Casting Simulation Drives Component Development for HPDC

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Introduction

To remain competitive in the new global marketplace, component manufacturers in the automotive industry are constantly being asked to increase efficiency while lowering production costs and shortening delivery times. This request from the OEMs for product solutions with low energy consumption in automotive and aeronautic applications, in tandem with new requirements by the government for increased fuel efficiency, can be satisfied using light metals like aluminum and magnesium. The high pressure die casting (HPDC) process enables manufacturing of large, thin-walled structural components to achieve weight reduction. In shape design (HPDC) castings, a large number of different functions can be integrated in one highly complex component, thereby replacing a group of smaller components that need to be manufactured separately and assembled together. Figure 1 shows an interior door panel, an example of a typical load-bearing structure, produced by Georg Fischer Automotive AG for Mercedes-Benz.

The trade-off for this high degree of component integration is the complexity of the manufacturing process. The intricate geometry of the die and numerous technical process parameters must be accurately developed. A critical aspect, in the case of the production of large, thin-walled components, is the dimensional consistency within narrow pre-defined tolerances. The foundries develop shrinkage allowances based on past experiences, which are specific for a certain process and alloy. Different chains of events in the manufacturing cycle can lead to non-linear part shrinkage that differ from these predefined allowances. The accumulated small errors in shrink and warpage allowances can have such an influence on the final outcome that the final part is not an acceptable deviation from the defined geometry. An expensive follow-up treatment like component straightening or a time-intensive correction of the die may be required. These corrective measures lead to increased costs and decreased efficiency due to time overruns.

Figure 1 – Component Geometry

The integration of casting simulation in the planning and design of the technical process offers a potential solution to avoid excessive prototypes from being built, eliminating time-consuming trial-and-error methods. By simulating the component deformation and taking into account all relevant casting process parameters, possible sources of tolerance error can be uncovered and minimized in the development phase itself. The presented article shows an industrial example of how the simulation tool was used early in the design cycle to drive component manufacturability.

Relationship between Process Events and Component Deformation

The die and casting are exposed to cyclic, time-dependent deformations during the manufacturing process, which are induced by a varying thermal load. For a better understanding of what happens inside the die during the manufacturing process, it is important to visualize the entire physics, from the time the molten metal enters the die cavity to the ejection and consequent cooling of the part.

Tracking the Die History

The production process starts with the pre-heating of the die. As the die is heated, it expands according to the thermal expansion coefficient of the specific tool steel. During each shot, the hot metal injected into the die cavity solidifies. The heat from the casting, gating system and overflows is transferred to the die. As a consequence of this thermal gradient that forms with hot steel near the cavity and cooler steel away from the cavity and near cooling lines, some parts of the die expand more than others. The die is then opened, and the part is ejected. The die cavity is sprayed, and as a result, the temperature of the die decreases in and near the cavity. Finally, the die is closed and the cycle starts once again. To compensate for the severe thermal loading, the die has a system of oil and/or water channels that regulate the temperature. After some cycles, the temperature level, and therefore also the deformation, reach a stable condition described in thermodynamics as the "steady state temperature." Temperature and deformation continue to be time and location dependent, but this behavior repeats itself in cycles that follow.

Tracking the Casting Component

This thermal history of the die and successive expansion and contraction of various die regions due to the heat release of the casting, cooling/heating lines, spray and other phenomenon creates a die cavity shape which is different, or "pre-deformed," from the initial shape of the cold steel. Each shot fills a slightly different cavity shape until a true "steady state temperature" is achieved. Depending on the distance the metal travels in the die, different regions in the casting may cool down in an

Table 1 – HPDC technical process parameters.

Technical Process Parameter			
Type of the Machine	**Die Temperature Control**	**Temperature**	**Flow Rate**
Casting Alloy	**Oil Channels Fixed Side**		
Casting Temperature	Frame		
Cycling Times	Lock Area		
Die Opening	Hinge Area		
Part Ejection	B-Pillar		
Die Closing	Sill Area		
Parameter of the Filling	**Oil Channels Moving Side**		
Diameter Casting Chamber	Frame		
Plunger Velocity First Phase	Lock Area		
Plunger Velocity Second Phase	Hinge Area		
Time of the Switch from First to Second Phase	B-Pillar		
Spray Parameter	Sill Area		
Spray Location	**Water Channels**		
Spray Duration	Cone Counter Part		
Temperature Spray	Casting Chamber		

irregular fashion. At the end of the filling, areas which are further away from the gating system are typically colder than those near the biscuit. The casting solidifies depending on the geometry and local temperature conditions. During solidification, most metals tend to shrink. However, due to the die constraints, certain regions are prevented from shrinking as the metal solidifies. In these areas, stresses are formed in the part until the yield stress is exceeded, which leads to plastic deformation. In other areas, where free shrinking can occur, the part loses contact from the die surface, and a gap is formed, influencing the heat transfer between the casting and die.

