SIGMASOFT®

Process and design integrated
injection molding simulation

Successful cycle optimization and quality improvements based on process simulation results

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Abstract

Injection molding is the first step in the production chain of MIM applications. It determines part quality, as faults induced here cannot be mended out later on. The green part quality and the scrap are therefore permanently targets for optimization. Additionally MIM producing companies start to care about cycle times of each sub-process. It becomes especially important when continuous sintering ovens are used. Consequently, the performance of injection molds for MIM becomes critical. Appropriate analysis tools are required to identify optimization potentials, in order to reduce cycle times and increase quality. This paper describes the experience of a MIM producer about how process-integrated injection molding simulation supported efficiently a new mold development. By understanding the interaction between feedstock, mold components and mold tempering system, drawbacks in the mold design were identified early. Innovative solutions were found to avoid local hotspots; cycle time was reduced and article quality improved in parallel.

Introduction

In the past, when discussing possible optimization potentials with MIM producers, the answers often lead towards topics like scrap, segregation, sinter warpage etc. Cycle time, the key topic in thermoplastics production, didn’t play a significant role for feedstock injection, due to the bottleneck of batch-wise sintering. Nowadays, based on the increasing success of continuous sinter ovens, the minimum achievable cycle time during the molding phase becomes economically interesting and thus the thermal performance of the injection mold.

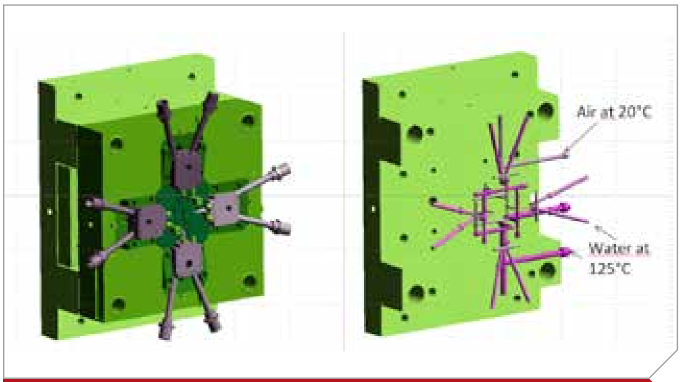
In the past years, MIM simulation and corresponding publications focused mainly on rheology [1, 2]. This topic was important as feedstock rheology is different compared to for e.g. thermoplastics simulation. Accurate rheology is the key to simulate flow patterns right, which is essential to reliably design gates and to decide for gate location. The feedstock solidification however was not discussed in detail and neither were the consequences regarding induced stresses or required cycle time. Even the performance of the injection mold was interpreted regarding the significant influence of rheology [2] but not regarding economical savings due to possible cycle time reductions. It can be concluded that injection simulation has been available in the industry for some years now, as an efficient tool to reduce time to market and to identify flow-related issues, such as jetting, pressure or flow front propagation. It has been proved that simulation can help identifying part quality issues related with the filling behaviour of the part. Effects such as particle segregation can nowadays be predicted [1]. It has also been proved that conventional thermoplastic simulation is not accurate enough to reproduce the complex rheological phenomena occurring in MIM applications and that expanded rheological models have to be used, in order to capture the increase in the viscosity which occurs at low shearing rates [2]. However, the state of the art in MIM simulation goes far beyond. Not only the part itself can be simulated, but the whole mold, with all its components, can be considered easily [3, 4]. The thermal behaviour of the mold, the way it heats-up due to heat exchange with the tempering channels, can be today predicted accurately. Furthermore, the coupled heat exchange between melt and cavity can be calculated [5].

Additionally, this can be done over several production cycles, so that the effect of residual heat from one cycle to another can be considered in the simulation, until the mold-melt system has achieved a steady production state - in the same way as it occurs in reality. And the case study presented in this paper nicely shows that MIM producers start to care about these details of their molding processes. They better understand how the green part quality develops. They can reduce mold trials and iteration in steel significantly. And they appreciate that reducing cycle time saves money.

