DETERMINATION OF PRESSURE CORRELATION FACTORS TO IMPROVE THE QUALITY OF INJECTION MOLDING SIMULATIONS

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Abstract

Injection molding simulation is taking an increasingly important part in the development of new plastic components and in tool and mold making. However, in particular, the results of the filling pressure simulation frequently deviate from the filling pressures occurring in the injection molding process, so that injection molding tools are often oversized and too large injection molding machines are used for serial production in order to ensure the complete filling of the component cavity.

The aim of this paper is therefore to define a correction factor which can be used to infer the pressure losses of an injection molding simulation to the real pressure loss that occurs in the injection molding process, the under- or over-dimensioning of injection molding tools and the use of injection molding machines which are too large or too small to avoid.

For this purpose, a correction factor has been defined which consists of three individual correction factors, each taking account of the influence of the material used, the influence of the injection molding machine used and the influence of the component geometry to be produced. In addition, an addendum has been defined which maps the pressure loss of the screw of the injection molding machine used.

The tests were carried out with five plastics: polypropylene (PP), acrylonitrile-butadiene-styrene (ABS), a blend of acrylonitrile-butadiene-styrene and polycarbonate (PC/ABS), polycarbonate (PC) and polyamide 66 (PA 66). Four factors from the control variables were defined and their influence on the injection molding process was systematically investigated using the means of statistical experimental planning. These factors are the melt temperature of the plastic, the coolant temperature, the injection speed, and the residual cooling time. Factor levels have been defined in order to examine the effects in a defined process window.

Introduction

The amount of plastic components processed by injection molding of plastic components takes between 25% [1] and 28% [2] based on the amount of all plastic processed. After extrusion, this is the second most important process in the production of plastic components [1, 2]. In the development of a plastic component, which is produced by means of injection molding, a corresponding injection molding tool is to be laid which contains the negative of the plastic component to be produced. Both the injection molding tool and the plastic component to be produced are increasingly subjected to simulations.

Primary forming simulations and reshape simulations are just as much a part of today's everyday life as structural mechanics simulations [3]. However, the ability to simulate sciences is often not sufficiently understood. The modeling for the different simulations cannot keep up with the increasing requirements as well as the effective and efficient use of modern computing machines [3].

Increasing demands on plastic products and a progressive functionalization of the components ensure that plastic components are becoming increasingly complex and that the potential for product development is being exhausted. In the same way, the production tools, in particular the injection molds, become more complex. In order to be able to estimate the fundamental possibility of the large-scale production and mass production of different plastic components by means of injection molding, more and more injection molding simulations are now being used. In addition, the production of complex plastic components by means of injection molding is simulated at various stages of the product development in order to be able to estimate, in addition to the basic filling capacity of the tool cavity, for example the required filling pressure, the temperature of the plastic melt or also the shrinkage and distortion of the plastic components.

While the rheological filling simulation of plastic components already achieves good results with imaging accuracies of up to 99% compared to practically performed filling studies, the further results of the filling simulation are always worse because they are based on the rheological results. With respect to the pressure, deviations of several hundred percent between the filling pressure from the filling simulation and the filling pressure which actually occurs can thus arise. At present, the results from a delay simulation are rather qualitative, since the results can be ten times the actual delay.

Due to these, in some cases considerable deviations, the injection molding simulation is not given much
confidence in practice. The work preparation, i.e., the definition of an injection molding process and the selection of an injection molding machine on which the components are to be manufactured, is also difficult since it is not yet possible to estimate the actual filling pressure. The injection molds are generally oversized, which means that the individual plates of the injection mold are selected to be thicker than necessary in order to avoid pressing or excessive deflection of the plates. The injection molds become larger, heavier and more expensive. Adjustments to the component cavity in the injection mold are still necessary in order to obtain salable components. The number of iteration steps can be reduced by the injection molding simulation, but if the distortion in the injection molding simulation is calculated incorrectly, further adjustments are necessary which cause high costs.

