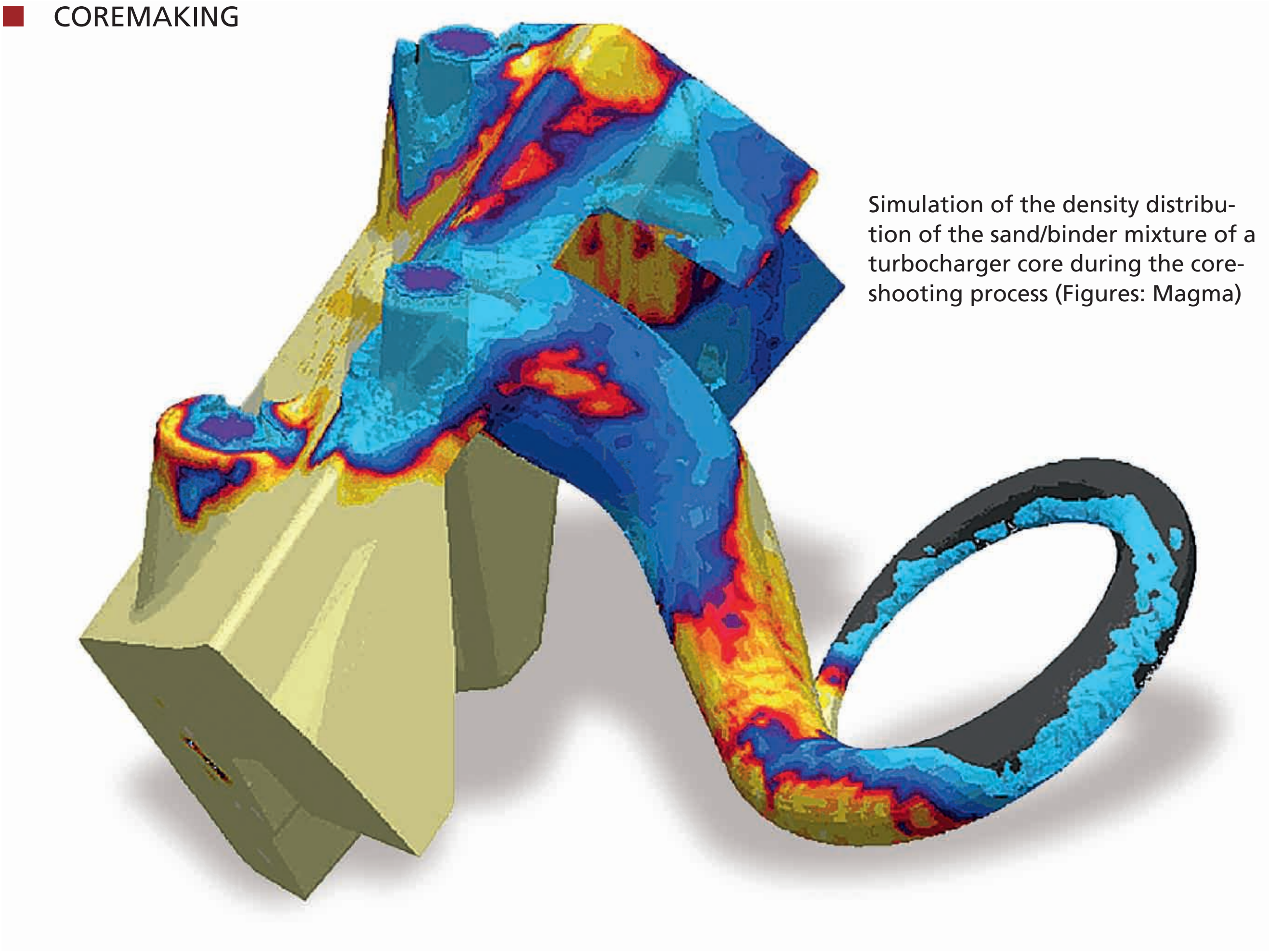

Simulation of the density distribution of the sand/binder mixture of a turbocharger core during the core-shooting process (Figures: Magma)

Authors: Dr. Jörg Sturm and Dr. Ingo Wagner, Foundry Engineer Development, Magma GmbH, Aachen

Practical use of core simulation for process optimization

Simulation of the production of sand cores is a new method for fundamentally changing tool and process design by exploiting insights into core-shooting and hardening processes. Important factors affecting the quality of the core can be determined and quantified in advance of tool production and serial manufacture. The system's physical basis and targeted procedures allow predictions to be made regarding the technical and economic feasibility of sand cores. This not only increases understanding of the processes involved but also opens up opportunities for improving the quality of castings

Core production still has the power to surprise tool- and core-makers. Core-related casting defects are a considerable cost factor in cast part production due to the additional reworking required. The design of core tools takes place on the basis of practical knowledge and through trial and error until a sufficient core quality is produced. Development of a new tool up to serial maturity regularly requires several time- and cost-intensive optimization cycles, including practical testing under serial conditions. Each trial run leads to more or less extensive changes of the tool, without the foundry expert being really sure that the measures will lead to the desired success. He or she only sees the result, and therefore cannot base decisions on a clear cause-and-effect principles that could explain such outcomes.

