Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

Part Mass Estimation Strategy for Injection Molding Machines

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Abstract: In injection molding, it is crucial to ensure high part quality over a long time period because typically these parts are produced in large numbers. Process variations influence the production and the resulting part quality. The part mass is frequently used as a quality measure as it can be easily measured by a scale after the part is finished. On the other hand, it is not possible to directly measure the part mass during the injection phase. This paper proposes a method to estimate the part mass by means of sensors, which are typically available in an injection molding machine. Compared to the state of the art, the proposed strategy also allows to estimate the time evolution of the part mass during the injection process. The accuracy of 0.25 % and the robustness, with respect to process parameter variations, of the proposed part mass estimation is demonstrated by measurements.

Keywords: injection molding, part mass estimation, process control, part quality, partial filling

1. INTRODUCTION

Injection molding is the most important production process to produce goods made of polymer. In this process, molten polymer is injected into a mold, cooled down and then extracted from the mold. The mold is part specific and can be very expensive (even more expensive than the injection molding machine). Thus, injection molding is economically viable for mass production only. This leads to long production periods where only one specific part is produced, see, e.g., Chen and Turng (2005); Abeykoon (2016). The production process and thus the product quality is influenced by a number of parameters, which may change during the long production periods. For example the ambient temperature, the cooling water temperature, the friction in the molding machine etc. are typically subject to changes. Furthermore, the composition of the raw material may vary or is influenced by other factors (e.g. humidity changes).

To account for changes in the machine parameters (e.g. friction, ambient temperature), the position of the screw and the temperature are controlled in state of the art injection molding machines. Variations of the raw material cannot be compensated by these control strategies, which in turn may lead to a degradation of the product quality. Therefore, it is desired to directly control the part quality instead of machine quantities as the screw position or the injection pressure. For this reason, the modeling and control of the part quality is the topic of current research, where an extensive overview of the different approaches can be found in Chen and Turng (2004, 2005); Abeykoon (2016). Subsequently, a short summary of the literature which is relevant for this paper is given.

Kamal et al. (1999) describe that part mass variations are correlated with the product quality and therefore can be used as a quality measure. They estimate the part mass by means of the mold volume and a Tait model for the density of the polymer, where in-mold pressure sensors and the temperature at the gate sealing point are employed. To achieve a reproducible part mass, a control strategy for the pressure in the mold cavity and the melt temperature is proposed. In a similar way, Umar et al. (2009, 2011) calculate the part mass from the difference of the polymer mass in the antechamber at the beginning and at the end of the injection process.

In addition to these physics-based approaches, also more empirical methods were published for the part mass estimation. For example, Schiffers (2009) uses linear regression models to estimate the part mass. Chen and Turng (2007) calculate the mass using the pressure-volume-temperature (pvT) behavior of the polymer and derive a nonlinear function between the part mass, the mold separation and the in-mold temperatures. Principal component analysis (Yang and Gao, 2006) and least squares support vector regression (Li et al., 2008) are also proposed in the literature to model the influence of process parameters on the part mass. The main drawback of these models is that they have to be trained by extensive measurement data and that they are only applicable to the specific mold.

Lucyshyn et al. (2011) derived a method to calculate the mass or part geometry deviations as a function of process parameters. This approach is limited by the fact that a number of parameters have to be determined from detailed experimental results and that the part quality estimation shows good accordance with measurements only in a narrow band around the working point. In a recent work, Mensler et al. (2019) analyzed the flow front position in the mold, which is a measure of the filling level of the mold, based on the measured pressure. To do so, the

authors matched specific events in the pressure evolution (e.g. steep pressure gradients) with the pressure obtained by a detailed finite element simulation of the injection phase. Since this method is based on an analysis of the pressure only, changes of the part mass due to variations of the polymer (e.g. viscosity) cannot be accurately captured.

Most of the cited works concentrate on the estimation of the mass of the final product. Experiments show that also the time evolution of the polymer mass in the mold is relevant for the final product quality. For example changes in the filling speed of the mold can generate surface defects even if the final part mass is kept constant. Thus, controlling the time evolution of the mass in the mold is an important and open point for a further improvement of the stability of the injection molding process. A main prerequisite for this task is the online estimation of the time evolution of the mass in the mold. In this work, an estimation method is proposed, which is based on measured quantities of the injection molding machine only. This is quite contrary to many existing approaches, which utilize additional sensors placed in the mold.

