Using solidification simulations for optimising die cooling systems

The goal for designing a cooling and heating system in a die is to achieve an optimal part quality and to improve tool life. Simulations provide important information about the cooling lines and their location in relation to the cavity.

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The diecasting industry is currently evaluating and discussing how close a cooling line can be located from the die cavity to influence the temperature of the casting and to restrict thermal stresses in the die. By influencing the cooling of the casting, in particular the hot spots, it is possible to reduce shrinkage porosity in the part. However, thermal stress levels have to be considered to avoid cracks in the die cavity.

The use of water-cooling in particular causes a large temperature gradient between the cooling line and the die cavity. To provide conclusive results, Schaufler Tooling tested a number of variations through filling and solidification simulations using Flow-3d simulation software.

Simulation as an aid to die design

During the last decade, simulation has become an essential tool in developing and designing a new diecasting die. It is true that, when evaluating the simulation results, it must be remembered that the simulation represents a model of the physical process. This model cannot represent reality in an absolute exact way.

When considering this restriction, the leading simulation programmes achieve great accuracy, so that, as will be shown, high conformity can be anticipated when comparing the results of the simulation with those of the actual casting process.

Simulations are still not common for the design of die cooling systems. Flow and heat transfer equations on which the calculations are based are complex and hard to treat mathematically. Also, most common simulation programmes used today do not calculate the flow of the heat transfer fluid (oil or water) in the cooling and heating lines.

If the influence of the medium is taken into consideration, the physical influence of the cooling and heating lines can be calculated by defining the cooling line as a cavity in the die, which has a heat transfer coefficient, a temperature of the fluid and a heat radiating surface. An example for the definition of such boundary conditions may be seen in fig. 1.

Example of a cooling optimisation

Optimised cooling depends to a large extent on the part to be cast, thin-walled structural parts requiring more uniform heating near the die cavity. This applies especially to magnesium castings, which need to be heated more than cooled.

Thick-walled castings like engine block dies behave differently. In this case it is not possible to remove the heat by means of cooling lines only so spraying a water-soluble lubricant on the die surface is added. With thick-walled castings, the cooling has, in addition to the general heat flow, the function to cool down hot spots in the casting to reduce shrinkage porosity or, if that is not possible, to shift this porosity towards areas where quality is less impacted and part functionality maintained.

Additionally, it is necessary to cool down superheated areas of the casting and/or the core pins, which otherwise are likely to break down prematurely.

To obtain information on the effect of cooling on both die and casting, Schaufler Tooling proceeded as follows. Initially, a solidification simulation of the casting with a uniform die temperature provides the designer an aid for the determination of the cooling lines (fig. 2). Secondly, total casting cycle simulations are carried out considering the cooling and heating lines. Similar to the actual production cycle, during which a steady state for temperature is reached after five to 10 castings, various casting cycles are simulated.