More than 20 years after the introduction of simulation for the casting process, simulation of sand-core production is a new method for fundamentally changing tool and process design on the basis of insights into core-shooting and hardening processes. The complex interactions during fluidization, trans-

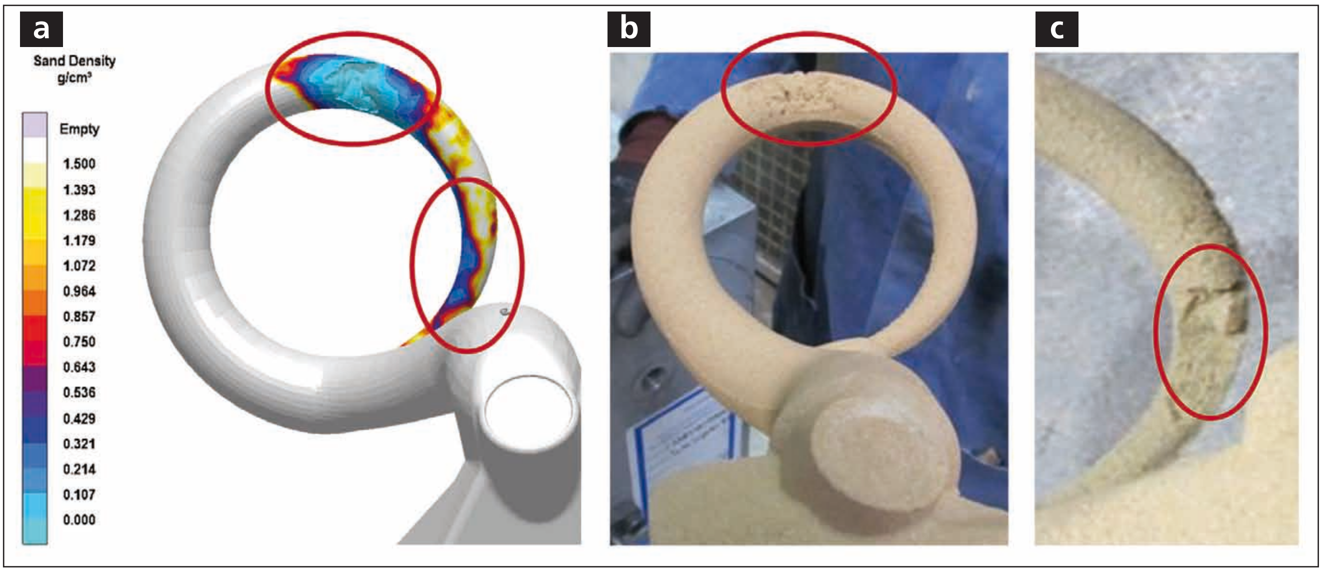

Figure 1: a) Predicted density distribution in the core's volute; b) and c) real flaws in the prototype core for the initial design of the core box [8]

port and the subsequent compaction of a sand/binder mixture in a core box or during the gassing, hardening and drying of a core cannot be determined with the usual "linear" thinking of the technician. Simulation of the core production process allows the important factors affecting core quality to be quantified in advance of tool production and serial manufacture. Core production and the process sequence can already be virtually represented during the planning phase for a cast part. The entire process sequence and the relevant physical values become transparent. This permits a targeted approach based on physical interactions and clear facts. The technical and economic feasibility of sand cores thus become quantifiable. As a result, understanding of the processes involved is also increased and the practical implementation of quality-improving measures simplified. Tool makers also obtain a three-dimensional insight into core production and can more efficiently align the design of the core tool to the demands of serial production.

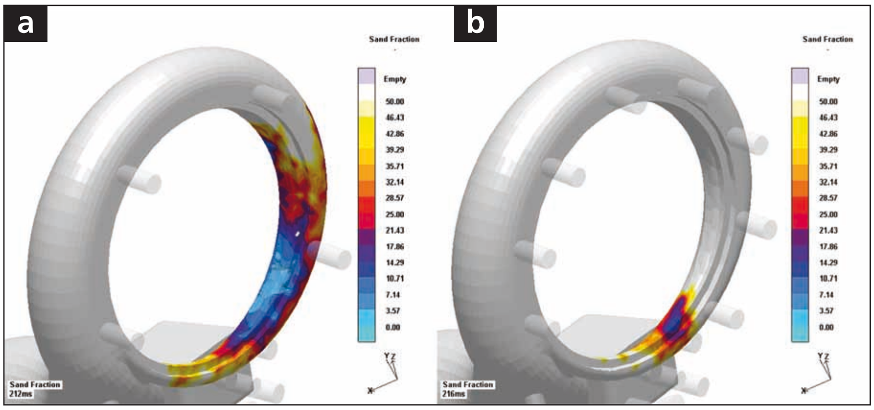

Figure 2: Simulated shooting result for differing venting configurations: a) four vents; b) eight vents

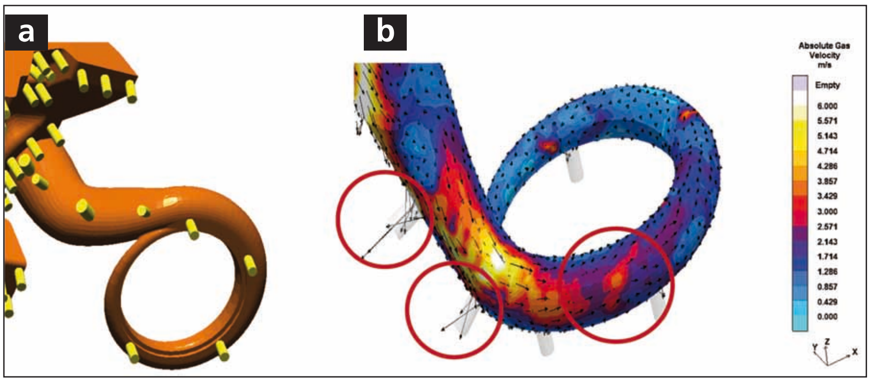

Figure 3: Configuration of the venting nozzles for a) the initial state and b) the flow profile in the air

