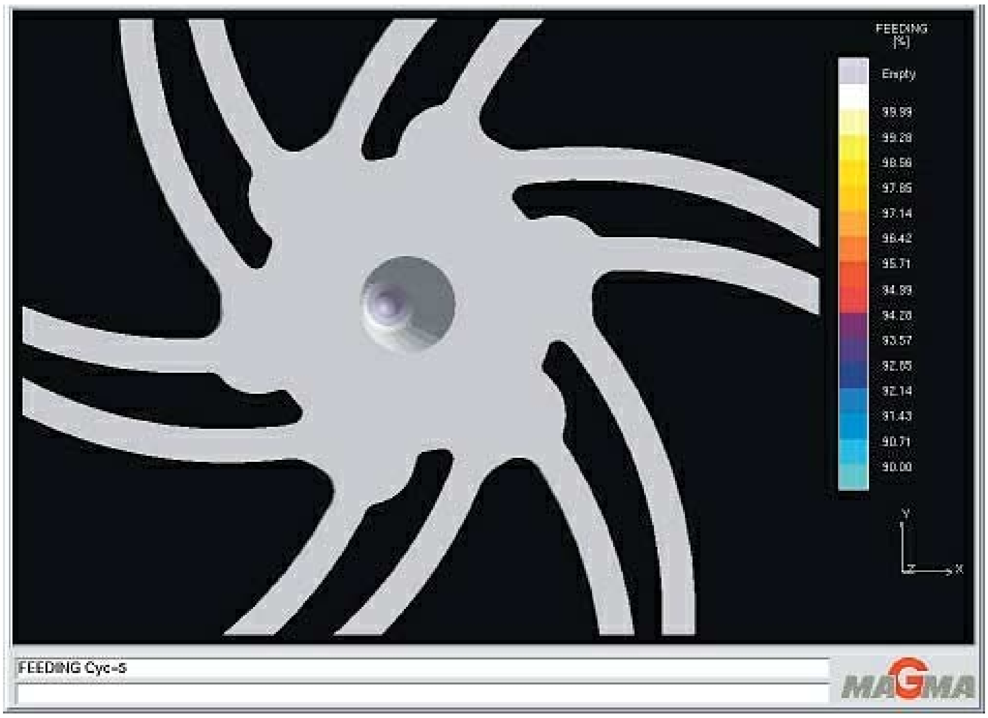


Figure 23: The additional point cooling enabled reduction of the mold temperature. This influenced the solidification behavior of the casting to the extent that there are now no critical feeding conditions in the hub region

Simulation in process control

Process control is aimed at ensuring that production processes operate under controlled conditions. For an effective control of the process the parameters decisive for the quality are already established in the process planning, these having to be controlled and monitored during production. In the example this is shown for the upper and lower limits of the filling rate. Simulation of the mold filling enables investigation of the influence of quality-relevant parameters on the casting process. Calculation of the different variants enables the determination of a process window for these parameters in order to obtain direct prescriptions for the production.

The filling rate of the mold is one of these critical parameters for the cast wheel. During low pressure die casting the melt is subjected to pressure. As in the real process, in the simulation the furnace pressures are represented by a pressure curve and taken into the calculation. The filling rate can be changed by modification of the pressure curve.

In order to maintain a good casting quality the mold should be filled without turbulence in the flowing melt. In the first version of the calculation on the basis of the changed component design, the set pressure curve resulted in fast filling rates. These lead to the collision of melt streams in the rim and non-uniform filling of the base of the rim **(Figure 24).** Changing of the pressure in the furnace results in a slower filling rate and thus better filling in the base of the rim region **(Figure 25).** These settings can be taken over for the upper limit of the mold filling rate. For determination of the lower limit the filling rate was further reduced in the simulation in order to still further „calm down“ the melt flow. However, the temperature during and at the end of the filling must be considered. The filling rate should only be reduced to the extent that during filling the melt temperature does not fall below the liquidus temperature of the alloy. According to **Figure 26** further reduction in the filling rate achieves a very uniform and quiet filling operation, at the end of which the melt temperature in the base of the rim falls below the liquidus temperature. In this figure the solidification interval is represented between the colors red and blue. With a further reduction of the melt temperature it must be reckoned that mold filling will not be complete. Consequently, the two filling rates can be considered to be the production prescription, between which the mold can be filled without turbulence.