**Thesis**

Between a real injection molding process and its simulation, there is a not negligible difference in the temporal printing process in the injection molding process. The filling simulation calculates the pressure loss over each filled element as a function of time. Non-filled elements are unpressurized. The result is a pressure profile in which the maximum pressure at the injection point is present and the flow fronts of the plastic melt are pressureless. The difference between a real injection molding process and its simulation can be represented by a correction factor (pressure correction factor) (1).

\[ p_{re} = K \cdot p_{sim} \]  

\( p_{re} \) Real injection pressure at the nozzle of the injection molding machine \[ \text{bar} \]  
\( K \) Total correction factor [-]  
\( p_{sim} \) Simulated pressure loss \[ \text{bar} \]

The pressure correction factor depends on three influences, each of which can be represented by its own correction factor. These factors form the influence which results from the material used, the influence of the geometry of the injection-molded article to be produced, and the influence of the injection-molding machine used (2).

\[ K = K_W \cdot K_M \cdot K_G \]  

\( K_W \) Influence of the material [-]  
\( K_M \) Influence of the machine [-]  
\( K_G \) Influence of the part geometry [-]

The pressure correction factors do not interfere with one another. It is assumed that the machine correction factor depends primarily on the material used, but not on the geometry.

The geometry correction factor depends mainly on the thickness of the structure, the flow path length, and the presence of geometric elements (latching hooks, snap connections, mass accumulations such as screw domes or ribs).

The material correction factor includes the quality of the data available in the material database, or the differences in the individual parameters for the currently used batch. It is independent of the component geometry and the injection molding machine used.

**Injection Molding Process**

Injection molding is one of the most frequently used primary molding processes in the plastics processing industry.

The plasticized (molten) plastic does not flow into the cavity by itself, since this is braked by flow resistors (for example, viscosity). The flow resistors are overcome by generating a mostly hydraulic pressure. In this case, pressure losses occur due to friction of the viscous media at each hydraulic element (lines, valves, hydraulic pump). These continue in the plasticized plastic. The resulting pressure profiles for an injection molding cycle are shown in Figure 1 [1]. The injection molding machine must generate a significantly higher pressure (item H1, figure 1) in order to completely fill the component cavity (item W2, figure 1). The pressures at positions H1 and H2 have been converted to mass pressures by multiplying the hydraulic oil pressure by the ratio of piston surfaces. At the measuring positions, which are between the H1 and W2, the pressure loss can be seen by the hydraulic consumers.

![Figure 1. Pressure propagation from the hydraulics to the flow path in the tool (all pressures are converted to mass pressures) [1]](image_url)
of the outer edge layers are influenced. The flow front speed is constant in this phase so that the internal tool pressure increases linearly. The point B is switched to reprint. The compression phase between points B and C follows. In this phase the contours of the tool are formed. If the pressures are too high, a burr may form and the injection mold may be damaged. Between points C and D, the pressure acts before the sprue is sealed at point D. During the holding pressure, the shrinkage is compensated, but also the crystallization of the plastic and the orientation of the macromolecules is influenced. The isochoric cooling of the component takes place between the points D and E until it is released from the tool wall at point E [4].

![Figure 2. Qualitative chart of the internal pressure of the mold [4]](image)

The injection molding cycle set on the injection molding machine is simulated with the aid of injection molding simulation software. The correction factor is then calculated from the differences between the real determined pressures and the corresponding pressures from the injection molding simulation.