Modelling core shooting

The modelling of core shooting is an extremely demanding process due to the continuously changing differences in the flows of the air and the sand. The flow process differs from mold filling with molten metal because the local properties of the "fluids" involved are constantly changing. In addition, the interactions between air and sand themselves and with their environment (shooting cylinder, nozzles, and tool) require the technological boundary conditions to be taken into account and specialist knowledge to be integrated [1,2,3].

Various model approaches were compared with one another during program development in order to assist selection of the model. A development partner tested, among other models, a “mixture model” (sand and air are calculated as a mixed phase) in a direct comparison with the solution that has now been adopted [4]. The characteristic dynamism of core shooting, during which the sand and air typically flow in differing directions at very different speeds, could not be satisfactorily physically represented for all application cases using this approach.

Therefore an approach by which an air and sand mixture and a sand and binder mixture were treated as two separate phases was selected for describing the dynamism of air/sand mixtures during core shooting in the simulation program Magma C+M [5, 6, 7]. Whereby, in addition to the dominant momentum transfer between air and sand, the interactions of the grains of sand with one another are also taken into account.

The consideration of equipment parameters such as the type of pressure build-up in the shot cylinder is also a component of process modelling. Shooting nozzles in effect connect the core-shooting machine with the core tool. In practice, a large number of individually designed shooting nozzle geometries are used in core production. Their properties are modelled using pressure loss laws. Nozzles of various sizes and designs are used for venting core boxes. The small nozzle openings retain the core sand in the tool and let the shooting air escape. Experimentally calibrated flow laws ensure realistic modelling of the pressure drop at the venting nozzles.

When simulating core shooting it is necessary to decide, according to the objective, whether the process has to be represented with the relevant units of the core-shooting machine or whether it is sufficient to define suitable boundary conditions at the shooting nozzles. Consideration of the entire machine leads to longer simulation times but is the only way to take into account the filling problems of core tools caused by the machine itself. This also applies for the use of multi-cavity tools, when it is necessary to examine whether all the cores can be equally filled. Consideration of the shooting head is also important when its sand level becomes so low during shooting that it leads to “through shots” at individual nozzles affecting the shooting process.

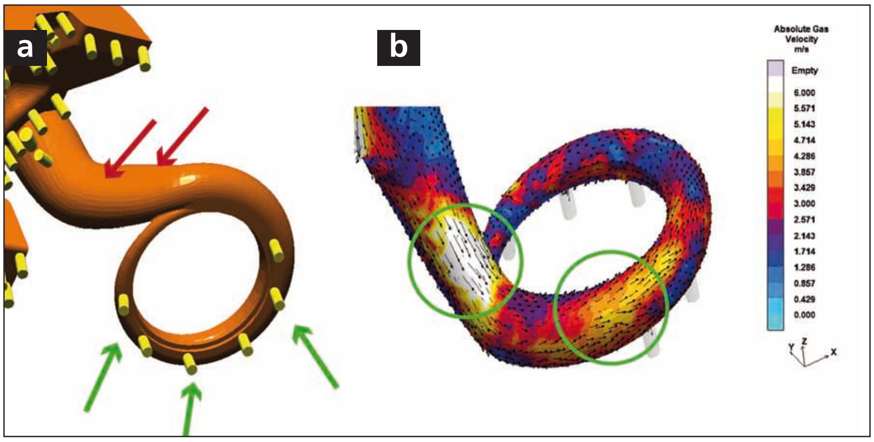

Figure 4: Configuration of the venting nozzles for a) the optimized core tool and b) the improved flow profile in the air

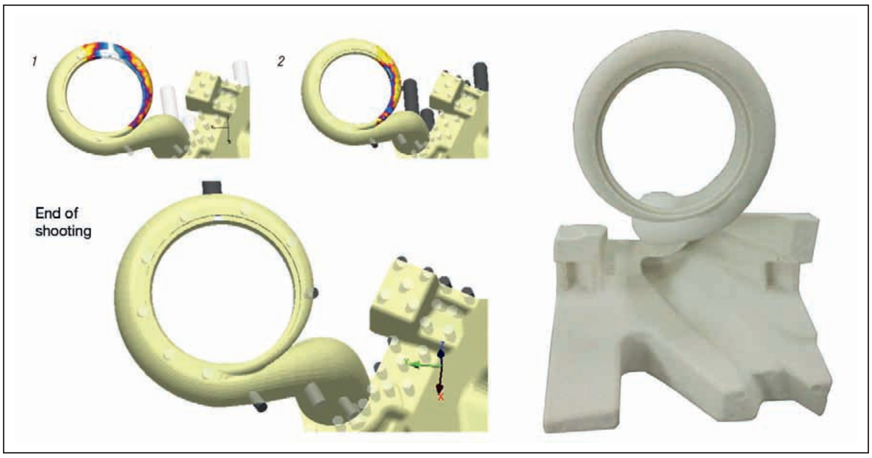

Figure 5: Compacting process in the volute at the end of the shooting process (left) and optimally shot-out core (right) [8]

Application of core-shooting simulations

Simulation breaks up the real process in detail, in terms of both time and space. At any particular point in time one has results and criteria. Even before production of a core box it makes sense to position the nozzles as well as possible. Effects that are, for example, caused by variations in the shooting nozzles can be objectively assessed and evaluated.