Problem description

A renowned European supplier of MIM applications had a new project with the challenge of producing a cylindrical MIM part with a dome-shaped end on the top, slightly outside the center line. This dome-shaped end had to be thin walled with wall thickness down to 0.3 mm and tight dimensional tolerances. To generate this thin-walled hollow cavity a quite long and slim mold core was required. Due to strong constraints regarding possible gate positions, an imbalanced melt pressure load on this core and a possible core deflection was expected. During the mold design, the magnitude of the expected deflection was completely unclear and thus whether the dimensional requirements on the part could be fulfilled reliably or not.

Additionally this mold showed up with a second challenge. The part designer needed a small hole of 1.6 mm diameter throughout the whole part, which again required a long slim mold core. Unfortunately this core goes through the thickest walled area of the part, which is supposed to be a huge hotspot. Questions regarding solidification of the feedstock in this area raised, void probability was discussed and different approaches about how to eventually cool down the core and to keep cycle time under specifications were discussed.



- Figure 1 – Movable half of the mold.
  Left: 4-cavity mold configuration.
  Right: Tempering and base of the mold.

To answer all these critical questions efficiently and on schedule, the costumer decided for a consultancy project with SIGMASOFT®. This paper discusses some of the project results. Due to confidentiality reasons, the actual part geometry cannot be shown. The company conceived a four-cavity mold, as seen in Figure 1. Each cavity had its own tempering for the core creating the dome-shape, to reduce the thermal-induced deformation and to increase the cycle time. The mold has a central tempering system for the movable half and another one for the fixed half. In both tempering systems, the set temperature of the coolant was at 125°C.

Initially, a thermal analysis of the mold was completed, in order to determine how effective was the tempering for the complete mold and on each one of the slides. Afterwards, variations in the tempering in contact with the parts were analysed. In a third stage, the filling and cooling of the part were considered and finally the magnitude and direction of the core deformation were calculated.

Thermal analysis of the mold

Instead of assuming a homogeneous initial temperature of the mold for the simulation, a complete thermal analysis was done, to reproduce the exact temperature conditions in each one of the cavities and thus to represent the real production status of the mold.

The first step was to analyse the actual thermal performance of the mold concept. All the parts in the mold, each one with its own thermo-physical material properties (e. g. specific heat capacity, heat conductivity, density), were integrated in the simulation and a so called “multi-cycle” analysis was completed. In this case, the real heat exchange conditions found in production are reproduced in the simulation.

To most people this multi-cycle simulation appears to be complicated and difficult to use. The reality is quite the contrary. Due to more than 25 years’ experience in the 3D technology behind SIGMASOFT® the setup of a multi-cycle simulation is easy and straightforward and its time-to-results is productive. All mold geometries are taken from 3D-CAD, the required finite-volume mesh is generated automatically and the necessary process parameters are easy to define for a MIM producer. The advantages for the small manual effort are significant: the actual transient, non-stationary behaviour of the mold becomes transparent at any location inside the mold - not only where a sensor is located.

In the analysis, the mold starts, just as in production, at room temperature, and heats up due to the action of the tempering channels. In this case, the mold was allowed to heat up during 30 min and then a “virtual production” was started: several production cycles where simulated, one after each other, with the same process definition parameters as in a conventional production cycle: closing of the cavity, injection of the feedstock, post-pressure, cooling stage and opening of the mold. All the time frames are reproduced, just as in reality, and by means of this multiple cycles run one after each other. The additional “heating up” of the mold, produced by the melt entering the cavity in each cycle, is also simulated. In each simulation all the thermal properties of the elements involved, as well as the heat transfer regimes, are considered.

As a consequence of this multi-cycle analysis, a statement can be made about the performance of the complete thermal system, regarding energy efficiency and – in this case – regarding the efficiency of the core cooling. Beyond this, the coupled heat transfer phenomenon between melt and cavity is considered, and the real production conditions are reproduced accurately, which is in this case important to simulate the core deflection accurately.

As shown in Figure 2, it was evident that the proposed system worked fine for the fixed half of the mold, delivering a homogeneous temperature for the cavity at the point where production should be started. The temperature differences in the cavity itself where of less than 2°C. However, the tempering system for the movable half was not efficient, and temperature differences between 114°C and 120°C where evident after 11 simulated injection cycles. This inhomogeneity in the cavity affected negatively the balancing of the cavities.

