The virtual core - modelling and optimization of core manufacturing and application

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Abstract. Development and manufacturing of high quality cast parts with tight dimensional requirements depend to a large extent on the stability and application of the sand cores. The core-sand is based on a complex granular multi-material system, where curing of an organic or inorganic system bond the grains into a porous core. The chosen combination of sand and binder determines the thermo-mechanical properties of the core. The paper provides an overview of current modelling capabilities along the life cycle of sand cores. A detailed analysis of the production steps is presented as well as the resulting properties linked to the application in the casting process. Several questions and some answers are given to the understanding of core related defects and how simulation can bridge the gap between core production and application of cores in the casting process. Today, process simulation of sand core production is an accepted tool for core box design and prediction of robust production conditions. The first modelling step is core shooting where expanding air is the driving force for sand flow from a core shooting machine into the core box. Coupled two phase flow modelling of air and granular material is required to represent the process sufficiently. The final process step in core manufacturing is core curing and moisture transport where porous media gas flow modelling is applied. Phase transformations as well as the relevant transport phenomena and the complete heat balance in case of thermally controlled processes need to be considered. During casting the deformation of the bonded sand material is generally governed by thermal expansion, phase transformation and the location of core prints. For long thin walled cores, buoyancy forces due to density differences between the cast material and the bonded sand material can play an important role due to creep effects in the organic binder systems. For inorganic systems moisture content and moisture transport during casting are affecting the mechanical behaviour, such as bending strength. The paper presents a detailed overview of a recent implemented soil plasticity model which is calibrated for different binder systems and sand types. The data are based on comprehensive mechanical tests to provide temperature, moisture and time dependent input data for the shown examples. This includes new steps and future challenges in modelling the anisotropy of printed sand cores and digitalization of the foundry in general.

1. Introduction
Sand cores play an important role in shaping complex casting designs, where a stable core design can be a challenge to achieve both during the manufacturing of the core as well as during the performance of the core in the casting process. The complexity and high quality standards of the cast parts today require a stable process with limited variations in the final part quality. To achieve this, the focus has traditionally been directly on the cast part itself, the alloy and variations in the process conditions. But in recent years it has been increasingly important to pay more systematic attention to the sand core to understand and control its quality and performance.
Simulation and optimization of the sand core manufacturing and the integration into classical casting process simulation have developed in parallel to the increasing focus on the quality of the sand core. Today it is possible to “virtually” analyse the flow of air and sand mixture inside the core box for different process conditions like shooting pressure and the interaction with different shooting nozzle geometries and layouts of the vents. The subsequent hardening and curing of the considered binder system is possible to evaluate by simulating the core gassing and purging. Pressure gradients govern the flow of gases through the porous media, where the permeability is dependent on the simulated porosity distribution. Similar models and approaches are used to simulate the transport of gases due to pyrolysis and binder degradation during the casting process. The results give a detailed knowledge of the gas pressure distribution and the risk of gas defects in the interface between the liquid metal and the sand core.

Recent developments have focused on the moisture content of inorganic cores to consider vaporization, transport and condensation of water during the casting process. The influence of temperature and hardening time on moisture content is possible to analyse and correlate to the mechanical strength of the sand core. Similar to predicting the risk of gas defects in the interface between the liquid metal and the organic bonded core it is possible to predict gas defects related to water vapor. These new functionalities follow the growing interest in industry to switch to inorganic cores where it is possible.

Simulation capabilities of the mechanical performance of sand cores in the casting process have been extended intensively in recent years. Constitutive models from soil plasticity and creep models to describe time effects at elevated temperatures have been tested and evaluated to describe the hot distortion of sand core. Various mechanical tests have been selected to provide input from different stress states to require mechanical data. Thermal expansion and expansion due to phase transformation in silica sand are measured and provide a significant contribution to the loading of the core material. Deformation due to small buoyancy forces can be considered in the simulation, which can have significant influence on the behaviour of long fragile cores. The new developments make it possible to analyse and optimize the location of core prints to reduce the risk of unwanted deformations and cracks due to high stress concentrations.

The objectives of the first part of the paper are to review the current status of simulating the life cycle of a sand core based on proper physical models and measured input data, including an extension in the field of moisture transport and associated risk of gas defects. The second part of the paper is presenting recent developments and new implementations used to simulate the mechanical performance of the sand core in the casting process. These activities are important steps in further digitalizing of the sand core material and for providing a virtual simulation tool for the day-to-day optimization of sand cores in the casting process. The integration of simulating core manufacturing and casting process simulation is illustrated in figure 1.

