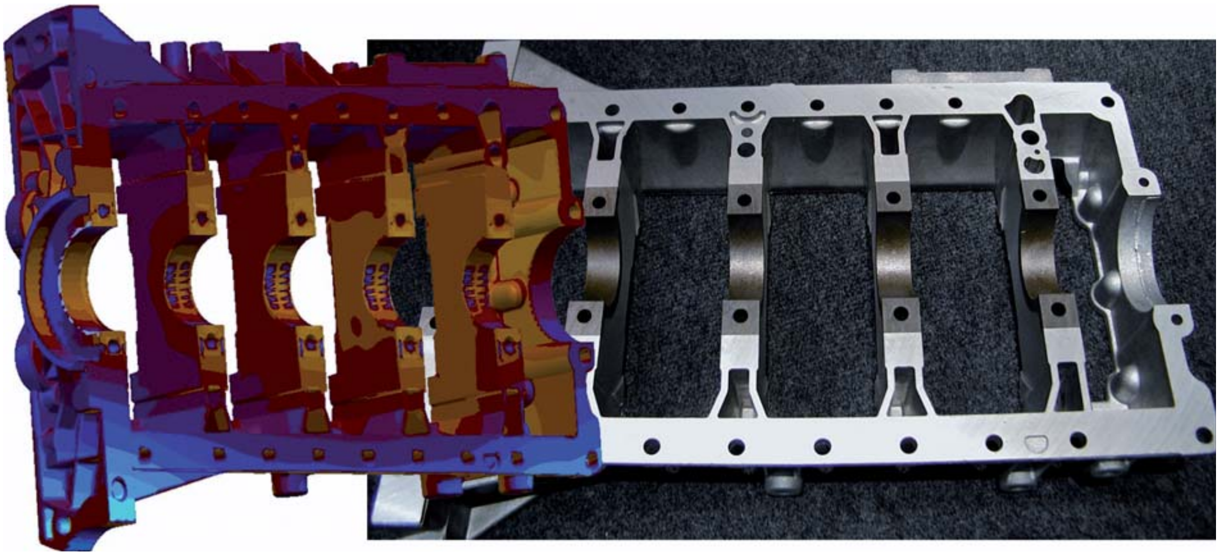

Castings whose properties are improved by inserts are technically challenging. However, effects such as the control of microstructure or distortion can be predicted with the help of casting simulation (Photo: MAGMA)

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Material combinations in light-weight casting components

Aluminum and magnesium castings play a major role in light-weight casting. The fields of application are being extended continually, and the specific demands on materials are increasing. More often the mechanical or tribological properties of the casting materials are insufficient, the operating temperatures are too high, or the environment shows a high level of chemical aggression. Local component properties can then be tailored to specific demands by cast-in inserts mostly made of steel or cast iron, depending on the requirements. During pouring, these inserts cause various and sometimes not uncritical phenomena. For instance, the molten metal is chilled locally, which can block flow paths during mold filling. Non-uniform cooling of the casting causes residual stress, distortion and, in some circumstances, cracks and fractures. The same problems may occur due to the differences in heat conductivity and thermal expansion of the paired materials. This article shows how possible residual stress, distortion and crack formation can be calculated and reduced, if necessary, even before the first parts are cast or prior to heat treatment

Predicting the properties of hybrid cast components

Light-weight components can be manufactured by using special designs or special materials. Amongst the numerous conceivable possibilities to achieve weight reduction, the combination of materials offers an enormous potential for cast components. From the design to the production of a casting, however, particular attention must be paid to the specific characteristics of combined materials.

In cast components a combination of materials may, for instance, lead to special complex residual stresses or specific phenomena during castings production.

Many of these phenomena can nowadays be predicted and assessed with the help of casting process simulation, i.e. computer simulation of mold filling, solidification, formation of microstructure and material properties, so that a methodically developed basis is available for the design and production improvements that are usually necessary.