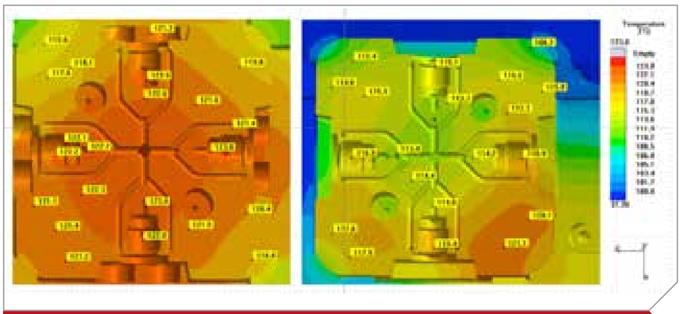
Optimization of the tempering system in contact with the part

In a second stage, the tempering in contact with the part was studied. The cooling of the small-diameter hole that went through the part was studied, as well as the tempering of the core responsible for the dome-shaped geometry.
Based on the basic mold design, two different variations were simulated to investigate alternative tempering approaches addressing the cooling of the long slim core and reducing the hot-spots there. Due to geometrical restrictions a tempering by pressurized air, at room temperature, was one of the most promising approaches.

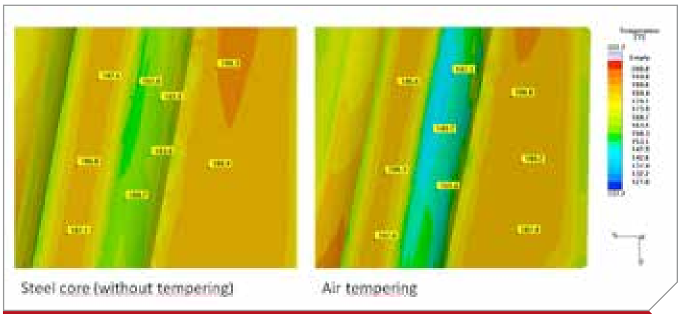
Figure 3a shows a comparison of two simulated variants of the core cooling. The simulations are compared just as the filling stage is completed. In the variant presented on left side, the hole through the part was achieved with a steel core, without any tempering. In the right side, the core used was tempered with pressurized air at room temperature.

The results show that a temperature reduction between 10 and 15°C is achieved in the part when the air-tempering system is used. This considerably reduces the appearance of hot-spots and the melt temperature in contact with the insert, with a positive effect on the cycle time. Based on these results the air cooling approach was realized in the mold and produced excellent results.

Afterwards, the tempering in the core which produces the dome-shaped part was studied. To reduce the temperature at this location as the melt flows over the core, initially water was used. The temperature at the beginning of filling (after 10 production cycles) is presented on the left side of Figure 3b. The



- Figure 2 – Temperature distribution in the cavity at the beginning of filling.
Left: fixed half. Right: movable half.



Steel core (without tempering)

Air tempering

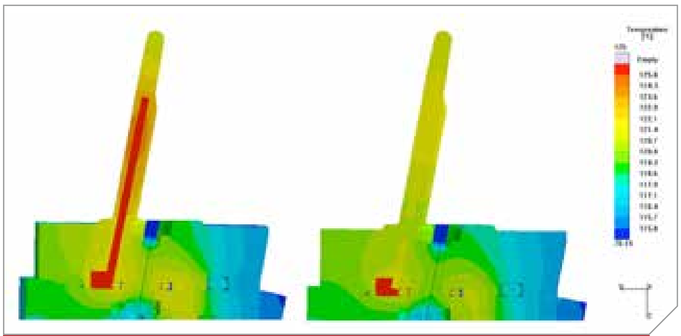
- Figure 3a – Temperature distribution in the part.
Left: region with a steel core without tempering.
Right: region with compressed air tempering at 20°C

water channel is visible. In a second variant, the water channel going inside the core was replaced with a copper road. The temperature is scaled between 115°C and 125°C.