2. Core manufacturing

2.1. Core shooting
Flow of liquid metal starts the manufacturing of cast parts followed by a phase change to the final solid state during solidification and cooling. Similarly, manufacturing of sand cores starts by the flow of
binder-coated sand particles driven by pressurized air followed by a state change to a porous solid state when the particles settle and the binder system is activated. The flow of metal and sand particles is obviously quite different in nature and proper analysis of the sand flow requires a two-phase flow simulation where the interaction between the binder coated particles and the air is properly described. For the Eulerian-Lagrangian method the binder coated sand is treated as discrete particles, while for the considered Eulerian-Eulerian formulation, presented in this section, the binder coated sand and air are treated as two separate continuum phases. For the considered formulation, the mass and momentum conservation equations for the sand/binder and air phases can be written as, [1,2].

\[
\frac{\partial}{\partial t}(\varepsilon_s \rho_s) + \nabla \cdot (\varepsilon_s \rho_s \mathbf{u}_s) = 0
\]  

(1)

\[
\frac{\partial}{\partial t}(\varepsilon_g \rho_g) + \nabla \cdot (\varepsilon_g \rho_g \mathbf{u}_g) = 0
\]  

(2)

\[
\frac{\partial}{\partial t}(\varepsilon_s \rho_s \mathbf{u}_s) + \nabla \cdot (\varepsilon_s \rho_s \mathbf{u}_s \mathbf{u}_s) = -\varepsilon_s \nabla P_g - \nabla P_s + \varepsilon_s \rho_s \mathbf{g} + \nabla \cdot \mathbf{T}_s + \beta (\mathbf{u}_g - \mathbf{u}_s)
\]  

(3)

\[
\frac{\partial}{\partial t}(\varepsilon_g \rho_g \mathbf{u}_g) + \nabla \cdot (\varepsilon_g \rho_g \mathbf{u}_g \mathbf{u}_g) = -\varepsilon_g \nabla P_g + \varepsilon_g \rho_g \mathbf{g} + \nabla \cdot \mathbf{T}_g + \beta (\mathbf{u}_s - \mathbf{u}_g)
\]  

(4)

where \( \varepsilon \) represents a phase volume fraction, \( \rho \) is density, \( \mathbf{u} \) is velocity, \( P \) is pressure, \( \mathbf{T} \) is a viscous stress tensor and \( \beta \) is a frictional coefficient that describes the momentum exchange between the phases. The subscripts \( s \) and \( g \) are used to indicate the sand/binder and air (gas) phases, respectively.

The interaction between the particles and by that the dissipation of the kinetic energy depends on the sand fraction. The three primary mechanisms of viscous dissipation are: kinetic dissipation, kinetic plus collisional dissipation and frictional dissipation [3,4]. The correlation between the different mechanisms and the sand fraction in the particle flow is shown in figure 2.

\[\text{Figure 2. Different mechanisms of viscous dissipation depending on the sand fraction.}\]

The two phase flow formulation ensures a separate flow behaviour of the two phases governed by the right physical coupling according to the illustration in figure 2. The flow of the two phases is possible to visualize separately with tracer particles as shown in figure 3.
Solving the governing equations of the discretized system, with proper constitutive information to describe the kinetic behaviour, makes it possible to analyse the complex flow of sand particles from pressurization in the hopper, to flow through the shooting plate and the shooting nozzle, to the final settlement inside the core box. The distribution of settled sand particles determines the density distributions which can be used as initial condition for the subsequent curing and hardening phase. Further details of the implementation and validation based on measurements can be found in [1].

2.2. Core hardening
The binder is activated after the core shooting process to bond the particles into a stable sand core with sufficient mechanical properties for the casting process. For the cold box system the hardening process is governed by the flow of amine gas, which is flushed through the pore space of the sand core. The gas flow through the core is primarily dependent on the core geometry, the nozzle design, the gas pressure and the permeability of the particle/binder mixture. The curing itself depends on many factors such as binder composition and amount, solvent type and amount, binder wetting of the sand grains, morphology of the sand grains and temperature. For inorganic cores the hardening process is governed by the flow of hot air and moisture transport of vaporized water. The model also takes into account condensation in colder regions of the core. Vaporization and condensation need to be fully coupled to the thermal simulation to get realistic temperature distribution in the heated core box.