**Injection Molding Simulation**

An injection molding simulation is the calculation of the rheological processes during the injection molding process and is today the standard of the tool construction and partly in the product development of new plastic components [5, 6]. The following steps must be performed when performing an injection molding simulation [7]:
- Reading of the component geometry
- Networking of the component geometry
- Replication of the distribution system with linear elements or 3D elements
- Possibly. Simulation of the cooling channel system with linear elements
- Selection of the simulation type (compact injection molding, sandwich injection molding ...
- Definition of the materials (plastic, tool material, cooling medium)
- Specification of the process data
- Specification of the calculation scope (filling, packing ...)
- Evaluation and interpretation of the results

In order to perform a simulation, a computable model must first be generated in order to reduce the infinite number of degrees of freedom that a real component has to a computable number. For this purpose, support points, the so-called nodes, are distributed on the surface of the component. The support points are connected to one another by the elements. This divides the surface of the component into small subregions for which the conservation equations can then be formulated. Network creation is therefore the basis for performing a simulation. The networking is usually carried out based on the CAD data of the component. The network maps the CAD geometry in the simulation.

In summary, the injection molding simulation can not sufficiently image the real injection molding process. The melting behavior of the plastic is hardly taken into account, so that a perfectly prepared isothermal pressureless melt is used. In addition, simulation models reality through models. Simplified assumptions are made. Various effects cannot yet be shown, such as inhomogeneities in the molten plastic or the crystallization behavior. The heat transfer from the plastic melt to the tool material and the cooling medium can also not be reliably imaged. General heat transfer coefficients are given, which in practice are dependent on a large number of factors.

The assumptions and simplifications lead to deviations in the results of the simulation. These deviations can be more than 100% when compared to the real situation. The rheological filling of a plastic component can be accurately represented up to 99%. The results of the temperatures and pressures prevailing during the filling are calculated on the basis of the rheological filling. Deviations from 20% of the results from the simulation with regard to the measurements made in real life are to be assessed as good [8, 9]. The results can be evaluated qualitatively and quantitatively from the graphics. Basically, all available comma points are specified, so that an accuracy of the simulation is suggested, which can practically never be achieved.

The experiments are carried out using the tools of the statistical experiment design (Design of Experiments, DoE). The following values are defined as target variables [10]:
- Total pressure correction factor $K$ [-]
- Influence of the machine $K_M$ [-]
- Influence of the part geometry $K_G$ [-]
• Influence of the material $K_W$ [-]

It is not possible to establish an identical injection molding cycle with the various materials listed in Table 1 and the components to be inspected (section Tested Materials and Parts). On the one hand there is no overlap in the processing window of the individual materials. On the other hand, the shot weights and, in particular, the cooling times of the components to be examined are too different. The creation of the test plan is therefore limited to the following process parameters:

- Temperature of the melt ($\Theta_m$)
- Injection speed ($v_{in}$)
- Temperature of the cooling medium ($\Theta_{KM}$)
- Remaining cooling time ($t_{rk}$)

The four factors considered have two factor steps each, resulting in 16 factor combinations. According to [10], a full-factorial experimental plan is to be applied. The Minitab 16 program creates a centrally compiled experimental plan. This is characterized by the fact that, in addition to the factor points, the center point is also recorded in order to create a linear model. Using the center point (mean values of all factors), it is possible to efficiently estimate a quadratic dependency of the target variables of the individual factors [11].

**Tested Materials and Parts**

The materials to be investigated are standard plastics and engineering plastics, which are frequently used in the product development of plastic components. As amorphous thermoplastics, polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS) and PC/ABS blends are investigated. Furthermore, semi-crystalline materials, in particular polypropylene (PP) and polyamide 66 (PA66), are investigated. A representative is selected from each material group, which is already present in the database of the injection molding simulation software. This is necessary in order to be able to compare the existing material characteristics with their own measurements. The materials listed in Table 1 are examined in more detail.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Material family</th>
<th>Material name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borealis</td>
<td>PP</td>
<td>HD 120 MO</td>
</tr>
<tr>
<td>Bayer Material</td>
<td>PC</td>
<td>Makrolon 2405</td>
</tr>
<tr>
<td>Science</td>
<td>PC/ABS</td>
<td>Bayblend T 45 PG</td>
</tr>
<tr>
<td>KUMHO</td>
<td>ABS</td>
<td>ABS 750 N SW</td>
</tr>
<tr>
<td>WIS Kunststoffe</td>
<td>PA66</td>
<td>Preamid A/A149 natur</td>
</tr>
</tbody>
</table>

Table 1. Tested Materials [14].