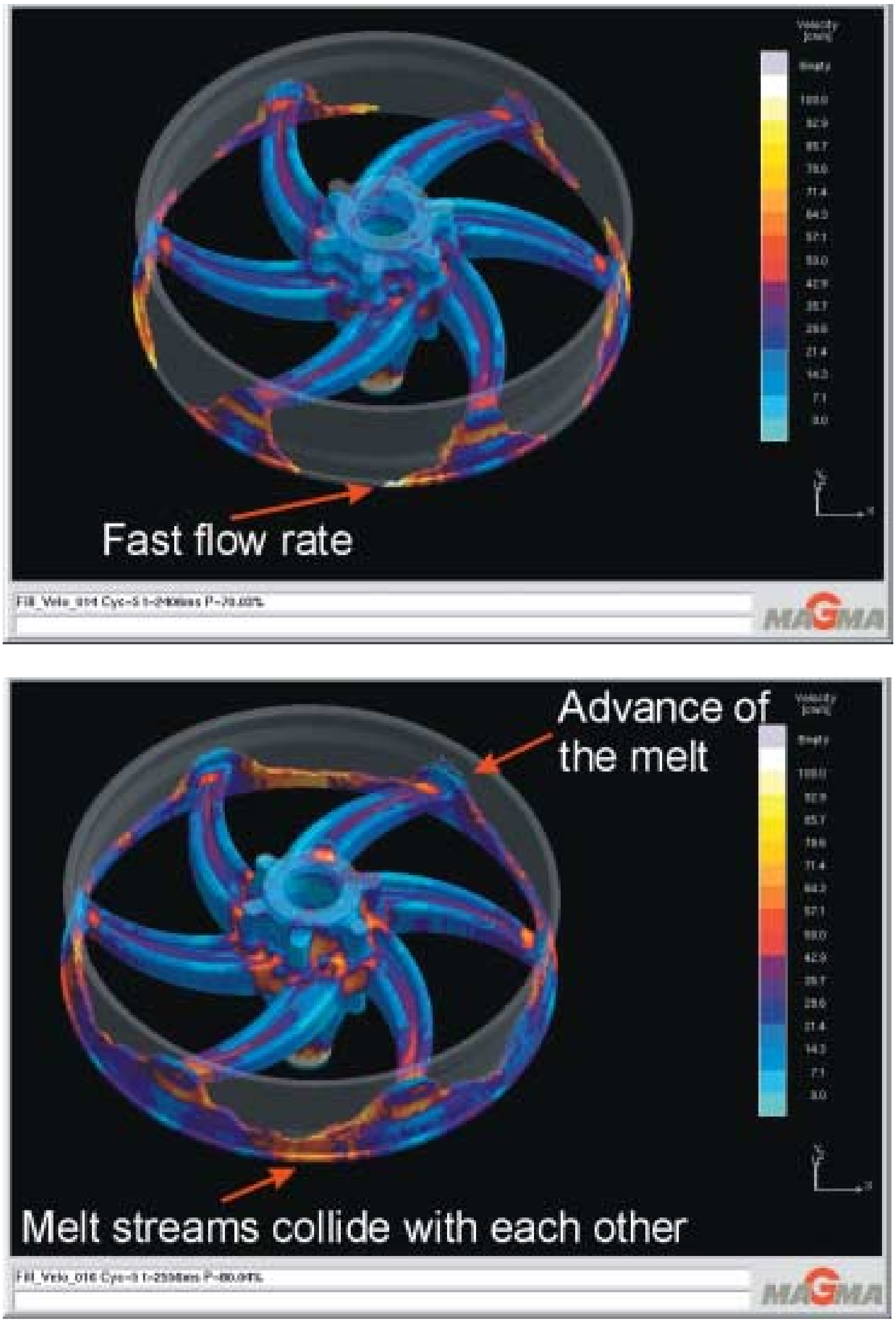
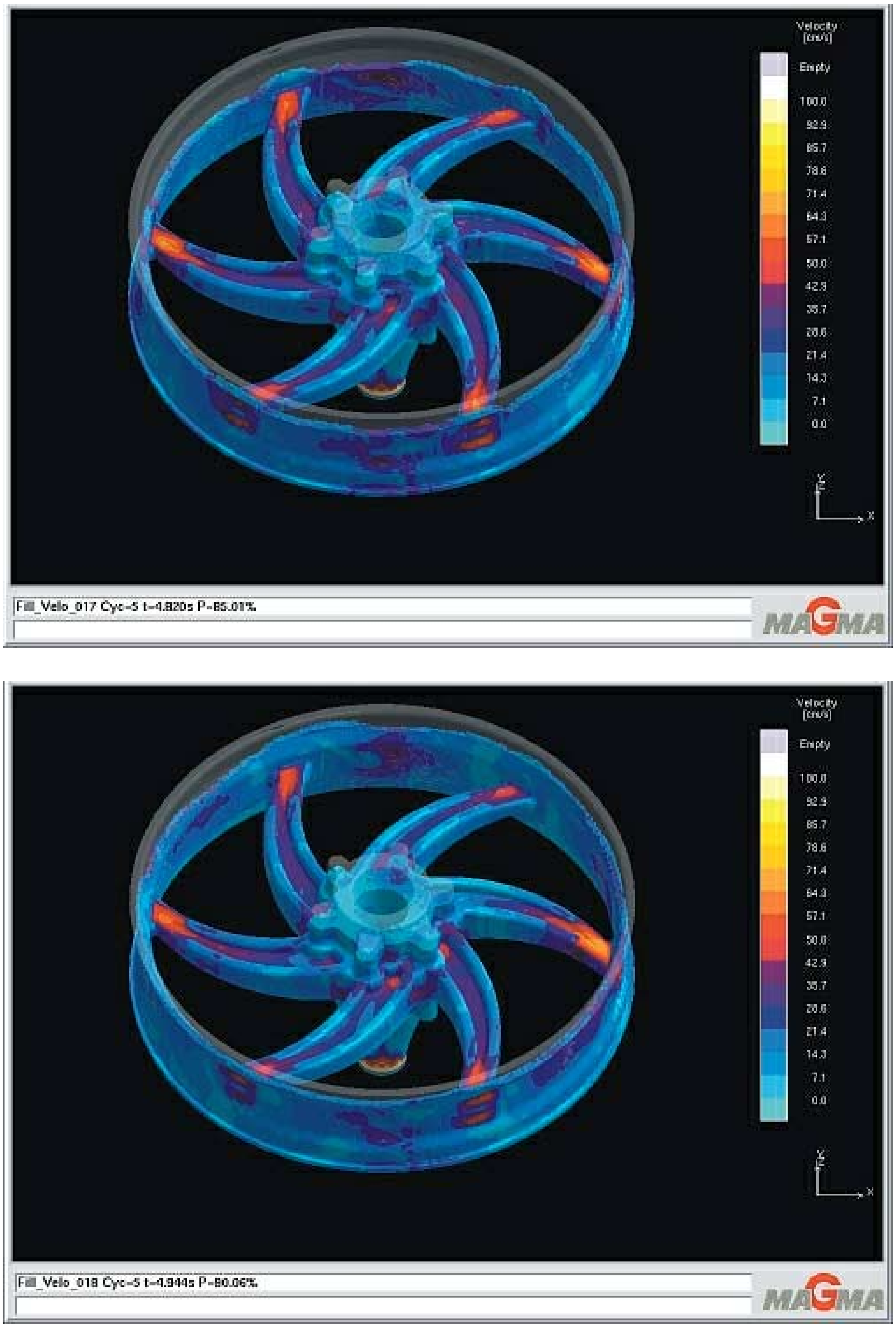