The transport of a catalyst gas or moisture during the hardening process can be described by using models for flow through porous media. The conservation of a chemical species $k$ during the gassing of the core can be described by

$$\frac{\partial}{\partial t} C_k + \nabla \cdot \left( \rho_k \bar{U} \hat{C}_k \right) = \nabla \cdot \left[ (1 - \varepsilon_s) \rho_k D_k \nabla \hat{C}_k \right] + R_k$$

where $C_k$ is the mass concentration and $\hat{C}_k$ is the pore space fraction of the gas component, $D_k$ is the mass diffusivity of the component, $\bar{U}$ is Darcy’s velocity, and $R_k$ represents in-situ mass transformations due to e.g. condensation/evaporation of the gas component in the core.

The gas phase velocity $\bar{U}$ is related to the pressure gradient in the pore space of the core by using Darcy’s law

$$\bar{U} = -\frac{K}{\mu_s} \nabla P_g$$

where $K$ is the permeability of the core and $\mu_s$ is the gas phase viscosity. Combining this equation with equation (5) and taking advantage of the fact that the pore space is always completely occupied by the gas phase, it is possible to derive an equation which describes the variation of the gas pressure. The local permeability in the core is possible to relate to the simulated density distribution from the core shooting process. Details on the experimental investigation and the reaction source for vapor can be found in [1].
The transport of gas through the porous media can be used to evaluate the distribution of amine gas in the cold box core to optimize the core box design, the time of gassing and the subsequent purging of dry air. The results visualize the local gas effectivity to highlight critical areas with insufficient core stability. The result of simulating the gas effectivity of a cold box core is shown in figure 4(a), which corresponds well to the observations on the real part in figure 4(b). Results from simulating the moisture content during hardening/drying of an inorganic core is shown in figure 4(c). The transparent zone represents the hardened shell and the wet condensation zone is visualized in the centre of the bulky zone.

Figure 4. (a) Simulation of gassing effectivity for a cold box core, (b) defects observed on the real core and (c) moisture content in an inorganic core.

3. Cores in the casting process

3.1. Binder degradation and gas defects

After manufacturing and storing the core, it is finally used in the casting process where the surface of the core is subjected to a thermal shock when the liquid metal enters the cavity and hits the surface of the core. The thermal impact on the core immediately degrades the cold box binder and gases evolve in the core. The gases have to escape out of the core at core prints to avoid critical pressure levels which may cause gas defects in the casting.

The thermal stability of the binder is possible to analyse by evaluating the kinetic parameters for polymer decomposition which are based on the weight loss for isothermal conditions or constant heating rates. The degree of binder left in the core is possible to describe by this information using an Arrhenius expression to describe the reaction rate of the combined decomposition, \[ R_k = \frac{dM_k}{dt} = M_B r_k(T) = M_B f_k \exp\left(-\frac{E_k}{RT}\right) \] (7)

where \( f_k \) and \( E_k \) are experimentally determined reaction frequencies and activation energies, respectively.

Evolution of gases and the associated thermal expansion of the gases increase the pressure locally which drives the transport of gas through the porous core. Simulating the degradation and the gas flow makes it possible to analyse the risk of gas defects caused by high gas pressure at the interface between the core and the liquid metal.

The core gas pressure is shown as an example in figure 5, where the red box in the simulation result in figure 5(b) indicates a critical level of gas pressure at the interface to the liquid metal. The pressure builds up because the gas transport in this section of the core is limited by the narrow passage indicated by the yellow box. As shown in this example it is possible to check the core design and check if the gas is able to escape through core prints or vents. The gas defect detected on the real part is shown in the photo in figure 5(a).
Figure 5. (a) Gas defect on the surface of the machined part and (b) result showing high gas pressure in the core indicated by the red box because there is only a narrow passage (yellow box) for gas flow out of the critical area.