Since the selected polyamide 66 is not present in the database of the injection molding simulation software, the comparison material Leona 1300S from Asahi Kasei is determined since the Preamid A/A149 nature [12] used almost identical thermal and mechanical parameters such as the Leona 1300S [13].

All tests were executed with the help of a piezoelectric pressure sensor which was placed in the runner system of the mold 3 mm from the screw nozzle (yellow triangle in Moldflow simulation software) as seen in Figure 3.

![Position of the pressure sensor in the mold](image)

Figure 3: Position of the pressure sensor in the mold

The examined components are so-called small plates according to DIN EN ISO 2943. These have an area of 60 mm × 60 mm and differing thicknesses.

The D1 plate represents a comparatively thin-walled component, which cannot be produced easily. Rather, adaptations of the injection molding process are necessary since production with a low melt temperature or a low injection speed is not possible. The cavity can no longer be filled completely since the plastic melt solidifies very quickly. The shot volume is 11.261 cm³. The D2 plate can be manufactured without any problems with all materials considered. The shot volume is 21.144 cm³. The D3 plate is rather a thick-walled component, since the thickness of the building is 3 mm in comparison to the construction length of 60 mm. The filling of the plate does not pose a problem. Care must be taken to ensure that the holding pressure is maintained for a sufficient length of time until the film inlet is frozen in order to avoid incisions or vacuoles in the D3 plate. The shot volume is 31.025 cm³.

A geometrical test body (GP) is used for imaging geometric elements. The geometric specimen was originally designed for ABS. The shot volume of the geometric sample body is 25.394 cm³. In the case of the geometrical test specimen, attention must be paid to the complete filling of the dome. On the back of the dome can not be avoided due to the construction.
The tension test body corresponds to the multipurpose specimen of the form 1A according to DIN EN ISO 3167 and DIN EN ISO 294 1. The tension test body is a classic rod-shaped product. The component width is not much larger than the structural thickness of 4 mm with 10 mm, the construction length is 170 mm against the other dimensions. There are no problems with the filling of the tension test body. Incisions can occur on the angled shoulder. However, these can not be avoided because the plastic melt freezes faster in the test cross-section than in the wider angled shoulder, so that the holding pressure can not have a sufficiently long effect there. The shot volume of the pull rod is 28.763 cm³.

A housing is used as a real component, which is used in automobile construction. In the original state, the housing has a hot runner. This is replaced by the depicted cold channel. The graduation at the upper end of the cold channel is used to determine the pressure near the inlet. The use of an angled remote pressure sensor has to be dispensed with for reasons of space. The shot volume of the housing is 13.38 cm³ including the sprue pin.

**Analyses**

Figure 4 shows the real measured pressure profiles and the simulated pressure profile of the D2 plate from PP. It can be seen that the pressure behavior is not correlated with the real injection molding process since the maximum filling pressure of approximately 460 bar is not nearly reached in the injection molding simulation. If the beginning of the progressive increase to the end of the mold filling (real approx. 100 bar, in the simulation approx. 100 bar), clarified by the red circle, it becomes clear that the values are nearly identical. However, this coincidence is a coincidence. There are differences of up to 200% in all other measuring series.

![Figure 4: Measured and simulated pressure signals (D2-plate, PP)](image)

The calculations carried out are carried out by way of example at the center point of the D2 plate made of PP. The evaluation of the other points of the test plan and of the other geometry and material combinations is analogous. Figure 5 shows the real measured and the simulated pressure losses of the proximity sensor position. The index "MF" stands for the material data set contained in the material database of Autodesk Moldflow Insight 2014. The index "AKT" (Applied Plastics Technology) stands for the material data set, which contains the self-determined material coefficients. According to (1), the total correction factor K is calculated as the quotient of the actual measured pressure loss and the pressure loss simulated with the material data set contained in the Material Database of Autodesk Moldflow Insight 2014.