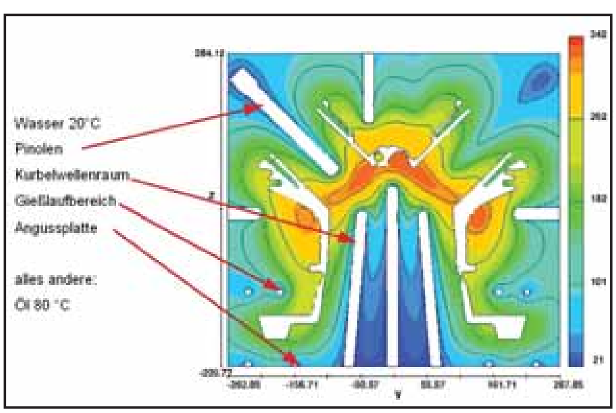

Fig 1. Initial layout of cooling lines for the simulation

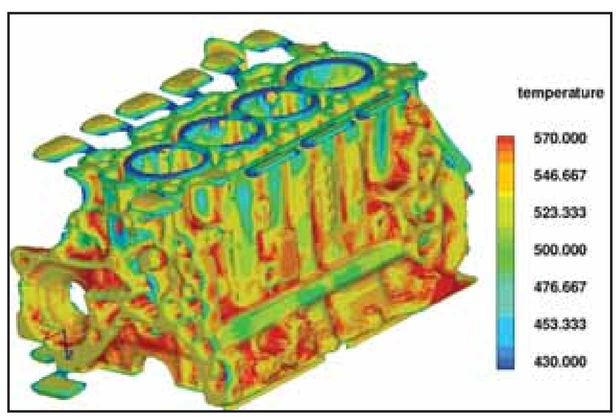

Fig 2. Temperature distribution after solidification

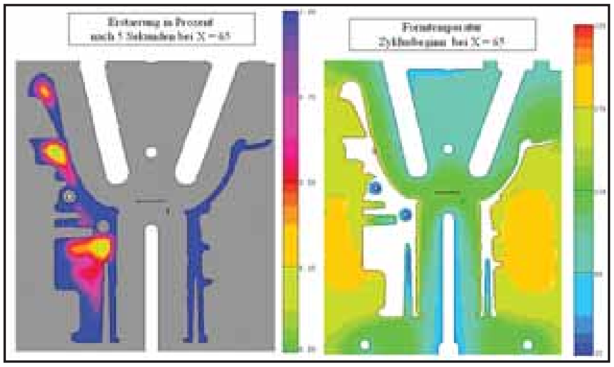

Fig 3. Percentage of solidification in the casting after five seconds (left) and die temperature at the beginning of cycle (right)

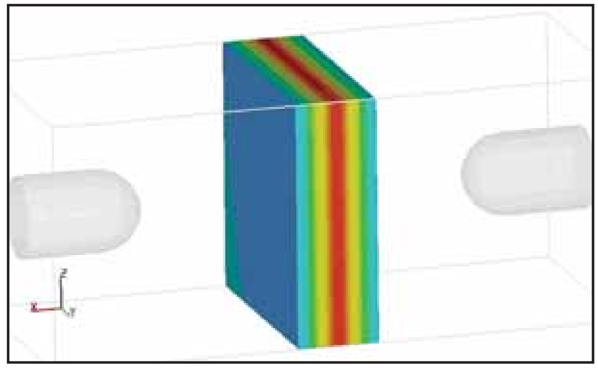

Fig 4. Simulated section: in the centre a section of the casting, left and right the cooling lines

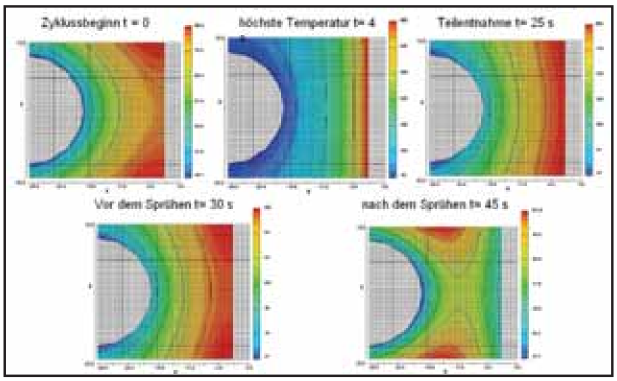

Fig 5. Temperature in the die between casting (right cavity) and cooling line (left cavity)

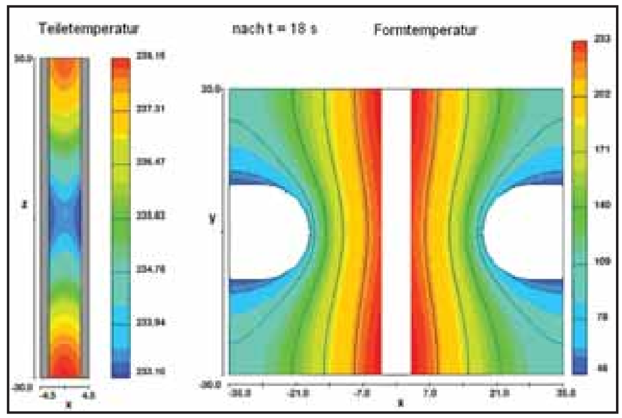

Fig 6. Influence of the casting temperature and of the die with a 6mm thick wall with cooling lines located 15mm from cavity

When a constant casting quality is achieved, a simulated die temperature close to reality is used and the actual solidification simulation can be conducted.

When analysing the simulation, the temperature distribution in the casting and the cooling effect can be evaluated (fig. 3). Then, the position of the cooling lines will be modified, if necessary, and another simulation carried out. The aim of an optimised cooling is to achieve a solidification pattern that allows an extension of intensification by the plunger.

Distance between cooling line and cavity

For a detailed examination of temperature and stress, a section of the casting and a matching die wall of the casting will subsequently be analysed using fountain cooling on both sides of the wall (fig. 4). To measure the effect for the proximity of the cooling line and the cavity has on the solidification behaviour of the casting and simultaneously the material fatigue in the die, the actual temperature pattern of the die is of great importance. The result of the simulation shows that the highest temperature in the die does not occur during the removal of the casting, but - as shown in the simulated example - approximately four seconds after the beginning of solidification.

When spraying a water-soluble lubricant, the die surface will have a remarkable temperature drop in this area. Up to the beginning of the next cycle, the temperature moves again from the centre of the casting towards the cavity (fig. 5).

For simulation purposes, a 6mm thick casting wall with the cooling lines at a distance of 15mm (fig. 6) was assumed, during this simulation the cooling effect on the die temperature and the solidified casting was determined. The result showed a drop in the casting temperature in the area cooled of about 5˚C.

