Simulation of the entire core production process

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SAND CORES IN FOUNDRIES

The production of sand cores is a complex process filled with technical challenges that can often times delay production, create scrap and rework, and increase the overall cost of a finished casting. As casting geometries become more and more challenging in their designs, the demand for intricate and high quality sand cores will also continue to increase. Examples of such castings can be seen in the latest generation of combustion engines that have been designed to endure extreme thermodynamic loads and guarantee the maximum performance at the lowest weight possible. Numerous geometrically complex and thin-walled sand cores are required to provide a clean representation of cooling systems in these new engines. The cored passageways for most of these castings must be free of burned on sand, veining, and uneven surfaces as any imperfections will greatly reduce the efficiency of the cooling circuits. Additionally, facilities that produce cores are continually being required to adhere to more rigorous environmental regulations that seek to decrease the amount of emissions that are generated by the core making process. For foundries to stay profitable while meeting these new environmental regulations and increasing customer demands it is essential that the core making process is optimized to maintain tighter process control while eliminating sources of wasted time and money.

Currently a high level of uncertainty exists when it comes to determining if the sand cores required for a new casting can be manufactured at an economical price. This uncertainty about the manufacturability of complex cores limits designers as they attempt to design castings that will meet the requirements of the final application. When it comes to core production there may be even more uncertainty about the specifics of how to efficiently produce a quality core. In most cases core boxes are laid out based on past experience or by using a trial and error method of testing different tooling set ups and process parameters. The process of getting a core box layout and core making process parameters fully optimized consistently requires numerous time consuming and expensive sampling cycles. This trial and error approach to process development may require multiple modifications to the tooling to get the desired results and does not provide any quantitative information about the actual cause of problems that are observed during the trials. A thorough scientific evaluation of all core making processes has yet to be conducted and the application of root-cause analysis to explain complex phenomena in the core making process are currently non-existent.

The complexity of the core making process is due in part to the large number of variables that interact to determine the final quality of a core. In the core shooting process the total number of shoot nozzles and vents as well as the size and locations of nozzles and vents used will often times have a dramatic impact on the final quality of a core. Additionally, process parameters such as the amount of pressure applied during shooting, total shot time, and sand to binder ratio can also affect how the core box fills. Once the core box is filled the binder must then be cured or hardened to give the core sufficient strength. The core curing process also involves many variables that will affect the final quality of the core. In the case of phenolic urethane cold box (PUCB) binder systems the number of vents, size of vents, and locations of vents along with the amount of curing gas and pressure profile used to apply the curing gas will determine if a core gets cured sufficiently. To further complicate the PUCB core making process, it is often the case that a venting scenario that will work well for the core shooting process may not be optimal for the subsequent curing process. Other binder systems such as inorganic and resin coated shell sand require a homogenous tempering of the core box to ensure sufficient curing and core strength. For these processes determining where to place heating units and how long to heat in each area is not easily determined. As a result, the process of getting a new core box into production can often times take several weeks. The time and costs associated with getting a core successfully into production are often times not tracked and rarely get tied back into the cost of the casting despite the significant impact that these costs can have on the overall production cost of the casting.

The simulation of the core making process can significantly improve the predictability of the entire casting production process. The technical and economic feasibility of sand cores can be predetermined prior to production as designers evaluate the feasibility of their designs and consider both the core production and casting processes during the design phase of the product development process. As a result, the entire process chain and relevant physical parameters become more transparent. Simulation also broadens the understanding of the core making processes and provides three-dimensional visualization of the core shooting and curing processes. This insight and understanding will help engineers understand root causes of defects in cores and also provide the means to more efficiently set up core box layout and process parameters that produce quality cores. As a result foundries that use core production simulation will ultimately realize improved casting quality and lowered overall production costs.

MODELING OF THE CORE SHOOTING PROCESS

The modeling of the core shooting process presents a significant challenge when attempting to adequately represent the dynamic flow behaviors of both air and a granular sand and binder mixture within the same flow process. The flow behavior of a granular solid and gas mixture is quite different from the flow of a liquid and as a result the physical-mathematical models required to simulate the core shooting process are quite different from those used to simulate the flow of liquid. To accurately describe the dynamic flow characteristics of an air and sand/binder mixture during core shooting, an approach has been chosen from existing models for such a system [i.e. 2-4]. The dual phase model described here effectively treats the sand/binder mixture as a completely separate phase from the air during the core shooting process. In this dual phase model the conservation of mass and impulse are required for both the sand/binder mixture and the air that is being forced into the core box. It is important that the modeling of the sand flow incorporates the different behaviors that the sand particles will exhibit over a wide range of different local sand densities distributions. For example, when high air fractions are present as shown in the area at the top of figure 1a, kinetic models are the most appropriate to describe the sand/binder movement in air. However, as the sand density begins to increase in an area, such as the middle of figure 1a the friction between the binder-coated sand grains increases and so does the amount of energy that is dissipated through the collision of sand grains. This transition from a kinetic to frictional and collisional energy transfer is an aspect of how the sand grains behave that must be considered in the simulation. As the sand density continues to increase in a given area of a core box, as in the bottom of figure 1a, the dissipation of the kinetic energy of the moving sand grains will begin to become dominated primarily by the frictional forces between the grains. This transition in the mode of energy transfer from frictional and collisional dissipation to primarily frictional dissipation must also be considered.