From the figure it becomes evident that the copper alternative achieves a far more homogeneous tempering effect over the core, removing the heat induced by the melt (after 10 production cycles). If only water is used, the temperature in the core is higher, and therefore the cycle time will also be increased. The effect of the part thickness and the heat accumulation over several production cycles is evident in the left side: the thicker region of the part is also the region where heat has lower chances to migrate towards the mold, an effect that over several cycles results in a heating-up of the core. On the contrary, when copper is used, the heat is efficiently transported from the core to the mold, and the positive effect of the lower mold temperature benefits also the critical region where the dome has to be shaped.

Filling and cooling behaviour of the part

In a filling analysis of MIM parts, it is possible to determine which kind of flow pattern is present in the melt, how homogeneous is the filling of each cavity and how do the melt parameters behave as the melt flows into the mold. Due to the 3D-approach of SIGMASOFT®, parameters as melt temperature, pressure, viscosity or shear rate can be determined at every point and at every time during the filling and cooling stages. Each cavity had two ingates, placed opposite to each other and symmetric around the core. With this configuration it was desired to balance the filling pressures around the core and to minimize its deformation, which could negatively affect the dimensional accuracy of the part as described above.



► Figure 3b – Tempering inside the dome-shaped core.
Left – tempering with water at 125°C
Right – tempering with a copper core

The analysis of the filling behaviour of the part allowed concluding that the part filled with jetting flow, due the abrupt change in the cross section between ingate and part. Towards the end of the filling stage, an imbalanced filling appeared, and a speed up of the melt was evident in the thinner dome of one of the cavities, precisely in the location which was critical due to the core deflection.

This unbalanced filling of the dome in the part was a result of the inhomogeneous tempering of the mold. Such an effect can also appear as a consequence of shear heating, resulting from the interaction of metallic particles. In a detailed analysis of the melt behaviour, it was possible to find locations where the viscosity was reduced only in some of the cavities, and only in one side of the part.

Another interesting parameter during the filling analysis is the behaviour of the shear rates. In this case, it is possible to identify locations where the shear rates are high, and therefore segregation of the metallic particles can appear. In this analysis, the highest shear rates were found at the ingate, where the melt entered the cavity, and at the dome-shaped end of the part, where the thinner section is present. While high shear close to the gate often creates surface defects, the high shear in the dome area helped here to actually fill the cavity completely despite the 0.3 mm wall thickness.

Once the filling has been completed in all the cavities, the cooling behaviour of all cavities can be analysed. Interestingly, it was seen that the gates at the cavities froze at different times, an effect that followed the inhomogeneous tempering of the mold, and therefore these cavities had a shorter effect of the post-pressure. This phenomenon was also confirmed later at mold trial by weighting the parts.

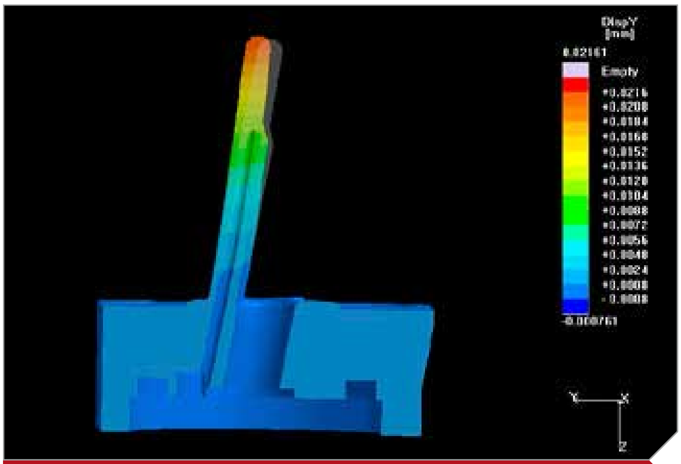
Core deformation

Because all the elements in the mold are considered within the model with its own physical and mechanical properties, the deformation of the core in the simulation, produced by differences in pressure in the melt during the filling stage or by thermal effects, can be analysed. In this case it was also important to determine how big was the thermal expansion of the core, to determine if this thermal deformation together with the pressure induced deformation could negatively affect the dimensional accuracy of the part, and particularly of the dome-shaped end. The deformation of the core, produced by thermal induced effects and by differences in the pressure distribution of the melt around the core, is depicted in Figure 4. The top of the core creates the dome shape of the part. The maximal deformation is present at the end of the core, as was expected for the cantilever configuration, and is measured as 22 µm at the end of the filling stage. The pressure gradient around the core, produced by the inhomogeneous filling of the melt, is partly responsible for this deformation.