2. MATHEMATICAL MODEL

An overview of the considered injection unit is shown in Fig. 1. It comprises a screw which is placed in a heated barrel. The screw can be rotated by an electric plastication drive (not depicted in Fig. 1) and is moved in z_s direction by means of a ball screw, which is driven by an electric motor via a belt drive. The injection cycle can be split into the phases: filling, packing and cooling. (i) In the filling phase, the molten polymer in the antechamber is injected into the mold by moving the screw in positive z_s direction. (ii) After the mold is (almost) completely filled, a high packing pressure is applied. During this packing phase the polymer in the mold starts to cool down and molten polymer is delivered into the mold to account for shrinking. (iii) After the delivery channel is solidified (there are also setups where the delivery channel is mechanically closed), the actual cooling phase begins, where the melt in the mold cools down until the whole part is solid. During the cooling phase, the screw is rotated to transport, melt and mix the polymer (plastication phase). The (homogeneous) molten polymer is accumulated in the antechamber of the barrel. When the part is completely solidified, the mold opens and the part is ejected.

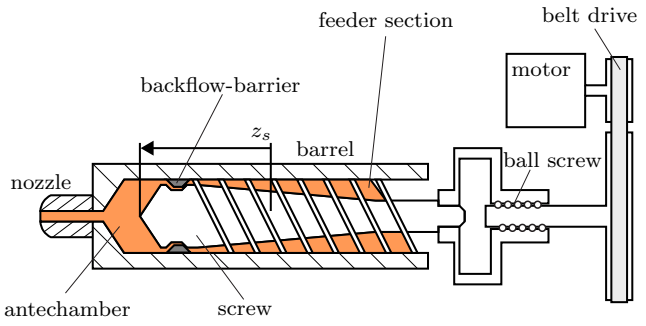

Fig. 1. Overview of the electric injection unit.

For the estimation of the time evolution of the part mass, only the injection and packing phase are relevant, since no polymer is transferred into the mold during the cooling phase. In these two phases, the backflow-barrier is (almost completely) closed, and thus the antechamber is separated from the rest of the barrel. For the mass estimation, the screw position z_s, the pressure p_{ac} and the temperature ϑ_{ac} of the polymer in the antechamber are considered as the only measured quantities.

2.1 Material Models

Knowledge of the material behavior, in particular of the mass density ρ (or equivalently the specific volume v), as a function of the pressure p and temperature ϑ is an important prerequisite for the estimation of the part mass. The most common and accurate model to describe the pressure-volume-temperature (pvT) behavior of polymers is the two-phase Tait equation, see, e.g., Rodgers (1993) and Padilha Júnior et al. (2015). It can be written as

$$v(\vartheta,p) = v_0(\vartheta)\left(1 - C\ln\left(1+\frac{p}{B(\vartheta)}\right)\right) + v_T(\vartheta,p) \quad (1)$$

where the liquid and solid state are separated by the characteristic transition temperature curve ϑ_T

$$\vartheta_T = b_5 + b_6 p. \quad (2)$$

Above the transition temperature $\vartheta > \vartheta_T$ the polymer is liquid and the functions in (1) read as

$$v_0(\vartheta) = b_{1m} + b_{2m}(\vartheta - b_5) \quad (3a)$$
$$v_T(\vartheta,p) = 0 \quad (3b)$$
$$B(\vartheta) = b_{3m}e^{-b_{4m}(\vartheta-b_5)}\,. \quad (3c)$$

Below this transition temperature the polymer is solid and the functions in (1) are given by

$$v_0(\vartheta) = b_{1s} + b_{2s}(\vartheta - b_5) \quad (4a)$$
$$v_T(\vartheta,p) = b_7 e^{b_8(\vartheta-b_5)-b_9 p} \quad (4b)$$
$$B(\vartheta) = b_{3s}e^{-b_{4s}(\vartheta-b_5)}\,. \quad (4c)$$

In these equations, $b_{1m},\ldots,b_{4m}$, $b_{1s},\ldots,b_{4s}$ and $b_5,\ldots,b_9$ denote material specific parameters whereas $C = 0.0894$ is constant. A sketch of a typical pvT-diagram is shown in Fig. 2. The two-phase Tait model is known to yield a good