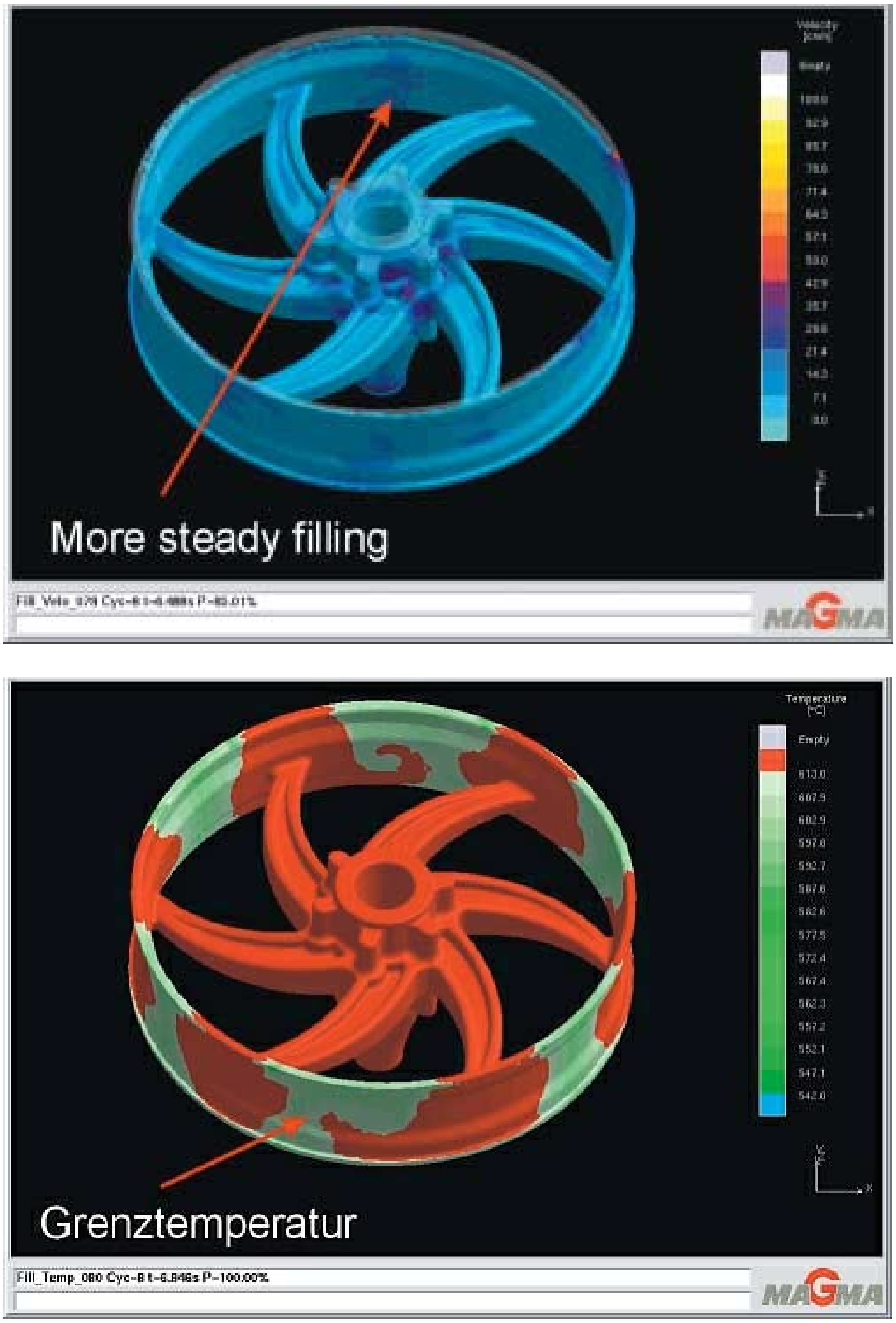
Figure 24: With the process parameter selected for the first simulation the too fast filling rate resulted in non-uniform filling of the base of the rim