In addition to accurate modeling of the core shooting process it is also of extreme importance that the physical properties and flow characteristics of the sand and binder mixture being simulated are also properly characterized. Extensive testing and systematic variation of sand and binder flow properties has allowed for the proper categorization of various commonly used core sand/binder combinations. The physical properties and factors that determine the flow characteristics of each are stored in a database that can be recalled and referenced within the simulation software. Each of these datasets can be adjusted or fine-tuned to match the properties of sand/binder combinations that are being used in production if necessary.

Core shooting process simulation also requires the consideration of all relevant process parameters, such as the manner in which the pressure is increased in the shot cylinder, and core box design variables such as the types of vents that are being utilized. In simulation the application of pressure in the shot cylinder is defined by simply specifying the amount of pressure that is applied at each point in time during the shooting. When it comes to venting a core box, the very small openings or slots in the vents, are intended to keep the sand within the core box while allowing the air in the core box cavity to escape. Within industry there are a large variety of different vent geometries and designs that are commonly used. In all cases pressure loss laws are used to describe the different behaviors of the vents in the simulation model and can easily be recalled from a vent database that retains the pressure loss curves for each of the different vent designs and sizes. Experimentally calibrated flow laws assure the realistic modeling of the pressure loss at the vents for this key design variable in the core shooting process.

With each simulation of the core shooting process it will be necessary to determine, depending on the goals of the particular simulation, if the sand hopper of the core machine needs to be modeled and considered in the simulation or if it is sufficient to assign boundary conditions to the nozzles that will introduce the sand/binder and air mixture from the nozzles without actually simulating the sand flow within the hopper. The consideration of the entire sand hopper requires more CAD modeling and simulation time, but in some instances may be the only way to accurately predict filling issues in the core box when they are caused by the flow of the sand within the hopper. One example of a problem created by the hopper is the creation of sand blockages and/or air channels that form within the hopper itself. Figure 2 shows a simplified example of an air channel forming in the sand hopper above the nozzle. This situation greatly changes the filling of the core box and can only be recreated by considering the sand and air flow in the entire hopper.

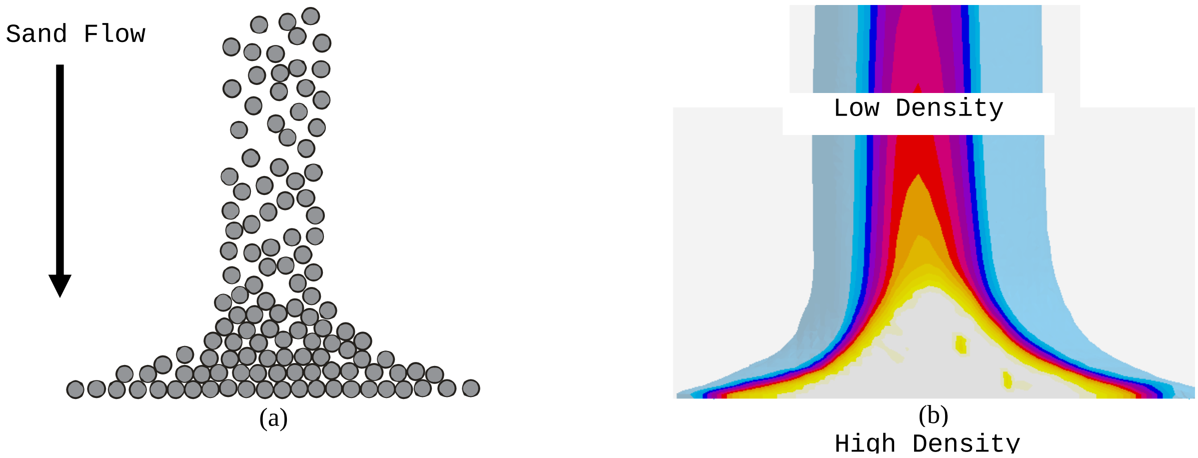


Fig. 1. Explanatory shere model (a) and 3D simulation (b) showing sand compaction.