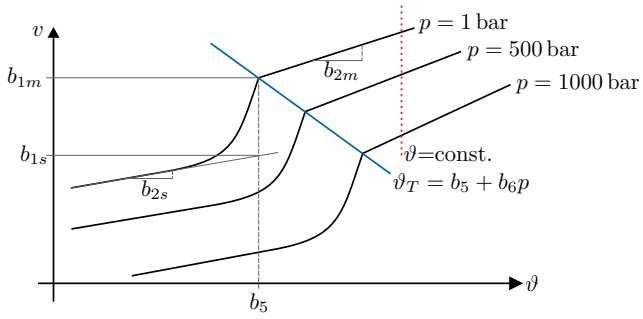

Fig. 2. Sketch of the typical pvT-diagram described by a two-phase Tait model.

approximation in the liquid state (Padilha Júnior et al., 2015) but is rather poor in approximating fast cooling processes (Chang et al., 1996; Kowalska, 2006).

This is no significant limitation, since the part mass estimation proposed in this work will be based on the estimation of the mass in the antechamber, where almost constant temperature can be assumed. The main problem for the practical application is that it can be difficult to get

the Tait model parameters for a given polymer. For this reason, a second material model, which is based on the assumption of a constant temperature of a liquid polymer, is formulated as an alternative to the complex Tait model. Assuming a linear behavior of the bulk modulus $\beta(p) = \rho(p)(\partial\rho(p)/\partial p)^{-1} = \beta_0 + \beta_1 p$, with constant parameters β_0, β_1, the density ρ is given by

$$\rho(p) = \rho_0 \left(\frac{\beta_1 p + \beta_0}{\beta_1 p_0 + \beta_0} \right)^{\frac{1}{\beta_1}} . \tag{5}$$

Here, ρ_0 denotes the density at ambient pressure p_0, see, e.g., Froehlich et al. (2018). This model is valid only on the dashed line shown in Fig. 2. Its parameters β_0 and β_1 can be identified directly at the injection molding machine, e.g. during the packing phase when no material flow occurs (cf. (7)).

2.2 Injection Unit

The antechamber is the relevant part for the part mass estimation in this work. Utilizing the previous assumption that the screw position z_s and the pressure p_{ac} are measured, the balance of mass in the antechamber can be written as

$$\frac{\mathrm{d}}{\mathrm{d}t} m_{ac} = -\rho_{ac} \left(q_{no} + q_l \right), \tag{6}$$

where $m_{ac} = \rho_{ac} A_{ac}(z_0 - z_s + r_{ac} p_{ac})$ is the mass of the liquid polymer. The density ρ_{ac} is defined according to the previous material models as a function of the pressure p_{ac} and the temperature ϑ_{ac}. Furthermore, A_{ac} is the cross section area of the screw tip and r_{ac} accounts for the mechanical compression of the screw due to the pressure p_{ac}. The volume flow through the nozzle into the mold is denoted by q_{no} and q_l describes the (unknown) leakage flow over the back-flow barrier. Using the material model introduced in the previous section, the balance of mass can be reformulated as

$$\frac{\mathrm{d}}{\mathrm{d}t} p_{ac} = \frac{\beta}{z_0 - z_s + r_{ac}(p_{ac} + \beta)} (\dot{z}_s - \frac{1}{A_{ac}} q_{no} - \frac{1}{A_{ac}} q_l), \tag{7}$$

see, e.g., Froehlich et al. (2018) for a more detailed description.

The flow into the mold q_{no} is in general a highly nonlinear function of the injection pressure in the antechamber and the filling level of the mold. A typical approach to approximate q_{no} as a function of the injection pressure p_{ac} and the filling level (equivalently described by the screw position z_s) is given by the model

$$q_{no} = A_{no} \left(\frac{p_{ac} - p_0}{r(z_s - z_{s0})} \right)^{\frac{1}{n}}, \tag{8}$$

see, e.g., Zheng and Alleyne (2003); Kazmer et al. (2004); Agassant et al. (2017). Here, A_{no} is the nozzle cross section area, $r(z_s - z_{s0})$ is the filling resistance of the mold as a function of the filling level (z_{s0} is the position z_s of the screw at the beginning of the filling process) and n is the constant power law index utilized to approximate the non-Newtonian fluid behavior of polymers, cf. Osswald et al. (2008).