Fill_Velo_017 Cyc=5 t=4.820s P=85.01%

Fill_Velo_018 Cyc=5 t=4.944s P=80.06%

Figure 25: Reduction of the mold filling rate by changing the pressure in the furnace led to a „quieter“ melt front and uniform filling of the base of the rim



Fill_Velo_078 Cyc=8 t=6.488s P=80.01%

Fill_Temp_080 Cyc=8 t=6.846s P=100.00%

Figure 26: Further reduction of the filling rate achieved even more „quiet“ filling. It is clear to see the difference between the temperature and the liquidus temperature

Summary

One of the main objectives of the quality management systems established by the automobile industry in QS 9000 and VDA 6.1 is the employment of planning and preventive activities in order to as soon as possible obtain assured information on the optimal design of the castings with regard to their production and the aptitude of the process. The use of timely simulation together with the complete planning process effectively assists the prevention of errors and/or defects. This helps to provide confidence in the ability of the foundry to be able to realize an optimal product.

Simulation of the casting technique is an important part of the CAE technologies integrated in modern QM systems. The example of a motorcycle wheel illustrates how simulation accompanies the development process, starting with the initial design up to the detailed component geometry. Simulation of the first casting design shows up the weak points with regard to casting. Design optimizations are checked for their effectiveness through several simulation loops. At the end of the optimization the casting designer has a component design that is correct for production with optimized cost. The following simulations for the design of the tool and the process provide the tool designer and the foundryman with important knowledge regarding the thermal balance of the mold.

Simulation of the influences of various quality-relevant process parameters enable the establishment of a process window for the foundry. In the early stages of the development process the component designer and the foundryman thus receive important information on the production technique. This procedure shows how effective the simulation technique is as a link between development and production. The degree of integration of simulation in the QM system is important and has to be an obligatory function, so that the simulation results are available in good time for optimization of the design and the process. If these requirements are fulfilled, simulation makes a substantial contribution to customer satisfaction, cost reduction and increased productivity.

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