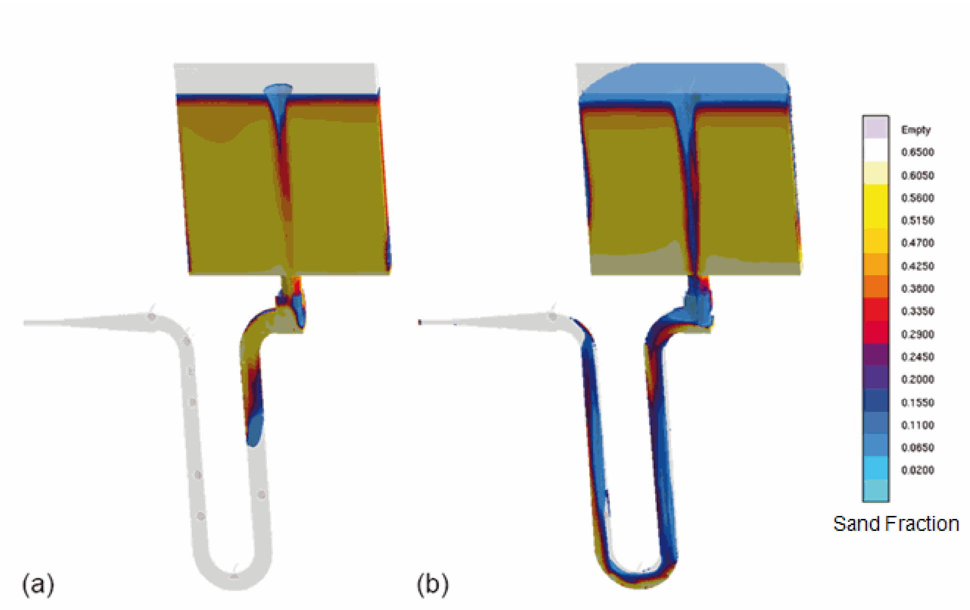


Fig. 2. Core shooting simulation with simplified hopper at two points in time (a) early in filling and (b) later in filling. In both instances the formation of an area of low sand fraction can be seen in the center of the hopper.

APPLICATION OF CORE SHOOTING SIMULATION

Aside from simulation, core box designers have very few options for evaluating the many different variables that effect how a core box will fill with sand. Simulation allows users to visualize the sand flow inside of the core box and evaluate criteria functions at any point of the process. Figure 3 for example, shows the sand fraction result at four separate steps in time throughout the filling of the core box. The areas with low sand fraction values at the end of this this simulation correlate very well with core defects that have been observed for this water jacket core in production as seen in figure 4. Core shooting simulation also provides a differentiating analysis of the inside of cores as well. Unintended volume deficits or voids inside of a core can be detected and evaluated by using sand fraction and sand density predictions. After such subsurface voids are identified they can then be eliminated with changes to the design and/or process parameters. The identification of areas of low density through simulation can also be useful for determining if a given area of low density will cause problems during the life span of the core. Using core density simulation results in conjunction with finite element analysis it is possible to simulate forces that are applied to cores when exposed to additional handling after removal from the core box as well as the mechanical and thermo-mechanical loads that the core will experience during the casting process. Critical and non-critical areas for core defect locations can be derived from an analysis of these loads.

Core shooting simulation also allows the user the ability to trace the flow of sand from each nozzle with different colored virtual sands. This sand trace result shown in figures 5 and 6 can be very useful for eliminating defects observed in areas where separate sand fronts from different nozzles try to merge together. While this result does not actually identify areas of low density or non-fill defects, it can be useful in assigning a root cause for these types of defects. For example, in figure 5 the defect shown on the left side of the production core would initially be identified using the sand fraction or sand density results to predict the defect. However, to better understand and troubleshoot the cause of the predicted void the sand trace result could then be utilized to give the user the additional information that the defect lines up with two merging melt fronts and therefore may require additional venting to allow the air between the merging fronts to escape. Obviously not all areas where fronts merge will have defects, particularly if the venting and nozzle placement create optimal conditions in these areas of merging fronts. It should also be noted that there is an area on the right side of the production core in figure 5 that appears to have a lower density as well. Although the sand trace result clearly shows that this defect is not in line with any merging sand fronts, the user could still identify this defect using the sand density and sand fraction results. By identifying areas of cores where multiple fronts of sand converge, the engineer is able to adjust venting and/or nozzle placement to avoid non filling and low density in these areas. Figure 6 shows a comparison of cores made using different colored sands from each shoot nozzle with the simulated sand trace result. The results of these trials show good correlation between the simulated cores and production test cores.

In situations where the quality of a core is highly variable in production, simulation remains an excellent tool to analyze the root causes of defects and to better understand the main sources of variability in the process. Once the sources of variability are better understood, simulation can then be used to systematically optimize the process parameters. Additionally, using simulation to test the effects of variability in the process (i.e. simulating at the low and high end of a range for a given parameter) will help to determine the acceptable amounts of variability that the process can operate under while still producing a core of an acceptable quality level. These acceptable levels can then be integrated into the utilization of statistical process control methodologies for the core making process.

