Ceramic injection molding material analysis, modeling and injection molding simulation
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Modeling and Simulation of Cell Growth in Injection Molding of Microcellular Plastics

Experiments and Simulation of Injection Molding with Microstructures
Ceramic injection molding
material analysis, modeling and injection molding simulation

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Abstract
In comparison to unfilled polymers, a ceramic feedstocks has a very high viscosity, a very high heat conductivity and a different pvT-behavior. So far standard simulation tools for plastic injection molding are capable of simulating unfilled or fiber filled compounds with their typical low viscosity and heat conductivity etc. but not for very high ceramic powder filled polymers. This article shows an approach of preparing and adding ceramic feedstocks to standard injection molding tools. Two different feedstocks are used.

Keywords: Ceramic injection molding, simulation, Cross WLF, Herschel-Bulkley

INTRODUCTION
Ceramic injection molding uses geometrical freedom to build ceramic substrates with the complexity of polymer devices. Simulation is a very useful tool to get information about the process before building a mold. Mistakes in part geometry can be changed more easier and cheaper in the computers than in reality. Moreover an important problem in powder injection molding is the powder binder segregation witch depends on the shear rate and causes altering of shape and local densities of the device. To prevent this, simulation of ceramic injection molding is important. But until now the problem is, that almost no material data is available for metal injection molding (MIM), there are no guidelines for acquiring material data and no standards for using material models for simulation and how to set up a simulation [1]. This also applies for the other field of powder injection molding, the ceramic injection molding (CIM). In this paper the focus is on the influence of using the viscosity model Cross-WLF or Cross-WLF with Herschel Bulkley on the filling pattern in simulation.

BASICS
For ceramic injection molding, ceramic powder is mixed with binder which has a very low viscosity. This mixture, called „feedstock“ can be molded to a green part with the process of injection molding. After this, the binder has to be extracted in the debinding process and the ceramic powder has to be sintered to get a dense part. The low viscosity of the used binder enables the injection of the ceramic feedstock in a mold. But there is a significant difference between rheological properties of a feedstock melt and of an unfilled thermoplastic melt. Based on the high filling degree of ceramic powder, the feedstock melts offer, for example, higher heat conductivities and lower viscosities and lower compressibilities of melt and temperatur-dependent change of density. Due to this they tend to wall slipping [2] and jetting [3].

Before execution of the simulation, material data like measured values have to be transferred in the simulation program and some values have to be fitted to coefficients the simulation program uses. In Fig. 1 the method of data fitting is shown. Measured pvT- or viscosity values can be transferred to specific coefficients (here: by using the Tait model for pvT values and the Cross WLF model for viscosity data). After the coefficient calculation, fitted curves can be compared with measured parameters and their matching can be verified.

In literature it is suggested to use modified Herschel-Bulkley model to include the effect of yield stress in the viscosity model of ceramic injection molding [4].
This enhancement causes a rise of the curve by lower shear rates after arriving at the Newtonian viscosity, Fig. 2. With standard high-pressure capillary rheometers, measurement of this behavior is often very difficult or not possible. So this rise cannot be modeled with help of measured values. Changing the measurement method for very low shear rates from standard high-pressure capillary rheometers to Controlled Shear Stress Rheometer (CSS) is suggested in literature [1].

But even if the yield stress could be identified with other measurements the results cannot be mixed with results of the high pressure capillary rheometry – this wouldn’t be consistent. Because of that problem in this paper the influence of a yield stress on the filling pattern in simulation results is analysed. To get clear results, a high increase of viscosity with decreasing shear rate is used.

**EXPERIMENTAL**

**Geometry:** For the experiments a bending bar with an insert in the middle is choosen, Fig. 3. The flow at beginning of the runner and around and after the insert was analysed by simulation and than compared with a real process.

**Material:** The material used are Inmafeed K1010 for a feedstock with alumina powder and Inmafeed K1012 for feedstock with zirconia powder from INMATEC Technologies GmbH are used. For modeling and simulation the material properties heat conductivity (K1010: 3,51 W/mK K1012: 1,06 W/mK), heat capacity (K1010: 0,9 – 1,15 J/gK 0,91 – 1,17 J/gK, K1012: 0,70 – 0,78 J/gK), pvT-behavior and viscosity were determined. The focus of modeling in this paper is on viscosity behavior. The Cross WLF with and without Herschel-Bulkley model was used for fitting viskosity and for pvT-behavior the Tait-model was applied.

Measured values were translated in coeffizients by the database modul of Sigmasoft 5.0.0 from the SIGMA Engineering GmbH, which was also used for simulation. The simulation software Moldflow Synergy 2013 from the Autodesk GmbH does not account jetting and cannot read the coeffizients that are used for Cross WLF with Herschel-Bulkley. This means that with this software the effect of modeling and filling pattern could not be analyzed. For this reason no study with this software is shown in this paper.