3.2. Inorganic cores – vaporization and condensation of moisture and gas defects

The physical effects of vaporization and condensation during the casting process can affect the quality of metal castings where inorganic cores are used. Any left-over water in the sand core from insufficient hardening/drying can lead to water vapor during the casting process, which either condensates in colder regions of the core, escapes to the outside or enters the mould cavity with a high risk of causing gas defects. Therefore, a proper understanding of transport of water vapor in inorganic sand cores during the casting process is very important. The implemented model considers a time-dependent three-dimensional flow analysis of mixed water vapor and air through a porous medium taking vaporization and condensation effects into account. The governing mass conservation equation for the system is

\[ \Phi \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U A) = S_p w \]  

where \( \Phi \) is the sand porosity, \( S_p \) is the specific sand area and \( w \) is the rate of mass transfer due to condensation or vaporization. Following the approach as described in [2], \( w \) is expressed as

\[ w = M_T \rho_k \left( \frac{p_{\text{sat}}}{p} - C_{v_k} \right) \]

where \( M_T \) is the mass transfer coefficient, \( \rho_k \) is the density of water vapour, \( p_{\text{sat}} \) is the saturation vapour pressure for water vapor, \( p \) is the pressure of the gas mixture, \( C_{v_k} \) is the volume fraction of the water vapour in the pore space, [6]. Darcy’s law, similar to equation (6), is used to relate the gas phase velocity to the pressure gradient. Vaporization and condensation are finally described by the two equations

\[ \partial_t C_k + \nabla \cdot (\rho_k U C_{v_k}) = S_p w \]  

\[ \partial_t C_{k} = -S_p w \]

Depending on the manufacturing of the inorganic core the properties and the distribution of moisture can be very different through the thickness of the core during the casting process. Ideally, the core would be completely dry, however in practice a small amount of unbonded water is typically left in the core. At elevated temperature the water vaporizes and depending on core design and possibility to vent the water vapor out of the mould there is a risk of vapor to enter the mould cavity. Depending on the pressure balance at the interface between water vapor and liquid metal there is a risk of gas defects. This risk is possible to analyse by highlighting areas at the interface where the gas pressure in the vapor is higher than the pressure in the liquid metal. Results on a water jacket core are shown in figure 6.
4. Mechanical behaviour of sand cores

The bonded sand core material is a brittle porous material at room temperature, with small bridges of binder between the grains, see figure 7. At elevated temperature the stiffness and strength of the core material typically decrease when the binder bridges degrade due to oxidation or increased moisture content. Mechanical loading can lead to pore collapse or shear failure of the bonded structure. The main objective of the work presented in this section has been to evaluate the distortion of bonded sand material during the casting process and use the information to improve the prediction of deformations of the sand cores. Both cold box and inorganic binder have been considered in this work and several tests have been performed to characterize the thermal and mechanical behaviour of the material.

4.1. Soil plasticity – modelling brittle material behaviour

The bonded sand material is fundamentally behaving differently in compression and tension due to the bonding of the granular structure of the quartz sand (or other foundry sand types). It is therefore not sufficient to use a standard $J_2$-plasticity formulation, which is only formulated in the deviatoric stress and strain space, [7, 8]. Two soil plasticity models have been evaluated to model the mechanical behaviour of the bonded sand, the Cam-Clay model and the Drucker Prager cap model [9]. Both models have a pressure dependent yield surface, with a high strength for high confining pressure and a lower strength for tensile conditions. The Cam-Clay model is not presented here.

The classical Drucker Prager cap model is fundamentally defined by two regions which define the yield surface of the model, see figure 8. Similar to the Cam-Clay model one region describes how the material dilates during plastic deformation and another region defines how the material is compressed during plastic deformation. The first region is described by the failure envelope, which is defined by the line with the slope $M$ and the pressure offset, $P_F$. The second region is described by the cap, which limits the deformation in compression. To improve the convergence behaviour of the implemented model smaller modifications can be done to smooth the interface between the cap and the failure line and the
failure line and the pressure axis. Smoothing the two interfaces reduces the unwanted influence of the vertexes on the yield surface. The yield surface can be described by the two yield conditions:

\[ \Phi^a(\sigma) \equiv \sqrt{J_2(s(\sigma))} + \eta[p(\sigma) - p_t] = 0 \]  \hspace{1cm} (12)

\[ \Phi^b(\sigma, a) \equiv \frac{1}{\beta^2} [p(\sigma) - p_t + a]^2 + \left[ \frac{q(\sigma)}{M} \right]^2 - a^2 = 0 \]  \hspace{1cm} (13)

**Figure 8.** Sketch of the classical Drucker Prager cap model. The yield surface is defined by the failure envelope and the cap. The slope M defines the failure envelope and the ellipse defines the cap.