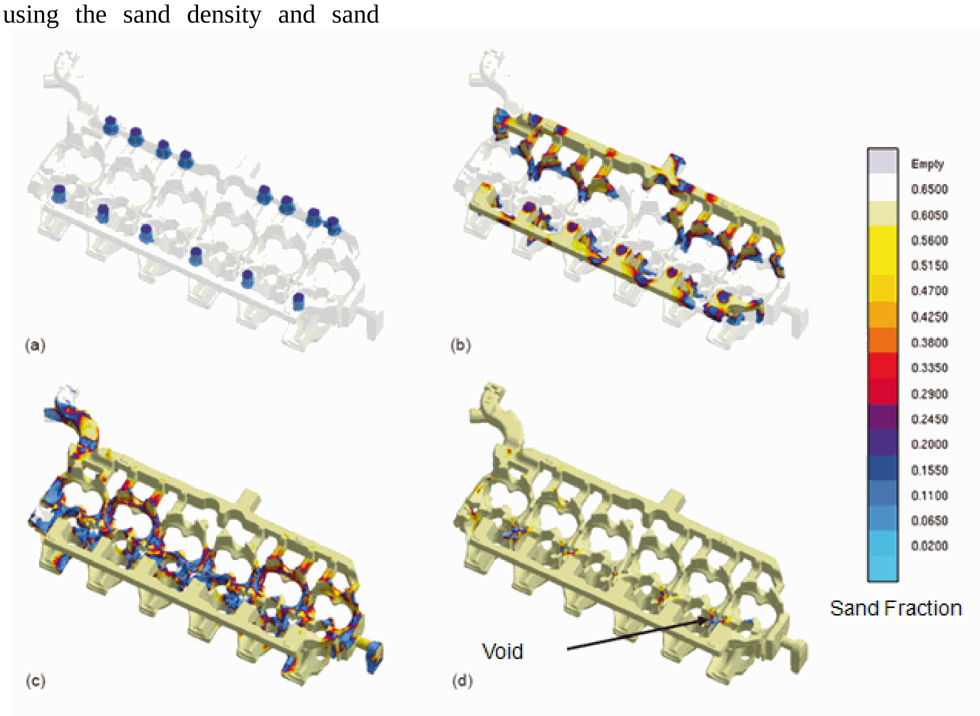


Fig. 3. Filling sequence for the core shooting process of a thin-walled water jacket core. The sand fraction result is shown for (a) 1%, (b) 25%, (c) 75%, and (d) 100% through the core shooting simulation. Problem areas that contain low sand fraction values are observed at the end of the shooting simulation (d).

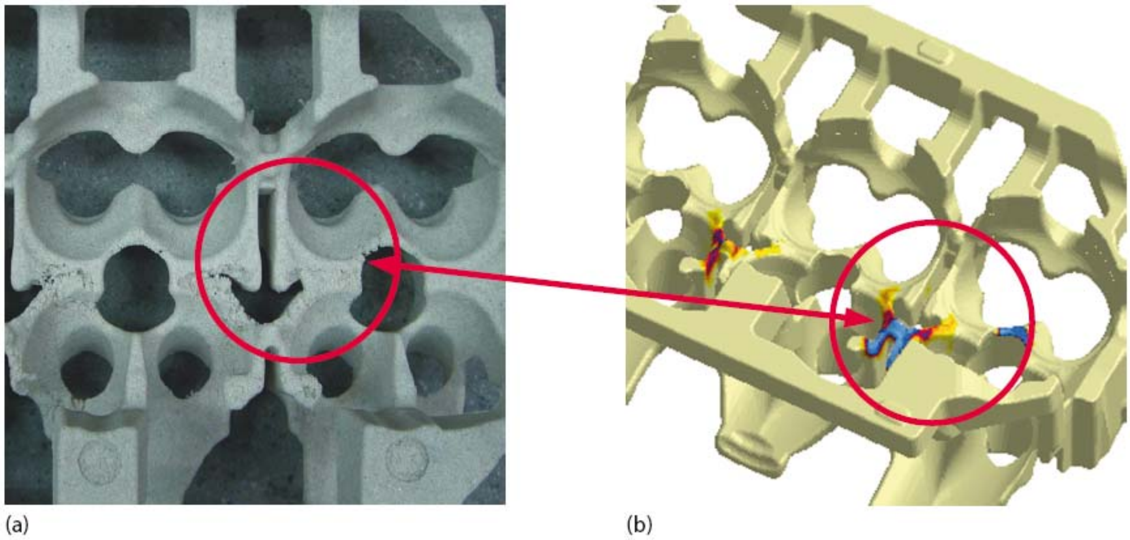


Fig. 4. Comparison of defects in a water jacket core (a) with respective simulation result (low values of sand fraction are identifed in blue) (b).