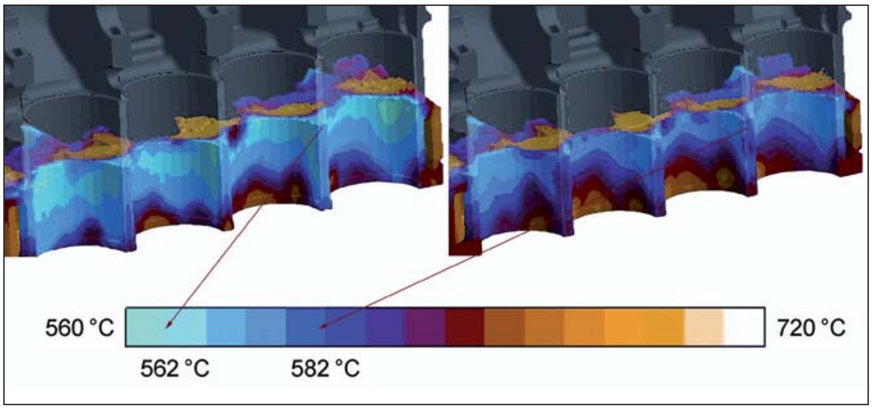

Figure 1: Temperatures of the aluminum melt flowing between the cooler gray-iron liners. When the pre-heating temperature of the liners is higher (left), the temperature is uncritical; when the temperature of the liners is lower, the liquid metal cannot fill the seam completely (right). This is an aluminum sand casting with induction pre-heated liners

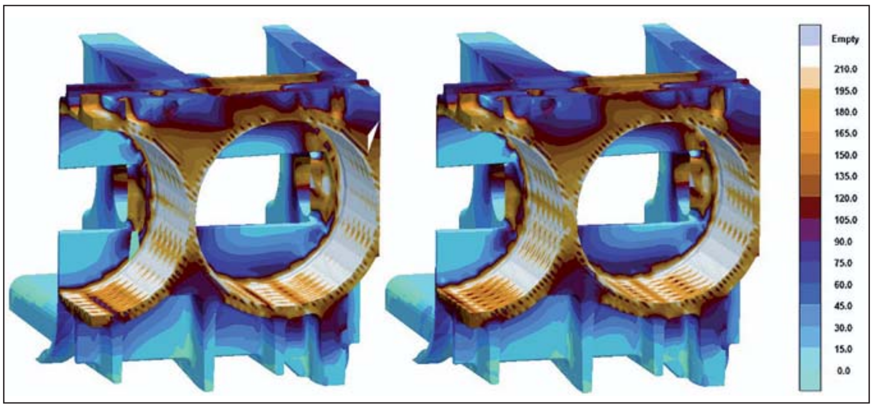

Figure 2: Maximum principal stress (the highest occurring tensile residual stress) in aluminum around a liner as cast. Notice the high internal stresses in the gap between two liners and the uneven stress around the liner. Closer distances of the liners (left) result in higher stress (206 MPa) than larger distances (187 MPa; right). This is a die-cast engine block

Material properties – local solidification and cooling conditions – distribution of component properties

The design and calculation of castings as regards stiffness or endurance limit are mostly based on the assumption of standardized properties. This disregards the fact that locally different conditions during the solidification and cooling of the casting to ambient temperature lead to locally different microstructures and, consequently, to locally different mechanical properties.

A high solidification rate, more precisely, a high speed of the solidification front, supports among other things the formation of small dendrite spacing, finer grains and, consequently, higher grain boundary energies or reduced segregation. All these microstructural parameters affect the mechanical properties of the material, such as elongation at fracture, tensile strength and modulus of elasticity, but also the Woehler curve. Since the solidification rate varies locally due to different wall thicknesses or the quenching effect of inserts in hybrid components, the above-mentioned mechanical properties are also distributed in the casting within certain limits.

For these reasons, further cooling after solidification also varies locally within the casting with different phases forming in different areas, or with one and the same phase forming in different ways. This also applies to heat treatment where e.g. different cooling rates during quenching can cause inhomogeneous distribution of mechanical properties.

Lastly, every casting method has its own, very characteristic distribution of mechanical properties. In die casting, the rapid cavity fill – most dies are filled in less than 100 ms – and high pressures in the liquid metal with the resulting good contact of the melt with the cold die wall lead to a very dense, fine-grained and segregation-free casting skin. This often results in higher creep rupture strengths under alternating stress than the material properties of the alloy may suggest.

The characteristics of castings also include residual stresses, which particularly in hybrid castings arise from the different stiffnesses of the materials typically involved. In all aluminum and magnesium castings in which inserts made of cast iron, steel or magnets take over specific functions the matrix material shrinks onto the insert. This process is fundamentally linked to the fact that the matrix material – i.e., aluminum or magnesium – builds up tensile residual stress, balancing the residual compressive stress in the insert. This process of stress development in hybrid castings is inevitable; it is, however, often ignored in component design.

Material models, geometry models and simulation of a casting process

For the computer simulation of casting processes material models are used that describe numerous phenomena characteristic of metal casting, depending on the alloy.