4.2. Soil plasticity – mechanical tests

Different mechanical tests are needed to provide sufficient input for the Drucker Prager cap model. The tests have to provide strength information for different stress states in terms of positive and negative pressure. The most general but also comprehensive and expensive test is the tri-axial test, where different load levels can be applied for different confining pressures. This is mainly relevant to get a good description of the compression cap. The failure line can be determined from three conventional mechanical tests, which have different stress states and by that different locations on the pressure axis. The 3-point bending test provides input to the tensile region, while the two cylinder tests provide information to the compressible region, see figure 9 below, [10]. The die compaction test can be used to collect information about hardening during compression of loosely bonded sand.
Figure 9. Different mechanical tests and the relationship to the definition of the yield surface.

The load information is easily used to calculate the $P$ and $Q$ values for the three simple tests, compression, indirect tension and 3-point bending while the $P$ and $Q$ information from the tri-axial test can be used directly. The formulas used to calculate $P$ and $Q$ are listed in the table below.

Table 1. Expressions to calculate strength as function of pressure for different stress states.

| Stress State         | $P$      | $Q$       |
|----------------------|----------|-----------|
| Compression test     | $\frac{4F}{\pi d^2}$ | $-\frac{1}{3} \sigma$ | $\sigma$ |
| Indirect tensile test| $\frac{2F}{nh}$      | $-\frac{2}{3} \sigma$ | $\sqrt{13} \sigma$ |
| 3 point bending      | $\frac{3FL}{2bh^2}$  | $\frac{1}{3} \sigma$  | $\sigma$ |

4.3. Soil plasticity – extracting mechanical data

To extract data for the Drucker Prager cap model the core material was generally tested at different temperature levels from room temperature to 400 °C. The results were collected in P-Q diagrams for the different temperature levels and average values were used for property extraction and for comparing the two binder systems, figure 10. The graphs show some trends which can give some indications of how strong and stable the different binder systems are at different temperature levels.
Figure 10. Response of the mechanical tests as function of temperature (a) compression test, (b) indirect tensile test, (c) 3-point bending and (d) the collection of stress state, including the tri-axial measurements.

For the compression tests, figure 10(a) and the indirect tensile tests, figure 10(b), the inorganic system is generally stronger than the cold box system. Curing of the cold box system increases the strength above 200 °C, followed by a rapid decrease in strength above 250 °C due to binder degradation. The inorganic system has a steady decrease in strength as function of temperature. For 3-point bending the inorganic system has a steady low strength, figure 10(c), probably due to a more brittle behaviour when compared to the cold box cores. The cold box cores start out stronger, again with a small increase in strength around 200 °C due to curing, followed by a rapid decrease in strength above 250 °C. The P-Q data are collected in one graph for the cold box binder and combined with the triaxial test data at room temperature, figure 10(d), to give an impression about the input needed for the Drucker Prager cap model.

4.4. Creep model(s) – modelling time dependent response
The cold box system has a tendency to deform as function of time, especially for tensile load conditions. This behaviour is also observed for cores in production. Different rheological models can be used to describe different time dependent behaviour. For the considered cold box system the Maxwell element was used and the strain contribution was added to the plastic strain component from the soil plasticity model to comprise a combined response, governed by both yielding and creep. The creep response from the rheological model is made pressure sensitive by using a pressure dependent viscosity. For the Maxwell element the inelastic strain rate of the material is described directly by a dashpot. A Hooke element is attached in a serial connection to describe the elastic response, see figure 11. The combined response of the Maxwell element is an instantaneous elastic response followed by a delayed viscous response of the dashpot.
The strain tensor in the dashpot can be generalized in two different ways, either in the same way as the elastic strain tensor in Hooke’s law, which includes both a deviatoric and a volumetric contribution or the deviatoric part only

\[
\dot{\varepsilon}_{ij}^p = \frac{1}{\eta} \{(1 + v)\sigma_{ij} - v\delta_{ij}\sigma_{kk}\} \quad \text{or} \quad \dot{\varepsilon}_{ij}^p = \frac{1}{\eta} s_{ij} = \frac{1}{\eta} \{\sigma_{ij} - \frac{1}{3}\delta_{ij}\sigma_{kk}\} \tag{14}
\]

where, \(\sigma_{ij}, s_{ij}, E\) and \(\eta\) are the stress in the Maxwell element, the stiffness of the spring and the viscosity of the dashpot, respectively.