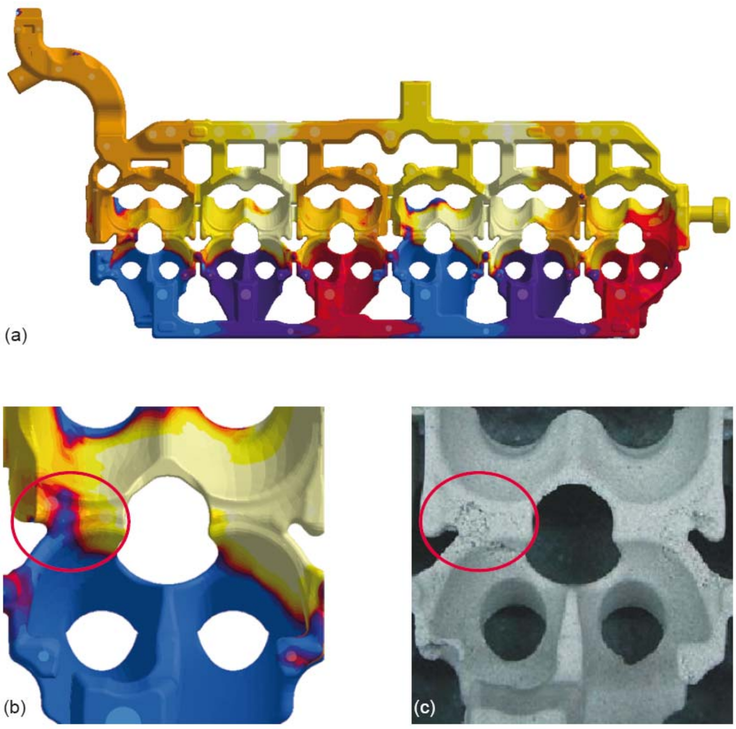
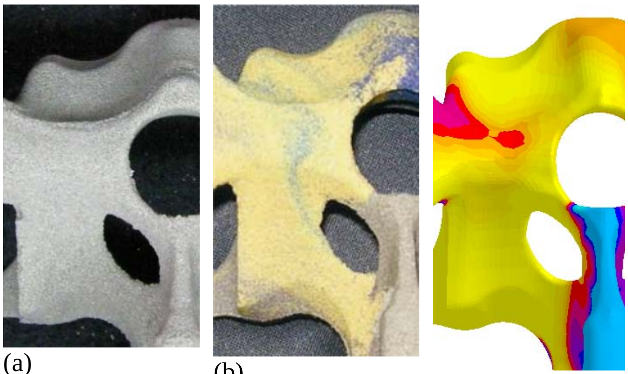


Fig. 5. Core shooting simulation of a water jacket core using colors to differentiate the sand flow from different nozzles (a-b) and experimental result showing a void where two sand fronts merge (c).



(a) (b) (c)

Fig. 6. Production core (a) and experimental core with colored sand (b) and corresponding simulation result for sand trace (c).

MODELING OF CORE CURING AND BINDER DEGRADATION

To effectively consider the comprehensive effects of the sand core throughout the entire core making and casting processes it is necessary to consider both the curing, or hardening of the binder system, as well as the binder degradation that occurs during the casting process when the binder system of the core burns off. In the case of core curing one of the primary concerns is that the core is getting sufficiently cured in a manner that will prevent core breakage during the core making and casting processes. Additionally, an insufficiently cured core may also increase the likelihood of erosion and sand inclusion defects during the casting process. In the case of binder degradation during the casting process the main concern is gasses that are not able to evacuate the core or mold in a manner that prevents them become trapped in the casting in the form of gas porosity defects. From a technical view point core curing and the binder degradation during the casting process are two completely different phenomena. However, the mathematical models used to describe both processes are very similar. Both processes are characterized by the transport of gas through the open porous area or gaps between sand grains in the sand core.

The mode by which a core is cured will depend on the type of binder system that is being used. The models for core curing have been formulated in a way that the common curing mechanisms such as gas curing of phenolic urethane cold box binder systems or heat curing of inorganic binders and resin coated shell sand systems can all be simulated [5]. Gas curing in a phenolic urethane cold box binder system is defined by introducing an air/catalyst mixture into the core. Mechanisms to be considered for the gas transport include not only how the air/catalyst mixture will flow through the porous core, but also how quickly it will catalyze the areas that it reaches. In the case of inorganic binders the core strength is generated via a drying process in heated core boxes. The heat flow into the core sand and the resulting evaporation of binder water is modeled. The practice of blowing hot air into an inorganic core can also be simulated.

GAS CURING SIMULATION

When designing a core box, it needs to be considered that all areas of the core must be reached by the catalyst. A venting configuration with a multitude of vents that is beneficial for the core shooting process can often lead to insufficient curing as not all areas of the core get exposed to enough curing gas. The curing process will often times benefit from a venting layout that forces the catalyst to remain in the core as long as possible and reaches all areas of the core before it can escape through the vents. Catalyst that remains in the core for an extended period of time may end up curing some of the insufficiently vented areas as it diffuses to such areas.

When curing simulation is applied to core production, it leads to a complex, three-dimensional, time dependent flow situation for the curing and purging process. The example in figure 7 shows the amount of catalyst, in this case amine gas, at four different time steps of the gassing simulation. The use of the fraction amine result can be used to identify areas where the amine gas has not reached the core in a sufficient amount and also areas where the amine has not been fully absorbed into the binder. A comparison between a production core and a simulated core can be seen in Figure 8 where the weak strength and breakage of the production core correlates with an area that did not receive sufficient amounts of curing gas. In addition to eliminating curing related defects, simulation can also be used to analyze and optimize curing process parameters to ensure that excess amine is not being used unnecessarily. Reductions in the amount of curing gas used result in lower production costs and fewer harmful emissions from the curing process.