In the next stage of the HPDC process, when the part is ejected, the die constraints are removed, and the stresses in the part transform or relax into further deformations. This behavior is called the "spring-back effect." A similar behavior can be observed during the trimming of the gating and the overflows. At the time of ejection, a varying thermal gradient exists throughout the casting part. Since areas with different temperatures contract in different amounts when they finally cool down to room temperature — hotter areas will shrink more than colder ones — the final part shape is based on this non-homogeneous temperature field.

Table 1 shows all the technical parameters that influence the final behavior of the casting and die. Since each process parameter influences the temperature field in a specific way, modifying any parameter will have an influence on the entire system. The influence of these parameters can be quite complex to measure without numerical simulation. A DOE will be a very time-consuming and costly alternative.

Deformation Prediction by Using Casting Simulation

The most important aspects of the computer simulation are not only to capture all the physics of the process, but to also simplify the model in such a manner to minimize the turn-around time without compromising on accuracy. A typical

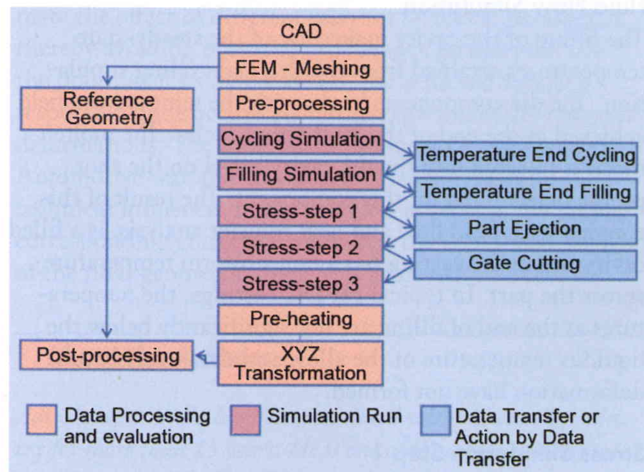

Figure 2 – Simulation procedure flow chart.

flow chart of the simulation procedure is shown schematically in Figure 2. All simulation steps were performed on the interior door panel model shown in Figure 1 with the ProCAST casting simulation software package.

Pre-Processing

The CAD-data from the die including cooling channels, casting component with gating system and overflows were imported into the analysis software. Based on this information, a finite element mesh (FEM) was generated for those die components, which had most effect on the production of the casting. During the pre-processing stage, the thermo-physical material properties and various boundary conditions were assigned to the FEM model corresponding to the specific process conditions.

Cycling Simulation

A cyclic thermal simulation is performed to achieve the steady state temperature in the die. For simplification, fluid flow effects are not considered. At the beginning of each cycle, the casting part domain is assumed "filled" with the

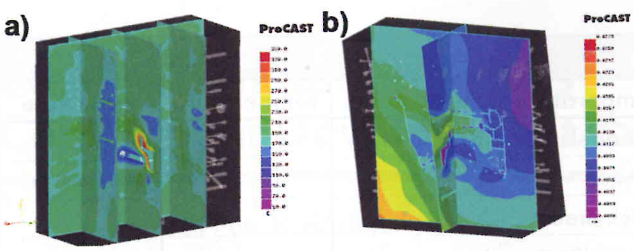

Figure 3 – a) Temperature distribution at end of 10 cycles; b) deformation due to thermal gradient.

alloy assuming the casting pouring temperature. Process steps like die-opening, spraying and die-closing were described by time-dependent boundary conditions. Figure 3a shows the temperature distribution at the end of 10 cycles in different sections of the die. Figure 3b shows the deformation of the die corresponding to the thermal field shown in Figure 3a. The maximum deformation observed was below 0.2 mm and was located far from the cavity. Therefore, the influence of this deformation in reaching the die operating temperature was not taken into account in order to save calculation time and to reduce the duration of the project.