It is possible to derive a modified Young’s modulus for Hooke’s law, which still relates the elastic strain to the stress, but also includes the contribution from the dashpot. The strain decomposition equation can easily be extended to include the plastic strain contribution from the soil plasticity model(s), which gives a corresponding change to the stress update equation.

4.5. Creep model(s) – mechanical tests

In the current work, tensile tests have been used to directly extract information about the viscosity. In addition two other tests, 3-point bending and buoyancy trials have been used to calibrate the pressure sensitivity of the viscosity.

![Figure 12](image1.png)

**Figure 12.** Creep tests - constant load applied at different temperature levels. (a) Tensile test, (b) 3-point bending test and (c) extracted viscosity for the dashpot.

The measurements confirmed that only the organic binder showed a clear tendency for continuous creep during loading in tension. This behaviour was also observed for 3-point bending, where constant loads in mechanical tests showed creep effects and submerged bars in liquid aluminum similarly showed time dependent deformation due to buoyancy. The tested inorganic binder system did not show a significant tendency to creep in any of the load cases.

4.6. Thermal expansion

In addition to the mechanical tests used for calibrating input data for the constitutive models, dilatometer measurements are needed to determine the thermal expansion.
Figure 13. (a) Thermal expansion of quartz sand showing the $\alpha$-quartz to $\beta$-quartz phase transformation. (b) Expansion of an E-motor housing water jacket core using quartz sand to the left and Bauxite sand to the right.

The measurements show a large expansion for quartz sand in general plus a significant amount of expansion for the $\alpha$-quartz to $\beta$-quartz transformation around 570 °C. The thermal expansion of quartz sand has a significant influence on the deformation of the sand core. Other sand types showing less thermal expansion should be selected in cases where expansion becomes critical for the performance of the sand core.

4.7. Buoyancy – organic cores
For cold box cores in general the deformation is not only governed by thermal expansion. Also, density differences between the core material and the metal leads to buoyancy forces, which leads to time dependent deformations in long slender cores. Several tests were performed in a demonstrator mould where several bars with different dimensions were submerged into liquid metal. Aluminium and lead alloys were used to promote different levels of buoyancy forces at different temperature levels to evaluate the difference of bending coming from thermal expansion and buoyancy forces. As seen in figure 14 below the bending of the sand cores is significantly larger for the lead alloy due to the bigger difference in density.

Figure 14. Bending of cold box cores due to different levels of buoyancy forces for (a) aluminium and (b) lead, respectively.

The results were compared to optical measurements, where in-situ deformations were measured on the tip of the small domes sticking out of the melt. The domes are seen on the bending bars in figure 14.

4.7.1. Marine application example. Buoyancy and creep effects can lead to critical levels of deformation in cast parts during production when organic binder systems are used. A core package used for marine application Al-castings is shown in figure 15. Requirements in the design are a free end of the relatively long cylinder shaped cores. For the cold box system this free end allows the core to deform
as function of time due to the small buoyancy forces, see the upwards deformation in figure 15(a). Results from the core simulation were used to pre-shape the core box to compensate the deformation in the final part and it was possible to obtain straight castings within the required tolerances. To illustrate the different behaviour of the inorganic system, where no creep is taking place at elevated temperature, a similar deformation result is shown in figure 15(b). The result shows that the cores do no deform in a similar upwards direction and only thermal expansion gives a volumetric contribution to the deformation components. This gives an almost straight casting without any pre-shaping of the core box.

4.7.2. Automotive oil gallery example. Castings used in automotive applications often include long slender cores to shape interior channels and thin-walled designs, e.g. water jacket cores and oil gallery cores. Similar to the example above this can lead to critical levels of deformations due to buoyancy and creep when cold box cores are used. An automotive example is shown in figure 16, where bending of a thin-walled oil gallery core is measured at room temperature by sectioning the engine block and scanning the interior parts optically. The predicted deformations are shown in figure 16(a) and compared to the measurements in figure 16(c). The comparison shows an overall good agreement between the predicted results and the measurements. The illustration in figure 16(b) indicates how the footprint of the core on the cast part is governed by the sand material before a sufficiently strong shell of cast material solidifies around the core. This might be obvious, but it is nevertheless important information which is needed to be considered for a proper description of the mechanical interface between the sand core and the cast material.