The filling simulation is also terminated after reaching the volumetric filling of the cavity, so that the pressure is increased to the defined holding pressure of 200 bar. The time at which the injection pressure from the filling simulation increases from the maximum of the mold filling to the holding pressure of 200 bar corresponds to the predetermined hydraulic response time (0.2 seconds). The actual occurring pressure tip is not visible. However, the pressure point is essential for the component quality, since otherwise the component is not filled completely and the holding pressure would be selected too low, which would lead to sinking points and vacuoles in the component. The pressure peak also represents the highest pressure in the injection molding cycle and is therefore necessary for selecting a suitable injection molding machine for manufacturing the corresponding components. The print tip also acts throughout the injection molding tool since the maximum of the near-green green curve and the remote black curve is the same. This means that the film is not frozen at this time. Without the knowledge of the pressure tip, there is the risk that an injection molding machine that is too small can be selected which can not maintain the closing force resulting from the maximum injection pressure so that the injection mold is pressed.

![Figure 5: Pressure measured](image)
of more than 100 bar between the actual measured pressures (blue dots) and the two simulated pressures (orange and gray dots) result. The pressure differences between the two simulated pressures are over 50 bar. If these pressures were the same, there would be no difference between the material data set (orange dots) in the material database and the measured material data set (gray dots). It is found that the self-measured material data better describe the plastic used, since the pressures from the simulation with the own measured material data set are closer to the real pressures than the pressures from the simulation with the material data set available in the material database.

The total correction factor $K$ is summarized in Figure 6. It can be seen that this is not independent of the set factor limits from the experimental plans, so that the formation of an averaged overall correction factor is not useful.

\[ K_W = \frac{K_{(MF)}}{K_{(AKT)}} \]  

Since the injection molding simulation was performed with the same component geometry and the same injection molding machine so that the difference of the total correction factor from the influence of the material is due. Assuming that the material characteristic values do not contain any errors, the material correction factor $K_W$ is calculated by Eq. 3.

In the following, the influence of the total correction factor, which results from the influences of the material used (material correction factor $K_W$), the injection molding machine used (machine correction factor $K_M$) and the component geometry (geometry correction factor $K_G$).

The material correction factor $K_W$ maps the quality of the material characteristics, which are contained in the database of the simulation software. In the course of the determination of the material correction factor, each point from the DoE tests is simulated with the material parameters from the material database and with the material characteristics from the own measurements so that the two total correction factors $K_{(MF)}$ and $K_{(AKT)}$ are determined.

In the case of the two total correction factors $K_{(MF)}$ and $K_{(AKT)}$, the influence of the geometry and the influence of the injection molding machine are identical in each case since the injection molding simulation was performed with the same component geometry and the same injection molding machine so that the difference of the total correction factor from the influence of the material is due. Assuming that the material characteristic values do not contain any errors, the material correction factor $K_W$ is calculated by Eq. 3.

In Figure 7, the material correction factor for the D2 plate made of PP is summarized at the proximity of the sensor. It is found that the material correction factor is largely independent of the varied factors and can be averaged. Figure 8 shows the mean value $\bar{K}_W$ and the twofold standard deviation. This is about 20% based on the mean value.
than those with which the material parameters for the material database were determined. These have probably occurred with the ABS used. This material data set was already produced in 1994 and last edited in 2006. The material data record of the PP used was created in 2009 and last edited in 2011. The other three material data sets were created in 2011 and have not been reworked since then.

Figure 8: Material correction factor of the investigated plastics.

It should be noted that special attention should be paid to current data in the material database. These should not be older than five years. Furthermore, care must be taken that the p-v-T data and the mechanical data do not contain supplementals. Supplementals do not reflect the real material behavior, but contain data from another unknown plastic. It is assumed that the chosen plastic behaves in the same way as the plastic from which the supplementals originate. In addition, care must be taken to ensure that the specific heat capacity and the thermal conductivity are given as a value table over the widest possible temperature range. If the material data are older than five years, supplementals are stored in the material data, or if the specific heat capacity or the thermal conductivity are only stored as constant values, a redetermination of the material coefficients of the current material batch is possible since it is assumed that the material characteristics are basic have not been correctly displayed.