Rheology

As long as metals do not cool down below the solidus temperature dur-

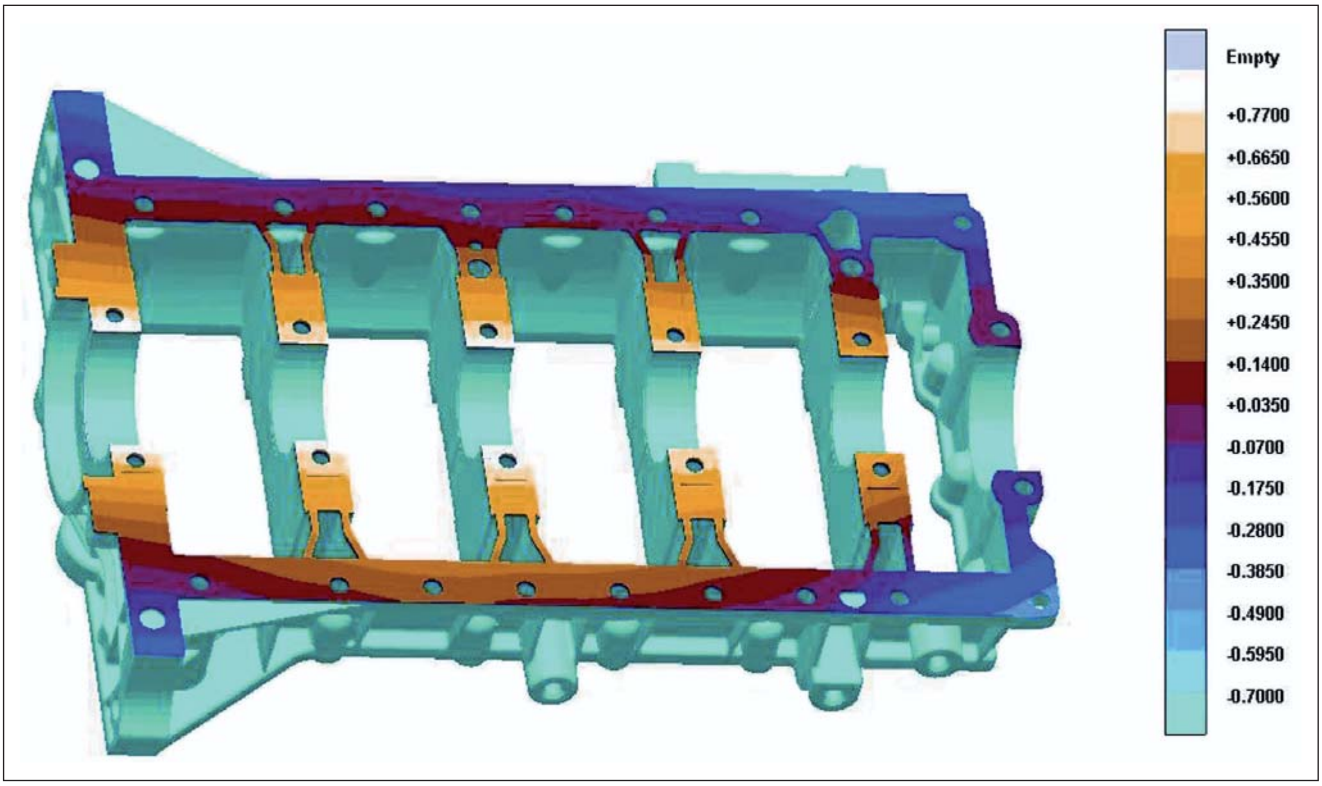

Figure 3: Dimensional variation of a ladder-type frame as cast. The illustration shows the dimensional variations in the direction perpendicular to the reference plane (Z direction). The simulation shows a dimensional difference of up to 1.0mm between the corner points of the ladder-type frame and the seats of the support surfaces of the bushings

ing mold filling, the viscosity hardly changes with the temperature or alloying element content. The surface tension can play an important role, especially when oxide layers are formed at the free melt surface. The pertinent models are state-of-the-art tools. The melt flow becomes more complex when solidification starts before the end of mold filling and the partly solidified melt displays a shear-rate-dependent and temperature-dependent viscosity. However, apart from casting processes where a partly solidified melt with more than 35% fraction solid is deliberately pressed into the mold, this condition is avoided. These models, too, are state of the art.

Solidification

The solidification of molten metals usually starts from a number of nuclei contained in any melt. Nucleation is mainly controlled by the foundryperson who, consequently, also influences the resulting characteristics of the castings, such as grain size, formation of eutectic cells or phase formation.