The back-flow barrier is installed to ensure that the liquid polymer is flowing only into the mold during the injection and packing phase. The (leakage) volume flow over the back-flow barrier is described by $q_l(p_{ac}, t)$. The back-flow barrier is passively closed by the pressure difference between the antechamber and the pressure in the feeder section, see the sketch in Fig. 1. A rough estimation of the closing behavior can be extracted from the pressure signal, since a pressure rise in the antechamber will force the back-flow barrier to shut, see, Umar et al. (2009). This uncertain closing behavior of the back-flow barrier and the inaccuracies of the used models make the exact estimation of the part mass a challenging task. If the back-flow barrier is closed, which is the case for sufficiently large pressures in the antechamber, $q_l = 0$ is a good approximation.

2.3 Test Mold

For the measurement results in Section 4 an S-shaped test mold depicted in Fig. 3 will be used. It includes a number of in-mold temperature (red squares) and pressure (blue circles) sensors, which can be used to evaluate the accuracy of the proposed mass estimation strategy.

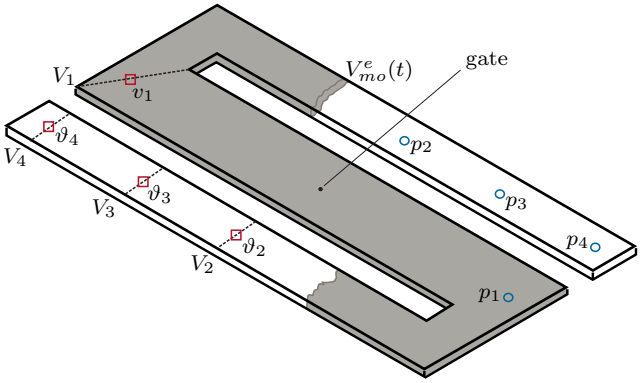

Fig. 3. Test part used in the measurement setup: temperature sensors (red squares), pressure sensors (blue circles).

The filling resistance r can be calculated from injection measurements by using (7) and (8). The measured filling resistance is then approximated by piecewise polynomials. The resulting resistance of this mold during the filling phase is depicted in Fig. 4.

It shows a pronounced increase at the beginning of the filling process followed by a moderate increase until the mold is completely filled at $z_s - z_{s0} \approx 48\,\mathrm{mm}$.

3. MASS ESTIMATION

The mass m_{mo} of polymer in the mold is described by the balance of mass in the form

$$m_{mo}(t) = \int_{t_0}^{t} \rho_{no}(\tau) q_{no}(\tau) \mathrm{d}\tau, \tag{9}$$

where ρ_{no} is the density and q_{no} is the volume flow of the polymer in the nozzle. The most direct way to estimate the part mass would be to measure the nozzle volume flow q_{no} and to obtain the mass by integration over time. Unfortunately, there are no flow rate sensors on the market which meet the requirements with respect to the high pressures ($p_{ac} \approx 2000\,\mathrm{bar}$), high temperatures ($\vartheta_{ac} \approx 220\,^\circ\mathrm{C}$) and the high viscosity of the polymer. Another

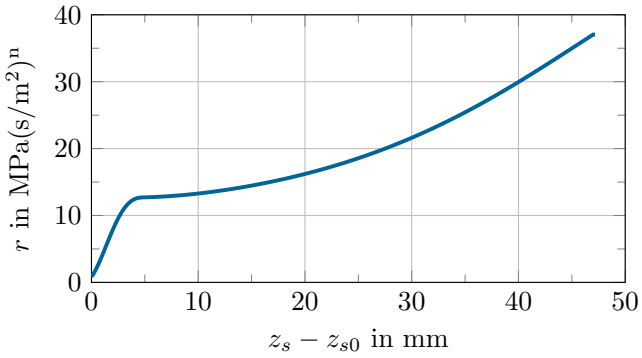

Fig. 4. Measured filling resistance r of the test part during the filling phase.

way to get information about the mass in the mold would be to use in-mold sensors which detect the filling level e.g. by means of a fast increase of the temperature at certain points of the mold. The drawback of this method is that additional sensors have to be installed in the mold, which is costly and may lead to problems in the surface quality of the final part. Moreover, this method would give information on the mass in the mold only for a number of discrete points. Finally, the volume flow q_{no} could be calculated by utilizing (8). The filling resistance r and the flow index n are typically not accurately known, and thus the integration of the volume flow to obtain the mass would lead to large errors.