The geometry correction factor \( K_G \) determines the influence of the component geometry. Since the material correction factor is known and the machine correction factor is assumed to be constant to the desired geometry correction factor (Eq. 4).

\[
K_G = \frac{K_{(MF)}}{K_M \cdot K_W}
\]  

(4)

The geometry correction factors of the D2 plate from PP are summarized in Figure 9. The formation of a mean value is not useful since the measured values are very widely scattered. For example, the mean value with a simple standard deviation of the geometry correction factor at the proximity sensor position is 2.86 ± 0.53. At the remote sensor position, the mean value with a simple standard deviation is 3.12 ± 1.34.

Figure 9: Geometry correction factors (D2-Plate, PP)

Figure 10 summarizes the geometry correction factors, ordered according to the examined component geometries. The geometry correction factors are distributed randomly so that no simplifications can be made. At this point, the approach is rather promising to collect further experiences with more specific components and fewer materials in order to define a narrower geometry correction factor from these values.

Figure 10: Determination of the geometry correction factor of the examined component geometries

Discussion

In summary, it must be noted that exact and valid initial data are the basis for an accurate injection molding simulation. Above all, the material properties have to be emphasized. These are often not controlled or critically questioned when the selected plastic is present in the injection molding simulation database. Frequently, this procedure leads to great inaccuracies in injection molding simulation, since material data sets can contain outdated parameters or supplementals. Both do not reflect the actual material behavior, so that an inestimable error occurs in the injection molding simulation. Furthermore, it is found that, in particular, the heat capacity and the thermal conductivity are stored only with a constant value.
in the material database, although both characteristic values can be stored at least as a function of temperature. Further dependencies, e.g. the dependence of the thermal conductivity on the pressure or the dependence of the heat capacity on the cooling rate can not be represented at all. Taken together, these inaccuracies lead to a constant material correction factor, which can have values between 1.2 and 2.0. It becomes clear that older material data sets can lead to a higher material correction factor, so that in the case of doubt, the redefinition of different material characteristics can be offered. It can be assumed that the material correction factor can assume values between 0.5 and 2. If the material correction factor is less than one, the real injection pressure is lower than the filling pressure that the corresponding injection molding simulation outputs. If the material correction factor is greater than one, the real injection pressure is higher than the filling pressure which the corresponding injection molding simulation outputs.

The geometry correction factor, on the other hand, depends on the component geometry used and the material used. However, these influences can not be summarized since no clear trends can be identified. Thus, it can not be determined that the material used has a clear influence, since the geometry correction factor partially decreases, but can also increase. Similarly, the dependence of the geometry correction factor on the component geometry used is similar. There is no dependency of the geometry correction factor on the component geometry used which is independent of the material.

Conclusions

In (5) and (6) the individual correction factors for the D2 plate from PP are inserted as an example, so that a total correction factor according to (7) of 2.9 [14].

\[ p_{re} = K_W \cdot K_M \cdot K_G \cdot p_{sim} \]  
(5)

\[ p_{re}(D2\ PP) = 1,63 \cdot 1,00 \cdot 1,79 \cdot p_{sim} \]  
(6)

\[ p_{re}(D2\ PP) \approx 2,9 \cdot p_{sim} \]  
(7)

This means that almost the threefold filling pressure must be applied by the injection molding machine used, compared to the injection molding simulation performed previously. In addition, it is useful to specify the total correction factor with only one decimal place, since further decimal places are subject to great uncertainty and can not be determined as valid.

The creation of a database in which similar real component geometries are compared can be used as an approach to further restrict the geometry correction factor. It is helpful that most toolmakers and mold builders often develop similar plastic products, which are usually produced from a few plastic families.

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