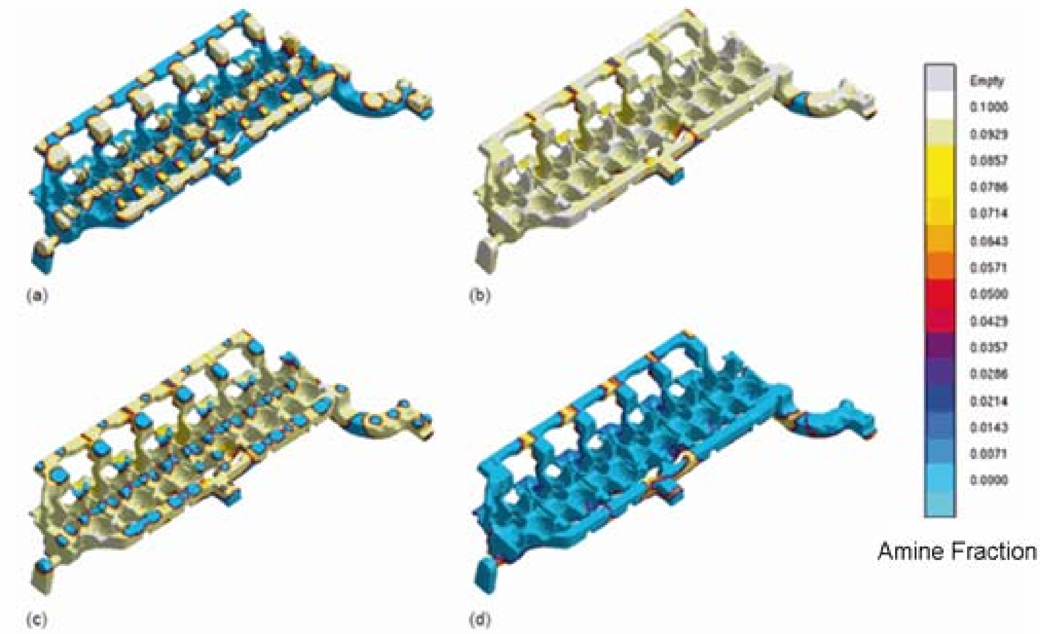


Fig. 7. Simulation of a two-step gas curing for the PUR-cold-box-process. Initially, a catalyst is introduced into the core, displacing the air previously occupying the porous areas of the core (a, b). Subsequently the amine containing gas is purged by the air pushed into the core (c, d). Amine fraction of 0.1 equals 10% amine.

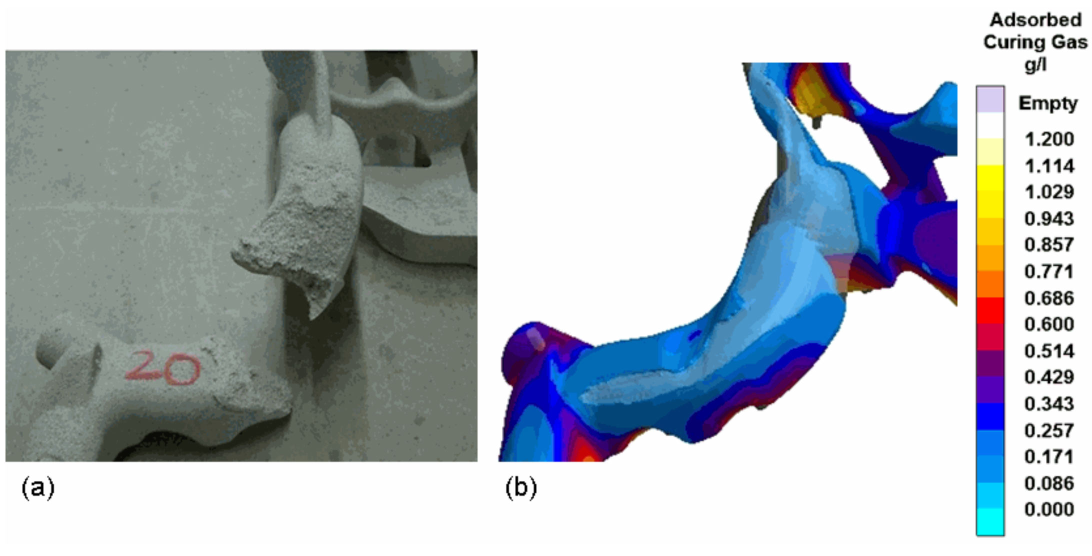


Fig. 8. Insufficently cured PUCB core (a) and uncured areas identified by transparent material in the simulation (b).