The visual analysis of the filling process already allows an efficient comparative assessment of different configurations. Small changes in nozzle positions can have a decisive effect on the dynamics of the filling process and the core quality to be expected.

A more precise analysis, going beyond assessment of the final result, is necessary in order to obtain clear assistance for optimization, and not just for complicated cores. Further results – such as the local speeds of air and sand, distribution of the sand from the shooting nozzles in the core, meaningful curve data for sand, as well as air quantities, speeds or pressures in the core or in the shooting and venting nozzles – are available for this purpose.

Optimizing a cold-box core for a turbocharger housing

Turbochargers make high demands of the quality of the inner surfaces as a result of the efficiency of the flow characteristics necessary during use. Defects in the core’s surface quality lead to immediate rejection of the casting. This means that special quality demands are made during production of the core. The design of the tool is often restricted by customer's requirements regarding the positions of the nozzles and vents.

Prototype cores for the initial tool design for a turbocharger core made of polyurethane (PUR) cold-box show reproducible flaws [8], particularly in the volute – critical regarding flow. The initial core-shooting simulations carried out in response provided good confirmation of the results (**Figure 1**).

Following the positive experiences with the results from Magma C+M, simulation of core shooting was accepted by the foundry as a predictive tool and consistently used for further optimization of the core box. Suggestions for optimizing the core were checked by specialists from the foundry using simulation of the core shooting.

A venting problem was initially suspected because of the incompletely shot out areas in the volute. For this reason, an initial optimization of additional vents in the area of the volute was appropriate and tested using simulation. The comparison of the starting situation with four vents and the version with eight vents, however, showed no decisive improvement in the shooting results – an outcome that was unexpected by the experts (**Figure 2**).

The detailed analysis of the shooting process in the simulation showed the real reason for the compaction problems. The air, as a carrier medium for the sand, was vented too early because the venting nozzles were placed at the entry to the volute. The flow speed of the air and the sand was therefore reduced before the sand could fully fill the core (**Figure 3**). Assessment of flow speeds in the air shows that the two marked venting nozzles lead to a substantial reduction in the speed (from over 5 m/s to about 2 m/s). This results in a loss of carrier air, reduced kinetic energy for the sand, and thus insufficient compaction.

As a consequence, a combination of improved venting in the volute and closure of the two critical venting nozzles was examined using Magma C+M (**Figure 4**). The result of the air flow speeds clearly shows that the speeds at the entrance to the volute are higher as a re-

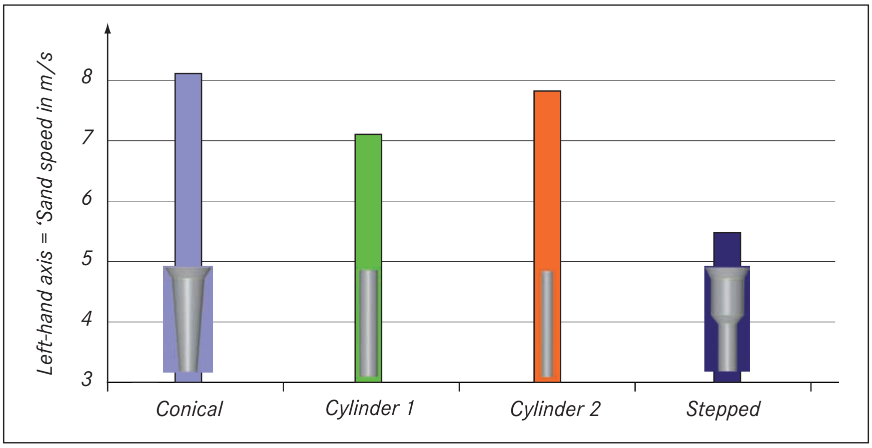

Figure 6: Measured speeds at outlet of differing shooting nozzles. Given otherwise identical conditions, the speed of the sand flows is largely determined by the nozzle geometry. With the same outlet cross-section, the "Cylinder 1" and "Stepped" nozzles exhibit clear differences