The benefit of computer simulation from a MIM producer‘s perspective

For several years, the company in this case study employed external services for the computer simulation of mold filling for challenging MIM components. Generally speaking, the main purpose was to collect information about the kinematics of mold filling as well as pressure and temperature distribution within the mold cavity. This data was utilized to optimise the gate position and geometry as well as the design of mold parting lines. This information alone is of great value. It enables to minimise the number of iteration loops since the tests are not performed on the real tooling, but in the tool design phase. Thereby the lead time of new parts can be reduced by one week on an average, which implies a much greater benefit than the considerable reduction of tool modification costs.

The quality of the finished MIM part is significantly determined by the mold filling characteristics of the green part which can be optimised as well by computer simulation of the mold filling process. Customer requirements on quality vary depending on the industrial sector and application of the component.



► Figure 4 – Deformation of the core.
Transparent is presented the original geometry.

It turned out, however, that this kind of optimisation adds to the stability of the manufacturing process for MIM components and therefore is in the immediate interest of MIM producers as well. However, the present capabilities of the simulation software allow obtaining even more information. In addition to the classical computation of mold cavity filling it is also possible to simulate effects coming from and affecting the periphery of the tooling. By including the subsequent tool design in the simulation the model is based on a broader assumption and more far-reaching results can be obtained. In particular, the thermal design of the tooling and the determination of core deflection should be mentioned here. The cycle time for injection molding has a direct impact on the manufacturing costs. Therefore the reduction of the processing time is always in the focus.

By involving tool design – position and size of cooling channels – in the simulation at an early stage it is possible to modify the thermal design at a stage where the cost-benefit ratio is still particularly high.

Furthermore, pressure distribution data can be utilized in such an extended model to calculate the deflection of sensitive tooling elements such as free standing cores. Hence the injection parameters can be optimised if required or the flow characteristics can be adjusted by modifying the gate position in such a way that the flow around the core is improved.

This multitude of benefits for the MIM parts producer outweighs the high investment and personnel costs for such a software.

At the company herewith referred, this calculation is performed at the own plant on every new part. In addition to the gain in know-how about tool design this investment is seen as a basis for further product and process development and thus as an immediate added value for its customers. •

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About SIGMA®

SIGMA® (www.sigmasoft.de) is 100% owned by MAGMA® (www.magmasoft.de), the world market leader in casting process simulation technology based in Aachen, Germany. Our SIGMASOFT® process simulation solution optimizes the manufacturing process for injection molded plastic components. SIGMASOFT® combines the 3D geometry of the parts and runners with the complete mold assembly and temperature control system and incorporates the actual production process to develop a turnkey injection mold with an optimized process.

At SIGMA® and MAGMA®, our goal is to help our customers achieve required part quality during the first trial. The two product lines – injection molded polymers and metal castings – share the same 3D simulation technologies focused on the simultaneous optimization of design and process. SIGMASOFT® thus includes a variety of process-specific models and 3D simulation methods developed, validated and constantly improved for over 25 years. A process-driven simulation tool, SIGMASOFT®, with its comprehensive simulation approach, provides a tremendous benefit to production facilities. Imagine your business when every mold you build produces required quality the first time, every time. That is our goal. This technology cannot be compared to any other conventional “Design” simulation approach employed in plastics injection molding.

New product success requires a different communication between designs, materials, and processes that design simulation is not meant for. SIGMASOFT® provides this communication. SIGMA® support engineers, with 450 years of combined technical education and practical experience, can support your engineering goals with applications specific solutions. SIGMA® offers direct sales, engineering, training, implementation, and support, by plastics engineers worldwide.