Figure 15. Evaluation of bending due to buoyancy and creep. (a) cold box – bending of the fee ends due to creep and (b) inorganic – no creep and hence no bending

Figure 16. Deformation of a thin-walled oil gallery cores due to buoyancy and creep. (a) Simulation result, (b) governing deformation contributions at different temperature levels and (c) results compared to optical measurements at room temperature.
4.8. Moisture content – inorganic cores

The influence of moisture content on the mechanical behaviour is possible to take into account for the simulation of hot distortion of inorganic cores. Wet inner regions of partially hardened cores and regions with high moisture content due to condensation are modelled by removing the elements from the simulation domain or by reducing the strength and stiffness in the elements as function of increasing moisture content. To illustrate the influence of different moisture content on the bending strength several sand cores with different hardening time are shown in figure 17. The diameter of the wet centre increases with decreasing drying time, in the curves going from left to right. Taking the different moisture content into account in the simulation shows how the overall different stiffness of the bars lead to a faster increase in the stress level on the lower surface of the bars, which resembles their lower bending stiffness and strength.

![Curves of applied load and Contours of longitudinal reaction forces](image)

**Figure 17.** Inorganic bending bars with different drying time and corresponding different measured bending strength.

5. Outlook

Printed sand cores have gained an increasing interest in the last years. The design freedom of 3D printing in general makes the technology very attractive for highly complex geometries where other methods are not applicable or would require assembly of several subcomponents. The process is based on a powder bed technology where a re-coater distribute layers of sand followed by a printing step where the print head bond the sand grains using the jetting process to form the final geometry of the core, see figure 18. Compared to the traditional manufacturing of sand cores the method is known to have directional dependencies in the mechanical properties and the density is typically reported to be lower compared to methods where the sand is compacted during manufacturing.

![Powder bed and print head](image) ![Binder nozzles for the jetting process](image)

**Figure 18.** (a) Powder bed and print head. (b) Binder nozzles for the jetting process. Images shown on [www.exone.com](http://www.exone.com)
The surface quality of the printed sand cores shows visible signs of the layered process. It is therefore necessary to have a post treatment cleaning step after the printing process to ensure a sufficient quality of the sand core surface, see figure 19.

**Figure 19.** (a) 3D printed water jacket core and (b) surface quality after preparation of the layered surface. Examples from www.voxeljet.com

Measurement of bending strength and thermal expansion coefficients indicate that simulation of the mechanical behaviour of 3D printed sand cores will require an anisotropic formulation to take the print direction into account. Especially the z-direction is reported to have a lower strength compared to the x-direction of printing.

### 6. Conclusions

Simulation of the sand core manufacturing steps from core shooting, curing and hardening, to the application of the sand core in the casting process is today state of the art in designing and analysing the stability of the sand core. The two-phase flow simulation of the core shooting step gives a detailed knowledge about the flow inside the core box, which is useful knowledge to ensure a core box design where the sand is homogeneously distributed. The subsequent curing and hardening analysis highlight critical areas using the gas effectiveness result for the cold box system and the moisture content result for the inorganic binder system. The moisture content result makes it possible to ensure that the hardened dry surface is sufficiently thick to avoid moisture from the inner part of the sand core to move to the interface of the casting during the casting process. Results from the core manufacturing process are used for the subsequent casting process to analyse the degradation of binder and transport of gases and moisture to evaluate if the pressure at the interface between the sand core and the liquid metal reaches critical levels to form gas defects.

Today, it is possible to simulate hot distortion of sand cores during the casting process. The material is described by porous soil plasticity models with a creep extension to include the time dependent deformation of e.g. the cold box system. Various standard mechanical tests are needed at different temperature levels to provide input for different stress states to the yield surface description. Dilatometer measurement of the thermal expansion describes the expansion of the sand core during heating, which is needed to analyse the dimensional stability of different sand types. In addition to the thermal strain it is possible to include the deformations from buoyancy effects due to density differences between the sand core and liquid metal.

The paper presents how the full lifecycle of the sand core is integrated into useful models and predictive tools which can be used to analyse the core design and stability before the sand core is put in production. The tools and results form the basis of the important digital twin used in industry today, where digitalization and quantification of material behaviour including sand cores become increasingly important to meet quality requirements.

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