Between the start of solidification at liquidus temperature and the end of solidification at solidus temperature the increase in the proportion of solidified phase as the temperature decreases follows certain solidification models. Both nucleation management and various solidification models are used in the simulation of casting solidification. These models are able to reproduce solidification conditions even under disequilibrium conditions – as is essentially the case in metal casting. In this manner, casting process simulation can not only determine the formation of the casting as a function of temperature, but also the formation of various phases in the microstructure or parameters, such as dendrite arm spacing.

Formation of residual stresses and distortion

In this area the use of elasto-plastic models is state of the art. Viscoplastic models are typically used for the mapping of creep processes at high temperatures or for heat treatment.

The simulation of casting processes is fundamentally about the calculation of components. Therefore, apart from the material models, the geometry models, i.e. 3-D CAD models of castings, gating and feeding systems, molds and dies are also needed.

They are cross-linked automatically, such that automatic cross-linking in just a few minutes of, for instance, entire pressure die casting dies with temperature-control channels, the casting with runner and overflows, complies with state-of-the-art technology.

Aluminum engine block with grey cast iron cylinder liners

Nowadays, such engine blocks are latest mass production technology. For sand casting, the grey-iron liners (lamellar graphite iron, LGI) are set into the mold and pre-heated, while for pressure die casting they are pre-heated and then placed into the die assembly. In both cases the liners are subsequently swept by a stream of liquid aluminum that cools rapidly when it comes into contact with the liners and solidifies more quickly than the molten metal that is not in contact with them. In the process, it may happen under certain circumstances that the melt does not fill the mold completely and already solidifies in some small areas before the end of mold filling. As the casting cools and solidifies, residual stress definitely occurs due to the existing temperature gradients as well as the different coefficients of expansion and stiffness of aluminum and cast iron. Both phenomena may become critical; they are, however, predictable with the help of casting process simulation.

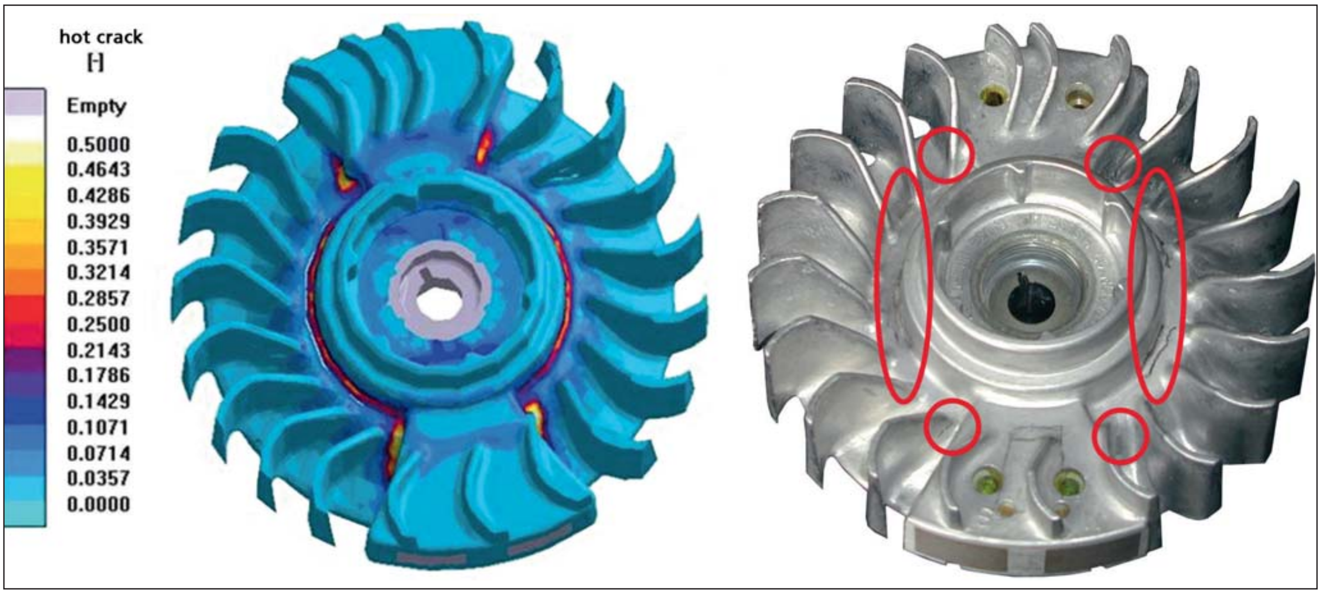

Figure 4: In the immediate vicinity of the magnetic inserts this flywheel/fanwheel develops hot cracks during solidification. The almost solidified melt is brittle, and critical shrinkage rates are exceeded