Fluid Flow Simulation

The filling of the cavity makes use of the steady-state temperatures attained from the thermal cycling simulation. The die components begin with the temperature field achieved at the end of the 10 thermal cycles. The molten metal is injected into the die cavity based on the shot profile determined for this component. The result of this, coupled with fluid flow and heat transfer analysis, is a filled cavity where the casting has a non-uniform temperature across the part. In typical HPDC castings, the temperatures at the end of filling are not significantly below the liquidus temperature of the alloy, and thus, stresses and deformation have not formed.

Stress Simulation Step 1

The stress simulation starts with the temperature field obtained from the end of fluid flow analysis (when the die cavity is completely filled). A coupled thermal-stress simulation was performed. For the casting alloy, an elasto-plastic material model with temperature-dependent mechanical material properties was applied. For sake of simplification, the die is regarded as ideally rigid. Small displacements in the casting appear in areas where the shrinkage is not prevented or constrained. In certain areas, the casting part partially loses contact with the die cavity surface, which dramatically reduces the heat transfer between the casting and the die. The casting simulation tool automatically accounts for this by reducing the corresponding local heat transfer

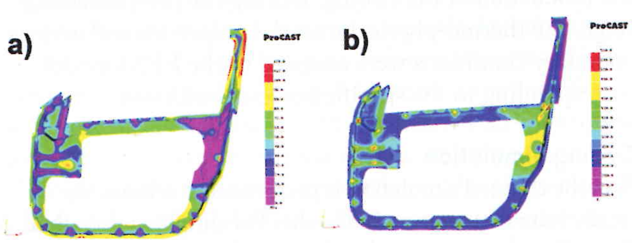

Figure 4 – a) Von-Mises Stresses before ejection; b) casting temperature before ejection.

coefficient during solidification, based on the thickness of the gap formed. In areas where shrinkage is prevented due to die constraints, stresses appear. Figure 4a shows the Von-Mises stresses just before ejection of the casting part, while Figure 4b displays the corresponding temperatures.

By comparing the two results, it becomes quite evident that areas with a higher temperature have low stresses and vice versa. To explain this behavior, the stress and temperature values at selected nodes were identified and plotted together with the temperature-dependent mechanical properties of the cast aluminum alloy. As seen in Figure 5, the observed stresses are all between yield stress and the ultimate stress limit. This can be explained as follows: before the temperature field displayed in Figure 4b is reached, the casting has already passed through a high temperature difference, at minimum a change of more than 200°C. The corresponding thermal contraction combined with local constraints formed by the features in the cavity induces stresses much higher than the yield stress. Therefore, the stresses developed in the local area are already partially reduced by plastic deformation.

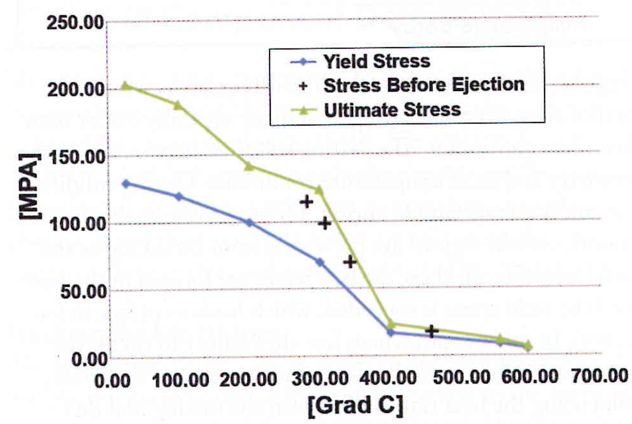

Figure 5 – Mechanical properties of the casting alloy.

Stress Simulation Step 2

This part of the simulation focuses on the ejection of the casting and the subsequent cooling to room temperature. The simulation is performed on the FE mesh of the casting part, including gating and overflows. In this separate analysis, the stress and temperature state of the casting region at the time of ejection in the previous analysis is transferred to the casting region of this new analysis, which now does not include the dies. On ejection, the component tends towards a new equilibrium state when it is free from the constraints of the die. The stresses on the component are relaxed and transform to a corresponding amount of deformation. Figure 6 shows the calculated stress state immediately after ejection. The second important influence consists of cooling down of the component to room temperature starting from the non-homogeneous temperature field at the time of ejection from the die. Figure 4a and Figure 6a clearly demonstrate the change in the part stress state before and after ejection from the die. Figure 6b shows the temperature distribution just after ejection. In Figure 6b, some hotter areas in the component are clearly visible (circled). When these areas cool down to room temperature (Figure 6b, right image), they shrink slightly more than the surrounding area on the left side, which is a bit colder. The upper part of the