HEAT CURING SIMULATION

Designing tooling to achieve the successful curing of cores with inorganic binders and resin coated shell sand can be a very challenging task for a tooling engineer. In addition to the task of creating a uniform and sufficient shell thickness the engineer must also consider the cycle time required to produce the core and the economic ramifications of the cycle time. A homogenous tempering of the core box will assure the creation of an equally thick shell throughout the core. If any area of the shell is not adequately tempered a thin shell can result in problems that occur during the removal of the core from the core box. At the same time if the core box temperature is too high in an area, it is also possible that the core may not have sufficient surface strength. Because the heating and cooling of inorganic and shell core tooling is so important to the core quality and production time it becomes critical for the simulation of these processes to correctly predict the heat up sequence of the cold core box and the thermal distribution during continuous production. Simulation can actively support the development of tooling layouts by aiding in the placement and activation on heating elements in the tooling as shown in figure 9. The location and capacity of heating elements can be evaluated even in the early stages of the core box design.

The drying process of an inorganic core is also a very dynamic process. After the sand is shot into the core box, the sand mixture is heated by the hot core box. The water in the binder then evaporates on the core surface and the surface of the core becomes cured. At this point it is possible that the evaporated water from the binder may condense inside the core and agglomerate in some areas. If a core is removed from the tool and stored with such condensation present, the already cured areas could soften. As a result, it is common for core makers to flow hot air through the core to remove the water vapor during the curing process. In this case the hot air is intended to remove the water vapor from the core box cavity and ensure that the core does not soften during storage. However, if vents are used that are incorrectly sized, not placed properly and or if an insufficient amount of hot air is used in the process it can lead to water vapor remaining in the core. The development of water vapor during curing and the removal of it during the blowing of hot air into the tooling are both considered during the curing simulations for inorganic binder systems. Figure 10 shows the local water content predicted in different areas of an inorganic core.

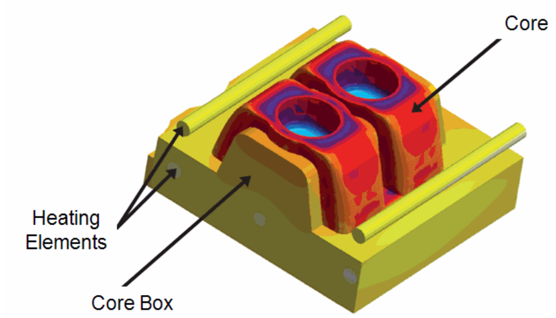


Fig. 9. Partial view of an electrically heated core box in the heat curing stage.

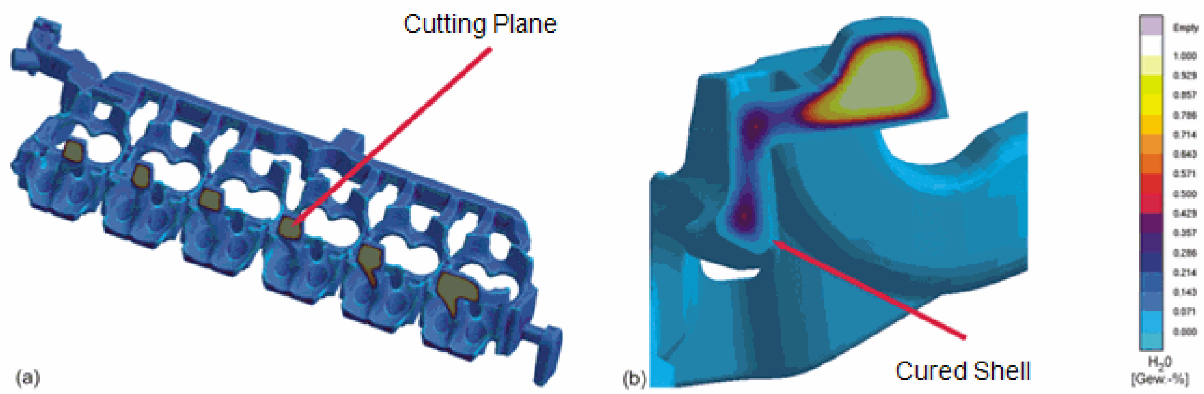


Fig. 10. Heat curing visualization of entire core (a) and close up of sliced section (b).

SIMULATION OF BINDER DEGRADATION DURING THE CASTING PROCESS

The casting process is the last process step in the life cycle of a sand core. Here the core is exposed to mechanical and thermal loads as liquid metal fills the mold cavity during the casting process. As the core temperature increases the binder will eventually begin to degrade or burn off. Using experimental data for binder degradation [1, 5], it is possible to simulate the local binder degradation during the filling and solidification processes. Figure 11 shows the binder content of a core at four different points in time during the filling of the mold cavity. The evolution of gas as the core temperature increases leads to an increase in pressure within the core and is shown in figure 12 for the same mold filling simulation. The increase in gas pressure within the core may force gas into the casting and cause defects during the cooling and solidification of the casting if the gas is not properly vented away from the casting. Utilizing binder degradation simulations aids in the design and placement of vents to ensure that the core gases do not end up creating gas porosity defects in castings.