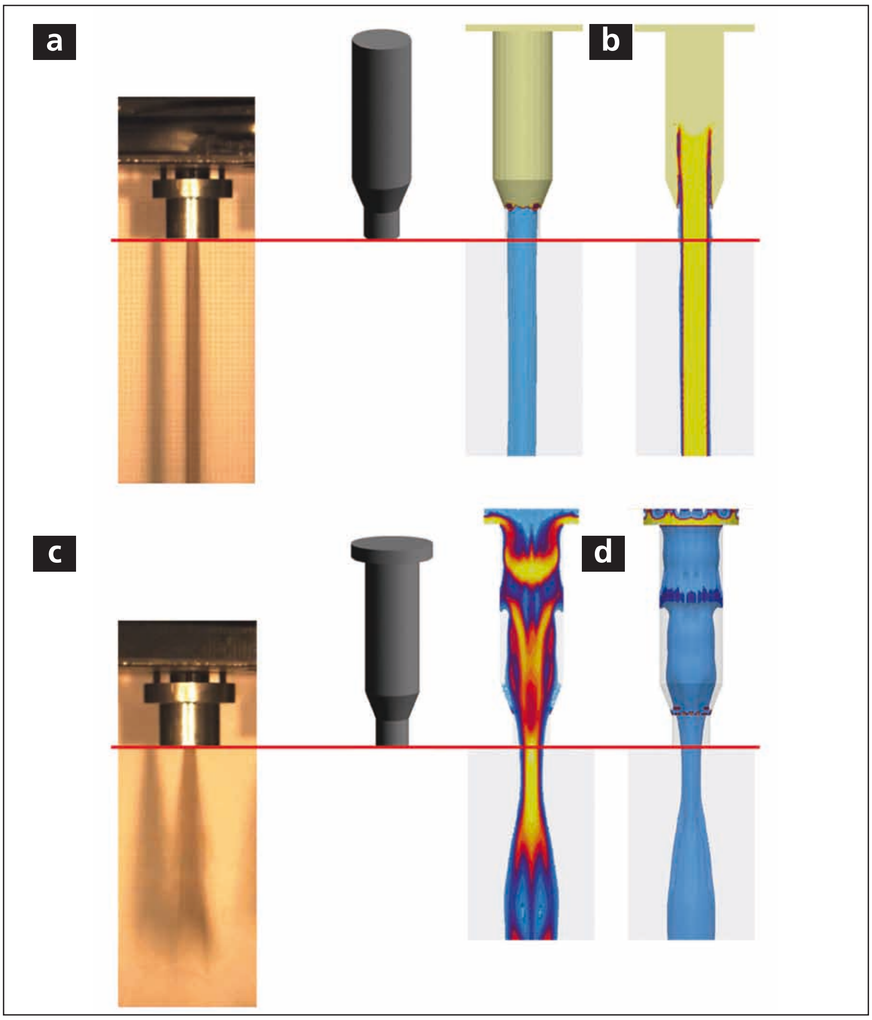

Figure 7: Comparison of real and simulated sand flows for differing nozzle geometries: a) the sand typically flows from the shooting nozzles as a continuous jet; c) a geometrical change causes the sand flow to exhibit intermittent pulsing, whereby the jet widens. Depending on the core geometry, this can lead to improved core quality. Simulation permits a differentiated examination of the flow processes in the nozzles, as can be seen in b) and d)

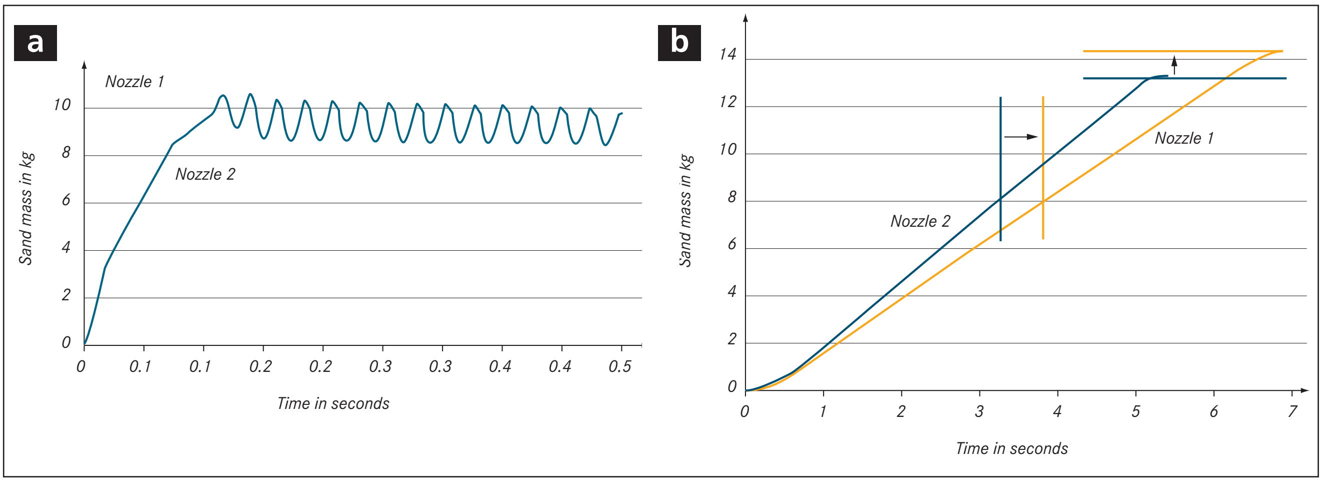

Figure 8: Simulated sand speeds and quantities as a function of time for two different nozzle geometries: a) when shooting nozzles have the same outlet cross-section the flow speed and the mass flow depend on the geometry; b) the resulting shot sand masses lead to differing levels of compacting (depending on the core geometry to be filled). In this case while "Nozzle 2" fills the core box more rapidly, the total amount of sand shot is lower. The core is thus somewhat less compacted

sult of the lower venting and simultaneously rapidly fall off within the volute, leading to a large local fall in pressure. Whereby a large fall in pressure is a good indicator for good compactability of the sand in the last of the areas to be filled. The rapidly flowing sand reduces its speed very quickly and can thus be well compacted as a result of its kinetic energy. At the same time, the rapidly reduced air speeds show that the air is efficiently removed through the venting nozzles.