In this work, a mass estimation strategy is proposed which is based on the measured quantities of the injection molding machine. Taking a look at (6) it is clear that the mass in the mold can be rewritten as

$$m_{mo}(t) = m_{ac}(t_0) - m_{ac}(t) - \int_{t_0}^{t} \rho_{ac}(p_{ac}) q_l(p_{ac}, \tau) \mathrm{d}\tau \tag{10}$$

where $m_{ac}(t) = \rho_{ac} A_{ac}(z_0 - z_s(t) + r_{ac} p_{ac}(t))$ is the mass of polymer in the antechamber. The calculation of the mass in the antechamber is easily possible from the measured position z_s, pressure p_{ac} and temperature ϑ_{ac}, where either the Tait model or the simplified model of Section 2 is used to calculate ρ_{ac}.

The main difficulty with (10) is related to the leakage volume flow q_l, which is given by the volume flow over the back-flow barrier. As discussed before, the closing behavior of the back-flow barrier can hardly be modeled and thus, no meaningful model for q_l can be formulated. The leakage volume flow can, however, be assumed to be negligible when the back-flow barrier is completely closed. It is discussed in Umar et al. (2009) that the increase in the pressure p_{ac} during the filling phase can be used to approximately determine the time when the back-flow barrier closes.

To make this clearer, the pressure and position of a typical injection cycle is depicted in Fig. 5. This figure shows that at the beginning of the filling phase the screw is moving towards the mold without a significant increase in the pressure p_{ac}. In this time interval, the back-flow barrier is moving from the open to the closed position. Approximately at $t = 0.18\,\mathrm{s}$, the back-flow barrier is completely closed, which is characterized by a

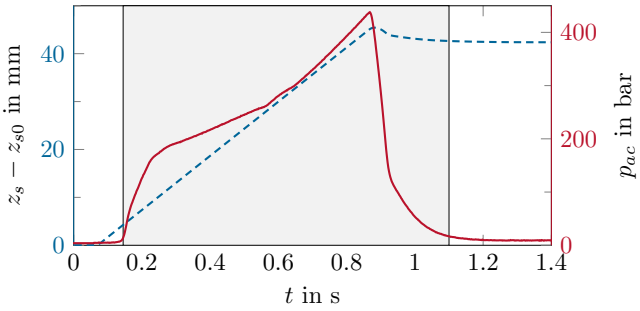

Fig. 5. Screw position z_s and pressure p_{ac} in the antechamber for a typical short shot injection cycle.

steep increase of the pressure p_{ac}. After the mold is filled to a certain level, at approximately $t = 0.9\,\mathrm{s}$, the pressure p_{ac} is decreased by moving the screw slightly backwards.

Given this figure, it can be assumed that the back-flow barrier is completely closed within the gray shaded interval, which is characterized by the pressure p_{ac} lying over the limit $p_{ac,min} = 15\,\mathrm{bar}$. At the beginning of the filling phase, a certain (small) amount of liquid polymer can already start to flow into the mold, i.e. the part mass will not be zero at the beginning of the interval. At the end of the gray interval the pressure in the antechamber has reached such a low level that no change in the part mass can take place as the flow (8) is negligible until the delivery channel is solidified. Thus, only the mass flowing into the mold in the interval $[t_s, t_e]$, with the time t_s when the pressure p_{ac} reaches the limit $p_{ac,min}$ for the first time and the time t_e when the pressure p_{ac} falls below this limit again, can be accurately estimated. This yields the following formulation of the mass in the mold

$$m_{mo}(t) - m_{mo}(t_s) = m_{ac}(t_s) - m_{ac}(t), \quad t_s \leq t \leq t_e, \tag{11}$$

where $m_{mo}(t_s)$ is the (basically unknown) polymer mass in the mold at $t = t_s$.

The estimation strategy allows to estimate $\Delta m_{mo}(t) = m_{mo}(t) - m_{mo}(t_s)$ but it is not possible to estimate $m_{mo}(t)$. Estimation of $\Delta m_{mo}(t)$ is, however, still very beneficial due to the following facts: (i) The mass $m_{mo}(t_s)$ is typically very small, since the small pressure p_{ac} before t_s only yields very small volume flows q_{no} into the mold. (ii) The main goal in injection molding is to minimize the variations from one injection cycle to the next. For this task, the mass Δm_{mo} is a very good measure, since only small changes are expected for $m_{mo}(t_s)$ between different cycles.

Thus, the evaluation of the estimation accuracy in Section 4 will also be performed for $\Delta m_{mo}(t)$ in addition to the overall part mass m_{mo}. Note that a similar approach is utilized in Chen and Turng (2007); Umar et al. (2009, 2011), where only the mass at the end of the injection cycle is considered. Moreover, the results in this work are compared to the results presented therein and exhibit a much higher accuracy. Finally, it is also possible to calculate the mass flow by means of numerical derivation utilizing e.g. Savitzky-Golay filters.

