A METHOD FOR CONTROLLING THE MOLD FILLING VOLUME FOR BMC INJECTION MOLDING

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Abstract

Bulk molding compound (BMC) compositions are characterized by a comprehensive property profile, which makes this thermoset material attractive for a wide range of high-performance applications. BMC processing by injection molding allows high production rates and the fabrication of parts with a considerable shape complexity [1]. Although the injection molding machine offers a high reproducibility and process reliability [2], several effects such as material induced disturbances or changing ambient conditions may cause fluctuations in BMC injection molding. The result is a varying part quality for example in the form of volumetric filling differences which causes rejects. The manual adaption of certain process setting parameters presents a possibility to react on disturbances in order to achieve constant part properties. However, the outcome of these adjustments is dependent on the experience of the operator, since an accurate knowledge of the influence of certain setting parameters on individual part quality features is required [3]. In this paper a correlation between process setting parameters and the part filling volume for BMC injection molding is introduced and discussed. The main aim is the development of an adaptive machine function which autonomously compensates occurring disturbances and ensures a constant part filling in BMC injection molding.

Introduction

Bulk molding compounds consist essentially of polyester resin, styrene, glass fibers and fillers. Glass fibers provide up to a content of 25 % by weight most of the mechanical strength to the compound. Usual filler loadings in the range of 50-80 % by weight are used as an extender for lower material costs and for modifying the matrix viscosity in order to prevent fiber separation or filtration during molding [4]. Due to the flexibility in formulation and the broad property profile including excellent mechanical and electrical properties as well as very good thermal and dimensional stability at low costs BMC is used in various sectors and has potential for substituting metal parts [5].

Besides the standard compression molding a major amount of BMC processing is carried out by injection (compression) molding due to the short cycle times, better consistency and quality [2,4]. Basically, the thermoplastic injection molding process can largely be adapted to BMC injection molding except for the thermal environment [1] and material feeding [6]. Due to its pasty consistency BMC is fed to the barrel by a plunger or screw feeding device [4]. In the barrel it is conveyed at ambient temperature and cured in the heated mold [7]. However, there are several aspects such as the temperature and time dependent cross-linking reaction [8] that make BMC injection molding complex and susceptible to instabilities. Scattering of the material properties like batch variations or changing ambient conditions regarding storage or temperature are causes for viscosity fluctuations during processing and the deviation of the part quality [9,10]. Furthermore, the high filler content of BMC accelerates the wear of the injection unit components, which for example gradually impairs the function of the non-return valve. Despite the precisely controlled and reproducible translational screw motion a varying volumetric part filling results [9]. These disturbing effects on the part quality make a large number of plastics-processing companies skeptical of using BMC and rejecting the use of the full potential this thermoset material offers [10].

The subject of this paper is about the compensation of changes in viscosity and the non-return valve closing with an automatic adaption of the machine settings in order to stabilize the part filling behavior in BMC injection molding. The basic process settings for the mold filling include a velocity-controlled injection phase and a pressure-controlled packing phase [3,11]. The switchover from the injection to the packing phase is set at a defined screw position, usually when the cavity is nearly filled. Investigations in thermoplastic injection molding have shown that viscosity fluctuations lead to a changing melt flow into the cavity. At a set switchover-position from the injection to the packing phase viscosity changes cause a differing degree of cavity filling. For example, with constant process settings and a lowered polymer viscosity produced parts tend to be overfilled, whereas a higher melt viscosity leads to an underfilled cavity. Furthermore, changes in viscosity affect the non-return valve closing behavior, which has also an effect on the mold filling [9].

Switching over from the injection to the packing phase by using a cavity pressure signal provides a common approach for the compensation of a changing non-return valve closing behavior or viscosity [9,12]. This method is based on monitoring the signal of a cavity pressure sensor by initiating the switchover-point as soon as a defined cavity pressure level is reached. In this way
an immediate reaction on disturbing effects in the same cycle is realized [13]. A disadvantage of this process control is the expense resulting from the costs and maintenance of the additional sensors, which are considerably wear susceptible due to the high content of abrasive fillers in the BMC compound [10].