Core-shooting simulation clearly shows this process through the density distribution (**Figure 5**). The optimized version led to reproducibly defect-free cores in practice.

The geometry-related functionality of shooting nozzles

The core making shop utilizes a variaty of nozzle geometries. In its simplest form, drilled holes in the shooting head plate act as shooting nozzles. Variation of the diameter of the drilled holes is then the only possibility for having a nozzle-related effect on shooting behavior. This is often a technically and economically favorable solution for simple core geometries. Normally, however, proper nozzles are used, connecting the shooting head with the core box. Whereby cylindrical, conical or stepped shooting nozzles are typically used in the core shops.

Differing shooting nozzle geometries lead to very different flows. The laws familiar from fluid mechanics cannot be applied for the special air/sand flows during core shooting. With liquids, for example, the use of a stepped rather than a cylindrical nozzle leads to an increase in fluid speed due to the continuity (given the same pressure conditions). During core shooting, on the other hand, the sand is agglomerated at the taper and the sand speed is lower (**Figure 6**). In addition to sand speed, the mass flows also change – depending on the nozzle geometry.

With increasing core complexity, the demands on selection of the shooting nozzle also rise. Up to now, nozzle geometries have been varied using knowledge gained from experience as well as

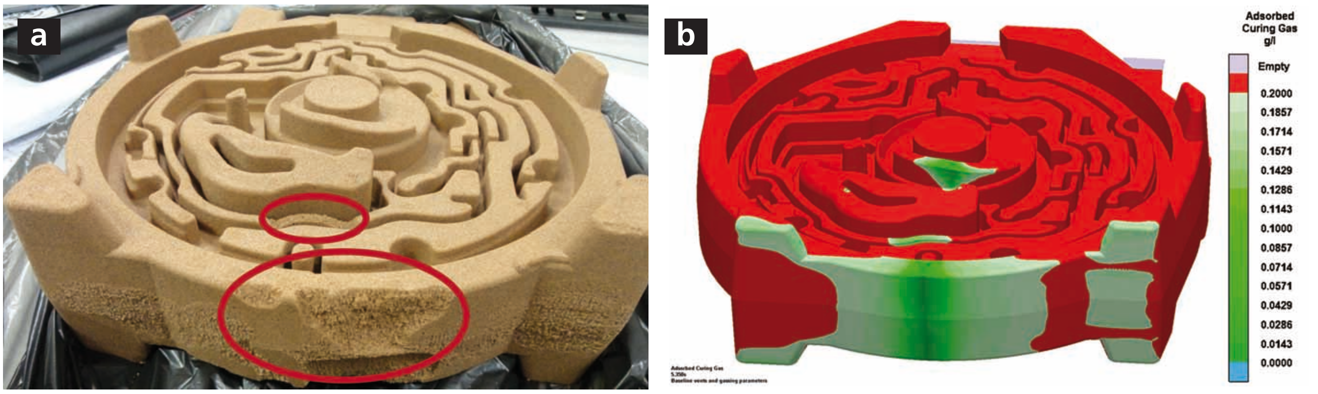

Figure 9: Defective core after hardening: a) the marked areas show where incomplete hardening has taken place with the gassing parameters applied; b) simulation of amine gassing. The picture shows the concentration profile of the amine taken up by the binder system and thus making an active contribution to hardening. Hardened (red) and non-hardened (green) core areas are shown

trial and error – even in difficult cases. Whereby the flow processes in the nozzles have largely remained a mystery. Experimental investigations on the outflow behavior of sand from shooting nozzles show that, for example, continuous sand flows with approximately constant speed and almost constant mass flows can be adjusted, as can intermittently pulsating sand flows, merely by making geometrical changes to the nozzle (**Figure 7**). The flow processes in the nozzle that lead to these characteristic flow processes have hitherto escaped experimental observation and detailed investigation. Simulation now permits a differentiated examination of the flow processes within the nozzles. The physical phenomena involved can be fundamentally understood and quantitatively evaluated. This knowledge of the influence of geometry-related effects on the shooting result is important for the core-maker. Sand speeds and effective shot sand masses can differ greatly depending on the nozzle configuration. This also affects the local compacting of the core, depending on the core geometry (**Figure 8**).

With the knowledge gained from simulation, nozzle geometries can be deliberately selected in future in order to be able to fill the various areas in the core box simultaneously and evenly. On the basis of the quantitative simulations systematic rules can be worked out showing which nozzle geometries are most effective for which core types.

Modelling core curing with gas

During gas curing, a hot gas mixture is introduced into the shot core. Appropriate models can be used to simulate conventional gas hardening mechanisms, such as PUR cold-box (or, similarly, the drying hardening of inorganic binders with hot air in a heated tool) [6]. The transport of gas through the open pore space of sand cores characterizes the flow process during core hardening. For PUR cold-box hardening this means transporting a catalytically effective tertiary amine into all areas of the core. The hardening itself depends on many factors, e.g. the binder (composition and amount), solvent (kind and amount), wetting of the sand grains by a binder film, amine type, and the temperature of the sand and gas [9]. The gas flow through the core sand primarily depends on the core geometry, the nozzle configuration, the gas pressure and the permeability of the sand mixture to gas.