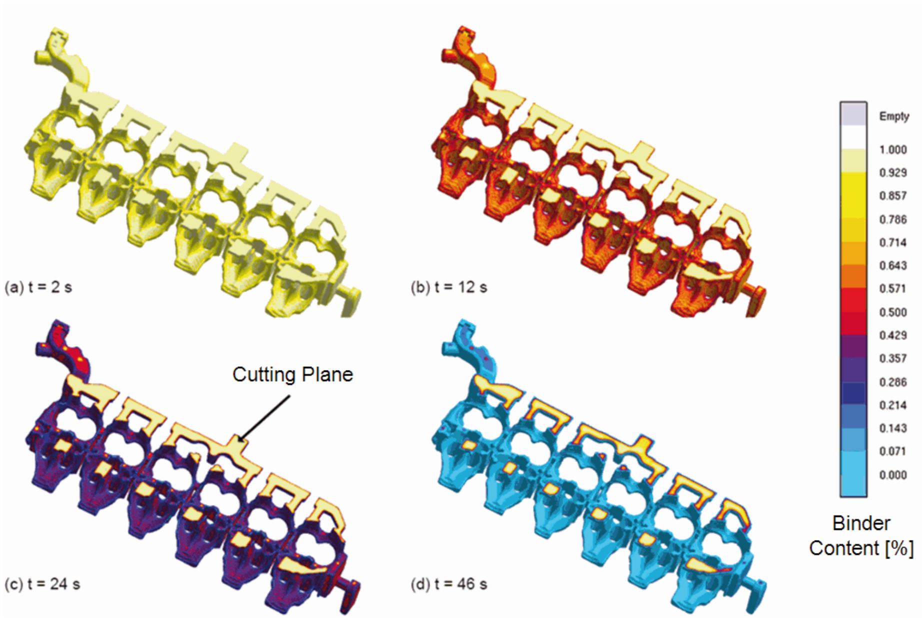


Fig. 11. Simulation of binder degradation using a starting pouring temperature of 750 C (1382 F).

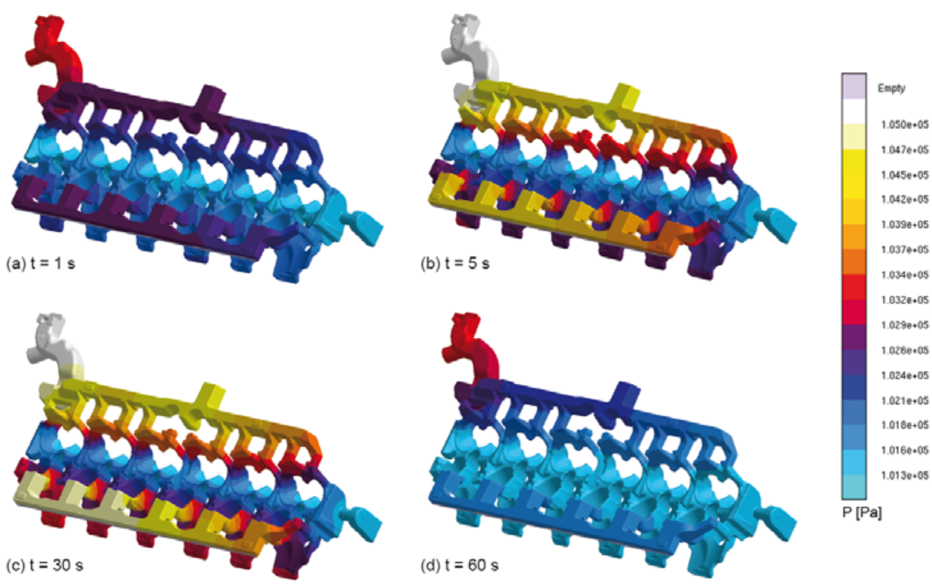


Fig. 12. Simulation of binder degradation during the casting process, displaying the pressure distribution of a core vented at its central axis.

SUMMARY

A tool to simulate the core making process along with descriptions and applications of the core shooting, curing, and binder degradation models that have been developed have been presented. The three dimensional visualization of complicated physical processes provided by simulation is an extremely useful tool for analyzing and better understanding the effects of complex interactions between different process variables. Through core making simulation root cause analysis can be performed to eliminate or detect tendencies for core defects to occur. The impact of tooling and process changes on the core quality can be evaluated without costly real world trials and the optimization of core box layouts and process parameters can be shortened and, thereby, costs can be reduced.

ACKNOWLEDGEMENTS

The fundamentally oriented research work was supported through DLR (Deutsches Zentrum für Luft- und Raumfahrt e.V.) Bonn/Germany with funding from BMBF (Bundesministerium für Bildung und Forschung) through the project "VIGI" (Kennzeichen 01RI05008). Another special Thank You goes to the research partners, BMW AG (Gießerei Landshut), Hüttenes-Albertus Chemische Werke GmbH, the IfG (Institut für Gießereitechnik GmbH) and the ITWM (Fraunhofer Institut für Techno- und Wirtschaftsmathematik) for the open and valuable cooperation and to the involved employees for the engaged and constructive exchange of experiences.

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