An alternative, state-dependent process control for injection molding adapts the switchover-position and packing pressure without any additional sensors only by using the existing machine signals in order to realize a constant mold cavity filling [14]. In the current cycle specific figures characterizing the viscosity of the plasticized polymer and cavity filling are determined by parameters like the screw position and injection pressure. These are used for the calculation of an index describing the displaced volume of plastic melt at the given flow resistance. Based on a reference cycle during a learning phase this molded part volume value is held constant by the control by changing the switchover-position and packing pressure. Thus, overfilling and underfilling of the cavity is prevented and the restarting of injection molding processes is accelerated [3].

In the following, a similar approach for adapting the switchover-position based on the calculation of the real, physical injected volume is introduced and examined for BMC injection molding. The aim is to control the volumetric cavity filling. Therefore, a comprehensive knowledge of the correlation between the process parameters and the cavity filling behavior is required.

**Background**

Softened or melted polymers are characterized by a viscoelastic material behavior, which includes a partly viscous and a partly elastic reaction to deformation. Accordingly, this deformation possesses characteristics of both fluids and solids to a varying extent [15]. This thermomechanic behavior is marked by the volumetric properties of polymers such as the specific volume due to their direct correlation to the polymeric molecular mobility [16]. The specific volume is the reciprocal of the density and dependent on pressure and temperature, which is described by a pressure-, specific volume-, temperature- (pvT) diagram [17].

During processing the polymer is exposed to varying pressure and temperature conditions that accordingly affect its density [17]. In the injection phase the softened or melted polymer is moved from the screw vestibule to the mold cavity by a velocity-controlled screw motion. After the closing of the non-return valve, it is first compressed, until it starts flowing through the nozzle into the cavity. Depending on the wall thickness, flow distance and viscosity, a certain pressure in the barrel and the mold results during the cavity filling and affects the polymer condition [9].

Correspondingly, pressure changes in the barrel induced by viscosity fluctuations cause a density change of the polymer. For instance, a viscosity increase leads to a higher pressure in the barrel, which in turn results in a higher compression and an increased density of the softened or melted polymer in the barrel. At the same screw position and correspondingly same volume there is more polymeric mass in the barrel than at a lower pressure. As a result, less decompressed polymeric melt is injected into the cavity at the same screw position. Thus, at a fixed switchover-position a viscosity increase leads to an underfilled cavity [18].

In [18] a method for predicting the injected polymer volume is introduced which is based on the knowledge of the volumetric compression of the polymer due to pressure changes during injection molding. The compression \( k(p) \) describes the relation of the volumetric change \( \Delta V(p) \) induced by the pressure \( p \) to the initial volume \( V_0 \) at ambient pressure conditions [18].

\[
k(p) = \frac{\Delta V(p)}{V_0}
\]  

(1)

In contrast to the volumetric temperature dependency the pressure dependent volumetric change behaves non-linear [16] which can be derived from the pvT-diagram. Additionally, it differs with the polymer type [6] and filler content, as filled polymers are less compressible than the pure matrix material [19].

Based on the calculation of the compressed polymer volume in the barrel the actual decompressed, injected volume is predicted at every screw position. Fluctuations of the non-return valve closing point are considered by an algorithmic characterization of the pressure increase at the beginning of the injection phase. As a result, between the occurred non-return valve closing position \( s_{nr} \) and the switchover-position \( s_{xfr} \) with the corresponding pressures \( p_{nr} \) and \( p_{xfr} \), the following real polymer volume \( \Delta V_{r,xfr} \) is predictably injected from the barrel with an area of \( A_b \) into the cavity [18].

\[
\Delta V_{r,xfr} = \frac{s_{ref} \cdot A_b}{1 - k(p_{ref})} - \frac{s_{xfr} \cdot A_b}{1 - k(p_{xfr})}
\]  

(2)

In the method of [18] the prognosis of the real, injected shot volume serves for controlling the mold filling volume. In a learned reference cycle the target injected polymer volume at the switchover-point is calculated. Hence, in the current cycle the switchover-position from the injection to the packing phase is set, as soon as the current prognosticated injected polymer volume corresponds to the reference volume at the switchover-point [18]. Furthermore, the packing pressure
level is adapted dependent on the viscosity in order to ensure a stable injected shot volume at the end of the packing phase.

The approach in this paper includes the validation of the volume prognosis for BMC injection molding and its potential for the use as a process control. Therefore, the pressure dependent volumetric change of BMC is determined. Furthermore, occurring disturbances in BMC injection molding are detected and analyzed. The influence of viscosity changes plays an important role and is evaluated by a figure during the injection phase, which is defined as the relation of the integrated pressure over time and the injection speed [3]. This viscosity index corresponds strongly to the viscosity measurements of a rheometer nozzle [20] and presents a valid online characterization of the melt viscosity.