If assuming a 20mm thick casting wall, the temperature level of the casting and the die remains considerably higher in comparison with the 6mm thick wall. The temperature gradient is considered an important factor to indicate the local differences in temperature. Therefore, with a wall thickness of 20mm in the die and approximately 20˚C per millimetre, the temperature gradient is much

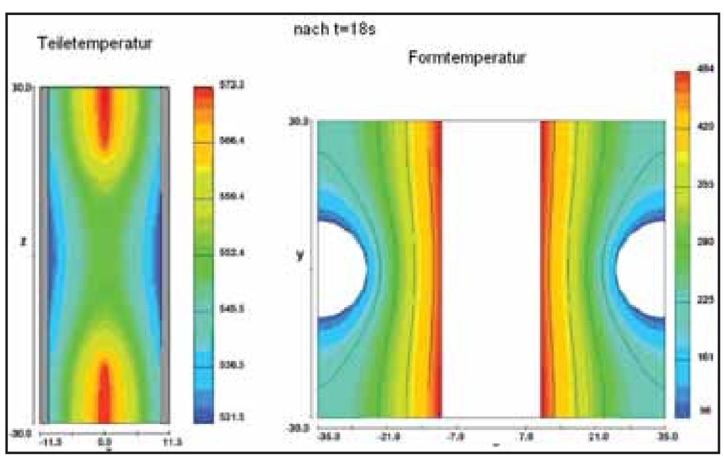

Fig 7. Influence of the casting temperature and of the die with a 20mm thick wall with cooling lines located 15mm from cavity