4. MEASUREMENT RESULTS

To evaluate the accuracy of the proposed mass estimation, a set of experiments were conducted on a typical injection

machine using the test part depicted in Fig. 3. The robustness of the estimation strategy is tested by varying several process parameters (injection volume, screw velocity, plastication pressure, temperature) and material parameters (mixture of the polymer) for the different experiments. Fig. 6 shows the results of the measured mass m^m_{mo} of the final part and the estimation error $e_m = m^e_{mo} - m^m_{mo}$, with the estimated mass m^e_{mo} obtained by (11). Therein, $m_{mo}(t_s)$ was chosen such that the estimated mass for the first shot 1 is identical to the measured one.

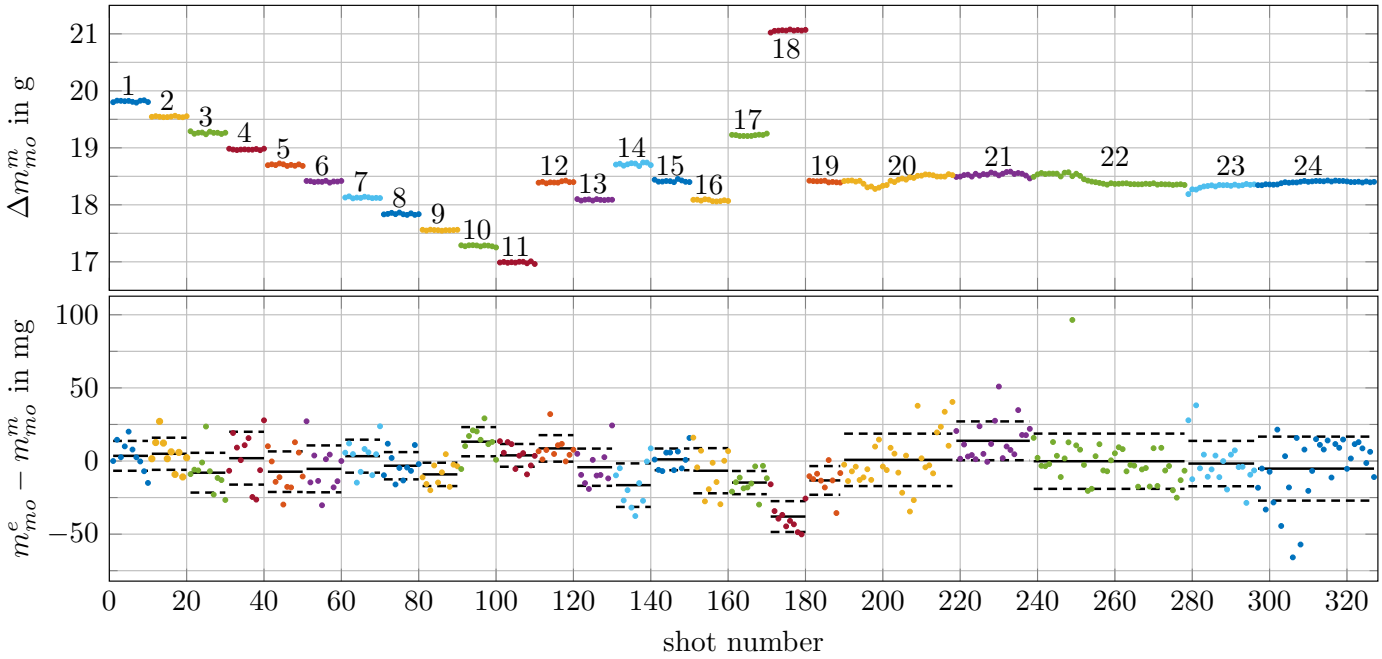

Fig. 6. Comparison of measured and calculated mass.

The measurement results 1 to 11 show the changing mass due to a change in the filling level, which is adjusted by changing the displacement z_s of the screw. The influence of the pressure in the plastication phase is studied in the measurements 12 to 14 and the influence of the injection speed, i.e. the screw velocity $\dot{z}_s$, is analyzed in the measurements 15 to 19. In the measurements 20, wax is added to the polymer to change the viscosity (the density is constant since the density of the wax is equal to the density of the polymer). In the measurements 21 a steady production with wax is depicted and in the measurements 22, the wax is removed again. The start-up of the production after a stop of 10 min is analyzed in the measurements 23. Finally, the measurements 24 show the influence of a decrease in the temperature by 20 K.