**Experimental**

The experimental procedure is focused on the stabilization of the shot volume by the introduced adaptions. Therefore, the influence of a viscosity change on the volumetric cavity filling is compared for parts processed with conventional settings and the adaptive process control. Furthermore, the main disturbances on the process are analyzed in detail.

The base for the volume prognosis is the knowledge of the occurring polymer compression. There are several possibilities to derive the pressure dependent volumetric change such as the use of a dilatometer or directly an injection molding machine [21]. In this case, the second method was utilized in order to derive the compression in the pressure range that is usual for injection molding and to obtain process-related measurements. Therefore, the plasticized polymer is pressurized in the barrel by axially moving the screw toward a blocked outlet nozzle, whereby the resulting axial position of the screw is measured [21]. In this way, the relative volumetric change of the injection stroke dependent on the pressure is quantified.

All trials are carried out on a hydraulic injection molding machine (KraussMaffei 300-1400 CX Polyset) with a screw stuffer (Polyload AZ 100) as the feeding system and a BMC formulation with 65 % mineral fillers and 10 % glass fibers by weight mainly used for the automotive light reflector production. The barrel is watercooled to 40 °C. The measured compression $k(p)$ is implemented into the volume calculation which is integrated in the software of the machine control. Furthermore, the machine software is modified, so that the switchover-position and the packing pressure can be changed adaptively in the current injection molding cycle. For the experiment, no additional hardware is installed. The mold geometry forms a prototype valve cover and is heated to 180 °C. The process setting parameters are listed in table 1.

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<th>$s_{\text{stroke}}$ [mm]</th>
<th>$s_{\text{frt}}$ [mm]</th>
<th>$V_{\text{inj}}$ [mm³/s]</th>
<th>$t_{\text{packing}}$ [s]</th>
<th>$P_{\text{packing}}$ [bar]</th>
<th>$n$ [1/min]</th>
<th>$P_{\text{back}}$ [bar]</th>
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<td>150</td>
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<td>30</td>
<td>1</td>
<td>400</td>
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First, approx. 200 parts are produced classically with a fixed switchover-position and packing pressure. The first 5 cycles serve as the reference cycles for the process control. The volume prognosis at the end of the packing phase is compared to the part volume by measuring the part weight and density. As the shrinkage rate of the used compound is low, the injected compound volume and the resulting part volume are comparable. The density of every tenth part is determined using the principle of Archimedes [22]. The following approx. 200 cycles include the adaption of the switchover-position and the packing pressure by the introduced control. In both cases a viscosity change measured by the viscosity index is induced by a change of the rotational speed of the stuffer screw due to a changing filling degree of the feeding hopper. The stuffer screw speed is controlled by the stuffing pressure measured by a sensor located at the stuffer output to the barrel. The ability of the process control to compensate this viscosity change is examined by comparing the shot weight processed with and without the adaptive process control. Furthermore, the main disturbances on the volumetric cavity filling are detected.

**Results**

In figure 1 the measured percentage volumetric change of the used compound dependent on the pressure within the pressure range of the machine is presented. This compression curve is implemented into the machine control. The influence of cyclical temperature changes on the compression of the compound are neglected in this study.

![Figure 1. Measured percentage compression of the used BMC formulation on KM 300-1400 CX Polyset](image)

In the following, 50 consecutive injection molding cycles each of processes with conventional process settings and the adaptive process control are analyzed. Therefore, various cyclical process parameters for both cases are presented in fig. 2 and 3.
Figure 2. Cyclical process parameters and the resulting shot weight of 50 consecutive injection molding cycles processed with conventional process settings (fixed switchover-position and packing pressure) on KM 300-1400 CX Polyset

Both figures 2 and 3 show from the top the viscosity index, the reference point of the volume calculation, the switchover-position, the packing pressure and the shot weight as well as the volume prognosis. In the last diagram the resulting shot weight with a tolerance of 0.1 g and the measured injected part volume at the end of the packing phase with a tolerance of 0.4 cm³ are compared by scaling the axes with the measured average part density of 1.935 g/cm³ and serve as the validation of the process control. The volume prognosis reproduces the shot weight with an average deviation of 0.12 %. Furthermore, the process control stabilizes the shot weight by reducing the variation coefficient from 0.98 \% to 0.43 \%. In the following, the main disturbances affecting the injected shot volume are detected by analyzing the listed process parameters and the undertaken adaptions by the process control.