Figure 10: The first core-shooting experiment for a PUR cold-box core (length 920 mm, shooting volume 68 kg). The lower area of the core completely collapsed as a result of insufficient strength [10]

A nozzle configuration favorable for core shooting is not normally optimal for gassing. A lot of amine is uselessly lost, for example, when the gas flow only has to travel short distances from the gassing nozzles to the vents while, on the other hand, other areas of the core are only perfused under higher pressure – and thus also require greater amounts of amine.

The initial aim of simulation is to correctly represent the timing of the amine gas flow. At the design phase of core tools it is already possible to examine whether and how all the core areas can be sufficiently perfused with hardening gas. Simulation realistically shows both the active gassing and the subsequent rinsing process with air. Thus the causes of faults are recognized early on and targeted corrective measures undertaken.

An important task for the core-maker is to harden the core as efficiently as

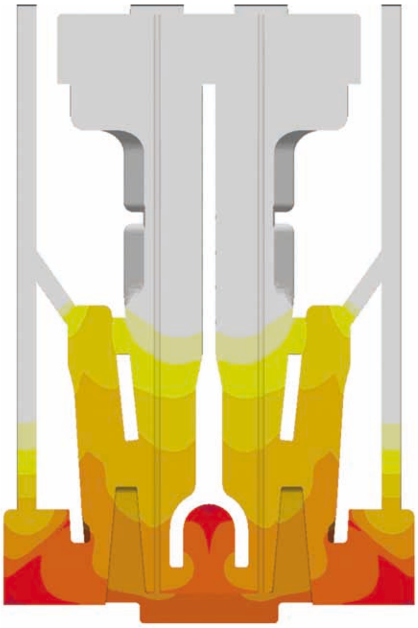

Figure 11: Maximum local concentration of amine. The hardening gas penetrates the core very unevenly

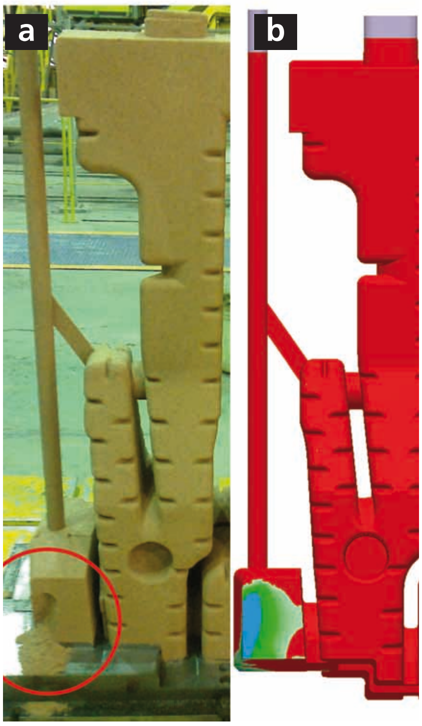

Figure 12: Shooting and gassing result with new process parameters: a) PUR cold-box core; b) predicted local concentration of absorbed hardening gas (red fully hardened, green critical, blue not hardened). The affected, unhardened area exactly corresponds to the predicted zone, with low amine concentration in the simulation result (blue)

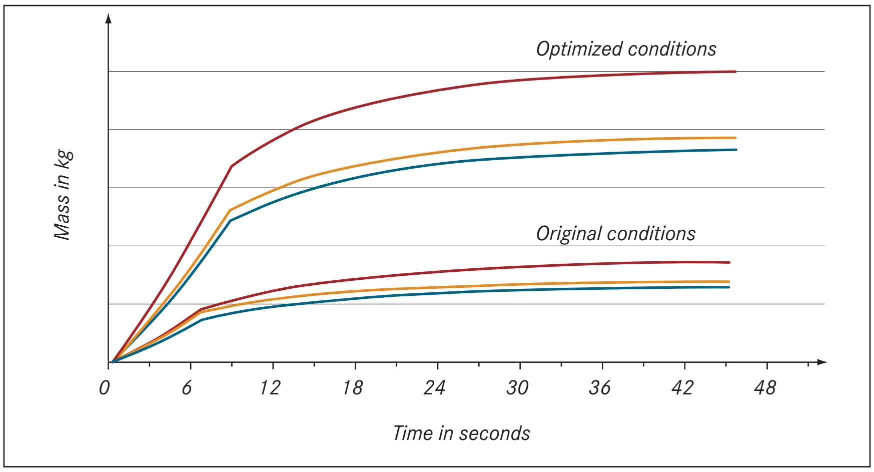

Figure 13: Total mass flow of air/amine gas through the lower venting nozzles. The removal of some venting nozzles in the upper and central area of the core led to a significant increase in the amount of air in the lower venting nozzles