These experiments cover a wide range of practically relevant variations of process and material parameters. The results given in Fig. 6 prove that a very good mass estimation is possible by the proposed estimation strategy, where the maximum error is smaller than 50 mg during most of the experiments, which is equivalent to a maximum estimation error of 0.25%. In most experiments, the estimation error is even kept well below 25 mg. The average error and the variance of the error are also indicated in Fig. 6. In comparison to the previously reported results in Umar et al. (2011), a significant improvement of the estimation accuracy is achieved. If this mass estimation is utilized in a control strategy for the mass, it can be expected that the mass error due to process and material variations can be significantly reduced. First simulation results of a control strategy developed by the authors confirm this supposition.

In the first experiment, only the final part mass is evaluated. As stated before, also the time evolution of the mass in the mold is essential to achieve a good part quality. To verify that the proposed mass estimation gives accurate results also during the injection process, the position of the flow front (i.e. the position of the start of the liquid polymer in the mold) is analyzed. The position of the flow front can be measured at discrete points in the test mold by the temperature sensors $\vartheta_1, \ldots, \vartheta_4$. These positions correspond to the filling volumes $V_1, \ldots, V_4$, see, Fig. 3.

To estimate the flow front position from the estimated mass m^e_{mo}, the corresponding volume V^e_{mo} has to be calculated. For this, the density distribution in the mold is necessary, which can be estimated by utilizing the pressure and temperature sensors in the mold in combination with the material model. Since the pressure and temperature can only be measured at discrete points, an interpolation is required. Here, the following method is proposed: (i) It is assumed that the polymer temperature in the whole mold is equal to ϑ_{ac}, which yields high accuracy for fast injection cycles. (ii) A linear interpolation of the pressure sensor values is utilized to estimate the pressure p_{mo} in the mold.

With these assumptions, the estimated mass in the mold can be written as

$$m^e_{mo}(t) = \int_0^{V^e_{mo}(t)} \rho(\vartheta_{ac}, p_{mo}(V))\,\mathrm{d}V. \qquad (12)$$

Here, $V^e_{mo}(t)$ is the current polymer volume in the mold and $p_{mo}(V)$ is the estimated pressure distribution in the

mold (parametrized as a function of the polymer volume). Using the material model (either the Tait model (1) or the simplified model (5)) of Section 2 in (12) gives an integral equation for the volume V^e_{mo}. The numeric solution of this integral equation finally gives the estimated filling volume V^e_{mo}.

Fig. 7 gives a comparison of the estimated volume V^e_{mo} with the measured volume V^m_{mo} by the temperature sensors. It can be clearly seen that a rather accurate estimation of the volume is possible. This allows to draw the conclusion that also the estimated mass $m^e_{mo}(t)$ will show a similar accuracy and thus also the time evolution of the mass can be considered to be rather accurate.

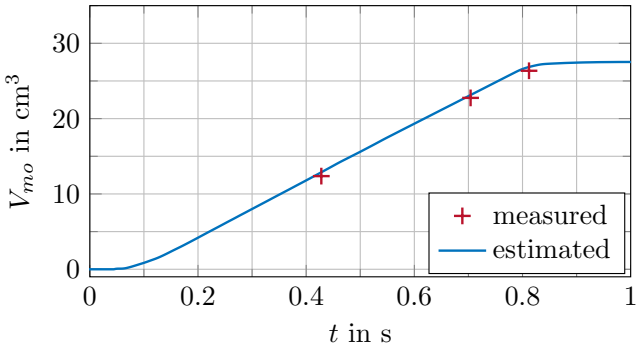

Fig. 7. Comparison of the calculated volume with the measured volume by in-mold temperature sensors.

5. CONCLUSIONS AND OUTLOOK

An estimation strategy for the part mass during the injection molding process is presented in this paper. This estimation strategy is able to accurately predict the part mass evolution by means of the position, pressure, and temperature measured at the injection molding machine. The proposed mass estimation strategy will serve as a basis for the active control of the part mass during the injection cycle. Current research is directed towards the development of an optimal, model predictive control strategy for the part mass, which is expected to improve long time product quality of the injection molding process.

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