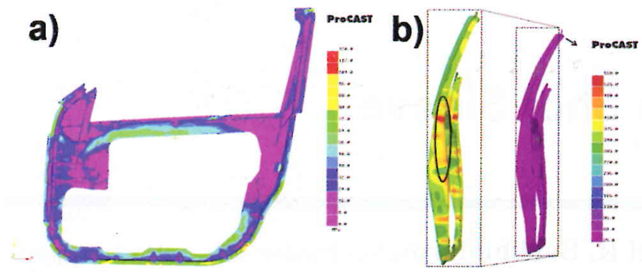

Figure 6 – a) Von-Mises stresses after ejection; b) temperature homogenization after ejection.

door structure deforms inward due to this phenomenon (see arrow) and, as a result, does not conform to the required geometric tolerance.

Stress Simulation Step 3

In this step, the cutting of the gating system and the overflows are taken into account. The principle is quite similar to the one in the stress simulation Step 2. The temperature and stress fields from the previous simulation are used as an input into this new analysis. Since the gating system is mostly hotter than the part (thicker cross-section), the gating system tends to shrink at a different rate than the component. As a result, transverse stresses are initiated in the area of the ingates, the point of contact between the gating system and the part. Here, the stress solver determines a new equilibrium at the first step of the calculation.

Post-Processing

Results are calculated in accordance to the CAD data of the die, including the initial temperature from the preheating cycle. Assuming a uniform pre-heat of the dies, the linear expansion of the die is given by the product of the temperature difference between pre-heat temperature and room temperature and the linear expansion coefficient of steel. In the presented example, a pre-heat temperature of 200°C was used, which corresponds to a scaling factor of 0.23%. The results are accordingly scaled by this factor. The point of interest is not just the deformation of the die but the displacement in relation to the part reference geometry. For this reason, the FEM mesh from the casting part is reduced by the shrinkage factor and used as the reference to determine the final deformation.

Deformation is always related to a certain coordinate system. In the quality assurance department, the deformation of the door panel was determined by clamping the component in a measurement device without influencing the part shape. Then, the coordinates were measured at pre-marked

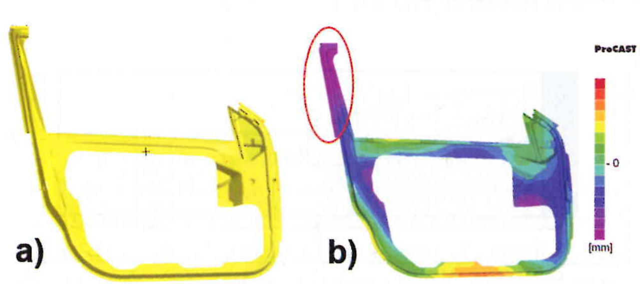

Figure 7 – a) Locations where deformation is measured (red dots); b) deformation prediction results.

measurement points (Figure 7a). In the same manner, the results from the simulation were transformed onto the same reference coordinate system. The final deformation results are shown in Figure 7b. The indicated area in Figure 7b shows where the component does not meet the requested tolerances (displacement values hidden for confidentiality).

The simulation results obtained by component-producer Georg Fischer Automotive accurately matched the direction of the deformation and the order of magnitude observed in reality.

Conclusion

The HPDC application enables large, thin-walled castings to be manufactured with a high degree of accuracy through the integration of multiple functionalities. An ambitious goal for the die design engineer during the process development stage is to maintain dimensional accuracy of the component while engineering the die and accommodating modifications during development and still be able to produce a quality part on the first run on the shop floor. Through casting simulation, one can estimate the effect of different relevant technical parameters, thereby avoiding potential problems in production. On the door panel study presented, the achieved results corresponded quite accurately to the experimentally observed deformations. The component producer Georg Fischer Automotive was able to correctly identify the critical technical influences in the production process. By taking corresponding corrective measures, the demanded accuracy of the final geometric shape was achieved.

About the Authors

Adi Sholapurwalla has been associated with the casting industry for more than 15 years. He is one of the core members in the development of ProCAST, the world leader in casting simulation software. He has been associated with several NADCA, AFS and ICI committees. He is currently the director of engineering at ESI NA.

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Ole Koeser (born 1964) finished his studies of physics at the University of Bremen (Germany) in 1993. From 1996 on, he has been working in the domain of casting simulation with ProCAST. Since 2003, he has been with ESI in Switzerland, where he is responsible for innovative projects.

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