Flow behavior of aluminum between gray cast iron liners

During cavity fill of aluminum cylinder blocks with LGI liners, the area between the liners is often critical. For example, the distance between the liners can be minimized in favor of lightweight construction, in which case numerous components in and around the engine may also be designed with smaller dimensions, among which the crankshaft, camshafts, air intake manifold and exhaust manifold are certainly the most important. Minimization of the liner distance, however, entails the increased risk that the molten aluminum may no longer fill the gaps between the liners. This risk can be assessed using casting process simulation and be calculated for various distances (**Figure 1**). It enables the design engineer to spot the manufacturing conditions and risks at the design stage and prevent them by taking engineering measures. Later, with the start of full-scale production, casting process simulation also helps determine the optimum pre-heating temperature. On the one hand, this supports the flow of liquid aluminum around the liners, and on the other hand, the cycle time or the energy needed for pre-heating is limited to the minimum possible.

As-cast residual stresses in the area between the liners

During cooling and subsequent solidification, the aluminum shrinks onto the relatively stiff, colder LGI liners. When this happens, tensile stress is generated in the aluminum, and at the same time the liners are put under compressive stress. Different internal stresses are developed depending on the distance between the liners (**Figure 2**). Often the tensile residual stress in the aluminum between the liners is high; however, this is probably uncritical as any cracks developing in this area will have a low effect on the overall rigidity of the cylinder block at operating temperature.

Pre-heating of the liners also has an effect on residual stress. Essentially, the tensile residual stress in the seam between the liners decreases as the pre-heating temperature rises.

Ladder-type aluminum frame with grey-iron bearing shells

In general, ladder-type frames are manufactured by aluminum pressure die casting with inserted bearing shells made of lamellar graphite iron or steel. Where the different materials are combined the same phenomena occur, in principle, as in the above-mentioned example of aluminum cylinder blocks with LGI liners. Distortion of the casting is made even more critical by the fact that the cold bearing shells are not completely immersed in aluminum. The temperature gradients resulting over the entire cooling of the casting, especially in the direction perpendicular to the mounting level, will generally cause distortion, in which the bearing shell arches away from the engine block toward the oil pan (**Figure 3**). Casting process simulation helps in providing proof that distortion is characteristic and is virtually impossible to eliminate by means of casting methods. Distortion, however, is quantifiable by simulation, so that appropriate machining allowances and measures can also be determined at the design stage.

Reducing the weight of the bearing shell would be quite desirable from the point of view of light-weight construction, which would automatically translate to a reduction of distortion.

Magnesium flywheel with cast-in magnets

For small engines used in mobile machinery, such as chainsaws, weight reduction has always played a major role. One example of a casting which, firstly, is weight-optimized and, secondly, contributes to the weight optimization of the entire unit by fulfilling several functions simultaneously, is a magnesium flywheel performing the function of an impeller and carrying the magnetos. Such castings are susceptible to hot cracking in the areas around the inserts, which is formed while these areas solidify. If a critical solidification rate – and, consequently, shrinkage rate – is exceeded here, cracks are formed because the liquid metal cannot get to that location quickly enough to “cure the crack” (**Figure 4**).

Summary and outlook

The weight of a cast component can be optimized e.g. conservatively by material-adapted design or through the use of design-adapted materials. Special opportunities, however, can be found in combinations of materials in one casting by cast-in components which locally make specific mechanical, tribological or even magnetic properties possible. On the other hand, this potential is certainly counterbalanced by more complex, high-risk and ultimately more expensive casting processes.

In order to minimize the engineering risks in connection with setting up new casting concepts, reliable yet rapid and low-cost simulation is one of the most important elements. Casting process simulation has been continuously updated at universities for over 35 years and, for more than 25 years, industrially and on a large scale. New models are developed, basic research is driven by the pressure of model developers, and every year hardware manufacturers offer more powerful processors and computer architecture. Taken together, all these measures will certainly lead to improved forecasting of simulation programs, the end of which no-one currently knows.

Nowadays casting process simulation is predominantly used to optimize casting processes. For maximum benefit, however, the identification of local casting properties referred to in this article can be applied well in advance of casting the first parts, namely at the stage of design and computational construction. Here, the state of simulation technology is considerably ahead of the current state of integrating the simulation of production-related issues. The potential for improvement of computerized casting construction by integrating casting process simulation is very high, since the main problem has been the distribution of mechanical properties and residual stresses linked to the casting process. Nonetheless, as the examples presented show, these effects are computable and can be exploited in computerized casting construction.

This article is based on a lecture held at the VDI conference "Simulation im automobilen Leichtbau" in November 2011 in Baden-Baden, Germany.

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