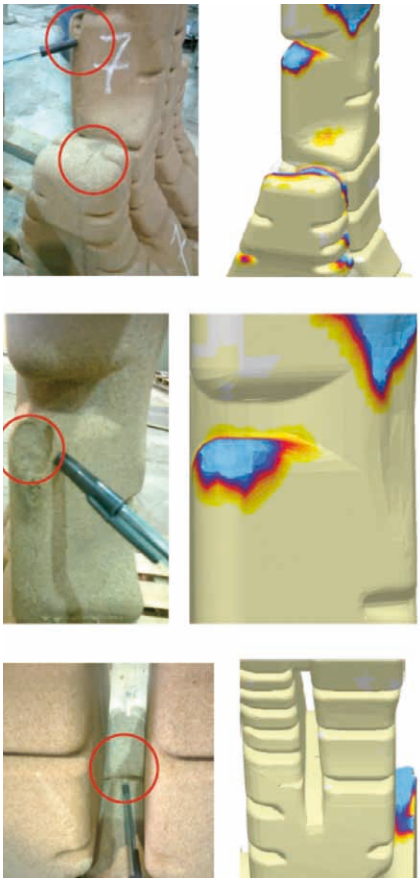

Figure 14: Comparison between core-shooting defects in the simulation and prototype cores. The defective areas are those that were filled last. This is the result of filling against the main shooting direction, hindering sufficient compacting. As the defects occurred near the mold joint it was assumed that the core box was insufficiently sealed

possible within a cycle time that is as short as possible. Problems during hardening are often first noticed when good cores have already been shot and the nozzle configuration for shooting has been defined (**Figure 9**a). Simulation of amine gassing for an incorrectly hardened core very quickly shows that critical areas are only insufficiently perfused and that the amine does not reach all the areas of the core within the production cycle (Figure 9b).

Practical measures for overcoming hardening-related core faults mostly involve increasing the quantity of amine, the gassing pressure, the gas temperature or, additionally, the gassing time. Variation of these process parameters is, however, only possible to a limited extent and is restricted by the need for economical core production. As the core-maker does not know the cause of the problem (which could simply result from the tool concept), the familiar measures often only serve to combat the symptoms and not to correct the cause. The actual cause of hardening-related core faults is mostly a “flow problem” due to unfavorable nozzle configuration. Even slight changes in the positions of the venting nozzles can seriously affect successful core production. In the case of complex core geometries and nozzle arrangements, the flow progression for gassing is also hardly predictable. Whereby simulation provides a detailed and objective flow analysis. Pressure profiles in the core, local flow speeds and representation of the timing of transient amine flow are important results for evaluating gassing efficiency.

Simulation already allows early coordination of nozzle positioning, both for shooting and for hardening, during the design phase. Trials in the works involving alterations to the tools and process parameters can be reduced to a minimum.

Optimization of gassing a cold-box core for a crossbeam

A core package made of solid PUR cold-box cores is used for the production of a crossbeam for railway bogies [10]. During the first attempts for one of the cores, for which the core box was conventionally designed, there were problems during production that led to a complete collapse of the lower part of the core (**Figure 10**). As a result, the core-shooting and hardening steps were analyzed in detail with Magma C+M so that conclusions regarding the defect could be drawn.

Even the first simulation (**Figure 11**) shows that the problem zones during gassing only have a very low concentration of amine, which was the fundamental cause of the fault. The lack of core strength could be connected to poor hardening on the basis of these results.

Differing process conditions such as gassing and purging times or gassing pressure were initially varied virtually. Further investigation with the help of Magma C+M focused on evaluating the local concentration of the adsorbed amine, because it showed up areas in which the catalyzing gas could not activate the chemical reaction. This result clearly shows that only very low concentrations of the catalyst were available locally to accelerate hardening in the imperfect areas. The optimized process parameters provided better results both in the simulation and in reality (**Figure 12**).

Evaluation of the simulated curves for the mass flow of the amine/air mixture through the venting nozzles made it clear that the catalyst gas did not reach the affected areas. The open ventilation cross-section of the upper and centrally located venting nozzles permitted early escape of the gas, before it reached the floor.

Instead of carrying out cost-intensive changes to the core boxes, the specialists chose a simple solution: some of the venting nozzles in the upper and centrally located areas were closed, increasing the gas concentration in the lower area. Optimization led to a considerable rise in concentration of the gaseous amine (~36 %) in the lower area of the core (**Figure 13**). In addition, the quantity of condensed amine in the binder also rose compared to that in the original project.

With the selected adaptations, the Brazilian steel producer Usiminas, in Belo Horizonte, produced a core without any hardening faults. As the venting was reduced, however, the expected shooting-related defects occurred.

The specialists, however, were well aware that these changes would also have an effect on the core shooting itself. For this reason, another investigation of the core shooting process was carried out with Magma C+M in parallel. The simulation results showed very good conformity between the real defects and the areas of low compacting. Animation of the flow behavior also showed that the problems in the critical areas were caused by a countercurrent of sand against the direction of the main flow (**Figure 14**).

All the remaining defects in the core lay near the mold joint of the core box. Whereby some of the flawed areas had a smooth surface, indicating that the sand was being removed by a strong flow of air in these areas during shooting. The results of the core-shooting simulation supported the consideration that an insufficient sealing of the molding box was responsible for the fault: air could escape at high speed through the mold joint.

This hypothesis was examined by inserting a silicon seal in the tool to improve sealing of the relevant area of the core box. After this adaptation it was possible to reliably and reproducibly produce an entirely fault-free core.

Summary

Magma C+M is a virtual tool for simulating core production. It is designed to meet the needs of operational practice. Simulation of core production is a technologically useful tool for analyzing the entire shooting and curing production chain. The core producer is thus efficiently supported in all relevant process steps of serial production – from tool design to quality assurance.

www.magmasoft.com

References:

www.giesserei-verlag.de/cpt/references