Figure 3. Cyclical process parameters and the resulting shot weight of 50 consecutive injection molding cycles processed with the adaptive process control (adaption of switchover-position and packing pressure) on KM 300-1400 CX Polyset

Due to an increasing stuffer screw speed the viscosity is reduced steadily by approx. 10 \% which is presented by the viscosity index in the first diagram of both figures 2 and 3. The viscosity decrease of both trials – processes with conventional setting and with the adaptive process control – is very similar, so that equal conditions regarding the viscosity change are created for the comparison of the shot weight with and without an adaptive process control. This viscosity change results in an injection pressure decrease of approx. 10 \% from 510 bar to 460 bar on average in both trials. According to the compression of the used compound presented in fig. 1 this maximal pressure change results in a maximal compound compression decrease of 0.12 \%.

The non-return valve closing point is characterized by the reference screw position where the calculation of the injected shot volume begins. It fluctuates maximally by
approx. 0.47 mm in both figures, which corresponds to an maximal deviation of 0.32 % from the average reference point. The switchover-position is constant in fig. 2 at conventional process settings and varies in fig. 3 due to its adaption by the process control by max. 0.56 mm, which accounts for 2.68 % of the reference switchover-position. Apparently, the adaptive process control sets the switchover-position mainly earlier as the injection pressure and the compound compression decrease. Furthermore, the switchover-position correlates strongly by approx. 80 % with the reference point, which indicates that the varying non-return valve closing behavior has a bigger influence on the injected volume at the switchover-position than the viscosity changes. Due to the low compressibility of the used BMC compound the occurring pressure changes evoke a compression change of max. 0.12 %, which corresponds to an adaption of the switchover-position of max. 0.024 mm, whereas the non-return valve fluctuations cause a switchover-position adaption of max. 0.47 mm corresponding to 2.27 % of the reference switchover-position.

The last diagram shows the resulting shot weight and volume prognosis at the end of the packing phase. With conventional process settings the injected volume and the shot weight respectively increase with a decreasing viscosity. This indicates on the other hand that there is an influence of the viscosity on the injected shot volume at the end of the packing phase. The process control compensates this effect during the packing phase by adapting the packing pressure dependent on the viscosity by max. 11 % of the initial packing pressure which is demonstrated in fig. 3.

Figures 4 and 5 illustrate the superimposed pressure signals over the screw position during the injection and packing phase for the 50 consecutive injection molding cycles of fig. 2 and 3 processed with conventional settings and with the adaptive process control. The pressure signals are derived from the hydraulic pressure. The adaption of the switchover-position and the packing pressure performed by the process control can be seen by comparing both figures. The range of the adapted packing pressure considered with all cycles resembles the range of the injection pressure. Furthermore, the remaining compound cushion is visibly stabilized by the adaptive process control.

![Figure 4](image1.png)

**Figure 4. Superimposed pressure signals dependent on the screw position during the injection and packing phase for 50 consecutive cycles processed with conventional settings**

![Figure 5](image2.png)

**Figure 5. Superimposed pressure signals dependent on the screw position during the injection and packing phase for 50 consecutive cycles processed with the adaptive process control**

**Conclusions**

Based on a precise volume prognosis with an average deviation of 0.12 % the introduced adaptive process control stabilizes the shot weight in this example by more than halving the coefficient of variations. A varying non-return valve closing behavior, the main disturbance during the injection phase, and viscosity changes which affect primarily the packing phase are compensated by the adaption of the switchover-position and the packing pressure. The base for the adaptive process control is the generated knowledge of the physical, specific BMC material behavior such as the pressure dependent volumetric change during injection molding. Pursuing, this approach can be applied to further BMC formulations in order to address a wider range of BMC applications.

Generally, the use of an adaptive process control contributes to a reduction of the rejection rate and a stabilization of the part quality for BMC injection molding, which is necessary in respect to increasing quality requirements of thermoset injection molding [23]. Furthermore, a stable injection molding production enhances the attractiveness of BMC compounds for additional areas of application and reduces the prevailing resentment of a number of plastics-processing companies towards this thermoset material. In this way, the potential of BMC can be used optimally.
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