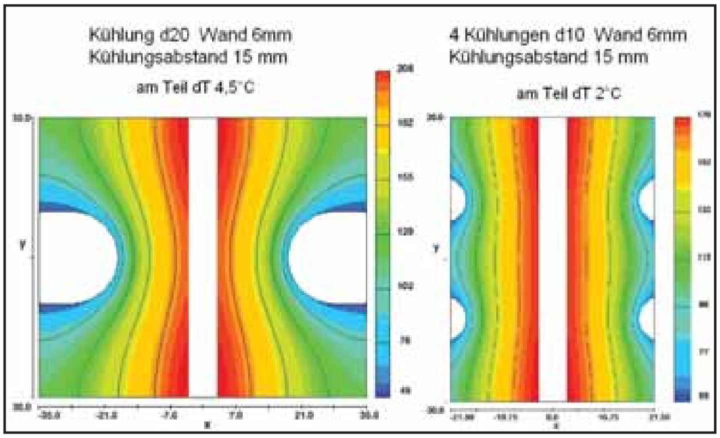

Fig 8. The effect of one or more fountain cooling lines arranged in parallel

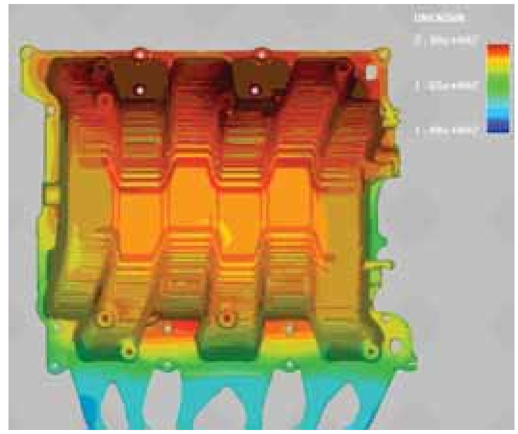

Fig 10. Simulation: of die temperature on the casting ISO surface

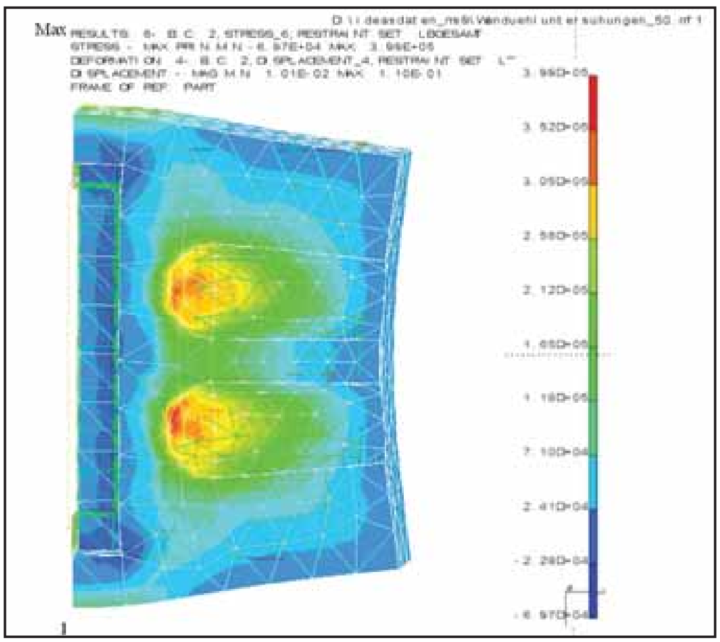

Fig 9. FEA calculation of thermal stress

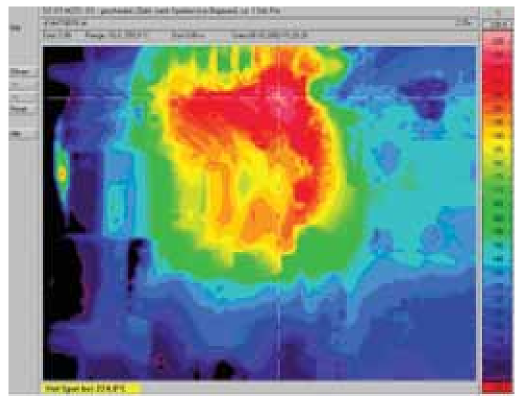

Fig 11. Picture of the die temperature made using the infrared camera

higher compared with a 6mm thick wall and approximately 15°C per millimetre (see figs. 6 and 7).

Subsequently, the distance of the cooling lines from the casting wall was varied during simulation. With a distance of 30mm between the cooling lines and the cavity and a 6mm thick wall, the variations showed a minimum influence, whereas no direct influence on the casting temperature could be noticed with a 20mm thick wall.

This is an important discovery regarding the cooling of single hot spots, cooling lines having a big influence on the temperature level of the die as a whole. As far as the cooling down of hot spots is concerned, cooling lines may only take effect when they are as near as possible to the cavity. However, thick-walled areas are generally difficult to influence by cooling systems and therefore the optimisation of the casting itself and the elimination of hot spots are the only ways to avoid shrinkage porosity in certain areas.

It can be concluded that a steady drop in the casting temperature can be achieved by the use of several fountain cooling lines arranged in parallel at a distance of 15mm (fig. 8).

Thermal stress

Another aspect regarding the design of cooling systems is the occurrence of cracks in the tool steel and thus reduction of die life. The temperature gradient in the die between casting cavity and cooling lines may serve as criteria for thermal stress in the die. The simulation results show that at the beginning of the casting solidification a high temperature gradient develops directly on the cavity and after one second, causes a high stress level in this particular area.

Subsequently, the temperature moves into the die. After some 11 seconds an almost linear temperature distribution is reached. The greatest temperature gradient on the side of the cooling lines appears after approximately 25 seconds, reaching a value of around 35°C per millimetre. After 45 seconds, the simulated spraying of water-soluble lubricants causes the die surface to be cooled down by 20°C, resulting in additional stresses on the die cavity.

In order to get a reference value for the developed thermal stress, the values obtained during the simulation were transferred to an FEA calculation programme (SDRC IDEAS) and thus the stress in the die was calculated (fig. 9). The stress calculation showed the following values. With a 6mm thick casting wall and a distance of the cooling lines of 10mm, the temperature gradient is about 17 °C per millimetre. On the cooling line, stresses in the die will reach approximately 400 Newton per square millimetre.

The variant with a 15mm distance of cooling lines showed the highest temperature gradient of 15.6°C per millimetre after approximately eight seconds. Because the temperature gradient is correlated to the stress level, it will be lower than the calculated 400 Newton per square millimetre.

The steel 1.2343 (H11) often used in the diecasting industry has a relatively high strength of σ_{02} = 1370 Newton per square millimetre. When calculating the strength on dies it is appropriate to set the yield stress to approximately 600 Newton per square millimetre providing a double safety margin.

Another important conclusion that can be drawn from the study is that with a 6mm wall thickness the distance between cooling lines and cavity can safely be 10mm, potential for cracks in the cavity being unsubstantiated. Further analyses shall demonstrate the effect of temperature gradients on a wall thickness of about 20mm.

Verification of solidification simulations

In order to verify the simulation results the analysed values were compared with those obtained during the actual casting process, tool temperature being recorded with an infrared camera.

A comparison of the pictures made during the simulation with those made with the infrared camera at the moment of opening the die shows the following results.

- The middle temperature at the runner lies both during the simulation process and with the camera pictures at about 130°C. During the simulation process the highest die temperature lies at 230°C and with the camera picture at 235°C (figs.10 and 11).
- It was therefore concluded that there is a good correlation of the measured results at the machine and those of the simulation. This confirms the benefit of using a simulation for the analysis and optimisation of the diecasting processes. Thus, the simulation can supply the designer with valuable information on the design of cooling and heating systems, especially if cooling lines near the cavity are desired.