After the material modeling process, parameters are setted, the part and the runner are meshed and then process simulation runs.

The process parameters used, are shown in Tabl. 1:

<table>
<thead>
<tr>
<th>parameters</th>
<th>unit</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate</td>
<td>cm³/s</td>
<td>5</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>W/mK</td>
<td>4000</td>
</tr>
<tr>
<td>Melt temperatur</td>
<td>°C</td>
<td>160</td>
</tr>
<tr>
<td>Mold temperatur</td>
<td>°C</td>
<td>55</td>
</tr>
</tbody>
</table>

**Datafitting pvT:** Before fitting the pvT-curves it has to be considered that the binder system of both ceramic feedstocks is a combination of materials and shows different crystallisation points. In DSC both feedstocks have one significant peak and two less significant peaks. This means that crystallisation points of different materials are overlayed and are shown in different clearness. In the pvT-diagram only the significant and one less significant crystallisation point can be seen and are marked with blue dotted lines, Fig 4. The third crystallisation point is too small to influence the curves noticeable. This local different acclivity of the pvT-curves can make it hard to determine the Tait-coeffizients. For fitting the pvT-curves of K1010 and K1012 the well-defined crystallisation point between 40-60 °C was fitet, the other curve progressions were linearisized. Due to different filling grades and densities of both feedstocks their specific volumes are arranged on different values but they behave similarly relative to compressibility and temperature dependency.
Datafitting viscosity. The possibility of a measurement of the viscosity of K1010 started at shear rate 10 \( \text{s}^{-1} \). Measured values of viscosity were imported in the simulation software Sigmasoft and approximated with Cross WLF model. Fig. 5 shows an example of automatically generated curves for feedstock K1010. The viscosity at low shear rates is too high in comparison to the expected trend.

A manual correction of automatical compiled coefficients must be done to get a better match of the measured and generated curves. With Sigmasoft it is possible to change coefficients by hand and to add coefficients for the Herschel-Bulkley model. Fig. 6 and 7 shows measured values from both materials and manually modified coefficients using Cross WLF and Cross WLF with Herschel-Bulkley. Because of the different material behavior measured shear rates of both materials are in different areas.

Simulation: Both materials are highly filled with ceramic powder but still have significant different material properties like density, heat transfer coefficient, heat capacity, and of course viscosity. So their filling pattern differ in simulation and in real process. In Fig. 8 the viscosity curves from the material Inmafeed K1010 (up) and K1012 (down) and the scales which demonstrate the areas of shear rate where the model Cross-WLF with Herschel Bulkley instead of Cross WLF without Herschel Bulkley can influence the flowing pattern are shown.

By filling 6\% (material K1010) only the surface of the melt that doesn’t touch the wall of the mold is influenced by Herschel Bulkley. Where the surface touches the wall the shear rate is too high to be influenced by Herschel Bulkley. By filling 12\% and 17\% a difference in the flow pattern can be detected but is getting smaller.

With comparing the colors more influence is expected by material Inmafeed K1012. But at filling 17\% the flowing pattern shows no big differences at all.
Modeling with Herschel-Bulkley has no big influence on the filling pattern around a small insert. Fig. 9 shows a cut through the part so the shear rate in the part and not on surface can be seen. The shear rate of the K1010 part is too high for being influenced of Herschel-Bulkley in the important area around the insert. Only on melt surface a small area could be influenced. So no significant different flow is estimated. For K1012 the shear rate is in the range that Herschel-Bulkley could influence. But only a small influence for a filling of 82.8% can be seen. The melt surface get together later by using Herschel-Bulkley – but this effect is not distinctive. Using different materials has bigger influence on the flow around the insert than modeling with or without Herschel-Bulkley. Feedstock K1010 needs more time to get melt fronts together after passing the insert. One reason for this is that the material has higher heat conduction. This means the melt is cooler at the time of flowing around the insert and the area of melt which is on the surface of the insert cools down faster and more than feedstock K1012.

Because of this result this device can be simulated with or without Herschel-Bulkley – without seeing big differences. In Fig. 10 a filling study processed in ceramic injection molding is compared with the simulation result. The filling pattern in real process and in simulation match adequate.
CONCLUSION

The flow of ceramic feedstocks can be characterized accurately by using the simulation software Sigmasoft. By filling the runner with smaller injection point the influence of using Herschel-Bulkley can be shown clearly. The reason is the big surface of the melt with no contact to the mold wall and the lower shear rate in this area. When filling a part around a small insert the influence of using Herschel-Bulkley is not significant. The shear rate in the part is too high for this model. This means that detecting the yield stress and simulate with Herschel-Bulkley will show different results if a big area of the melt surface and mold are not in contact during injection.

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