Adaptive process control for stabilizing the production process in injection moulding machines

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Abstract

Plastic injection moulding machines are a positive example of the possibilities in terms of performance and energy efficiency of modern hydraulic drives technology. In addition to the performance and energy efficiency of the machines, the quality of the plastic mouldings and an easy to use machines control is the focus. To ensure a constant plastics part quality the set process parameters of the injection moulding machines are kept constant by appropriate closed loop control strategies today. Assuming a constant quality of the processed plastic raw material, this strategy is effective. If it comes to a qualitative variation in the processed plastics, which often leads to a change in viscosity of the plastics melt, keeping processing parameters constant will not lead to a constant quality of the moulded parts. The deviations in the plastics viscosity have such a great influence on the moulding process that the relevant process parameters have to be adjusted manually in many cases. Often the stroke of the reciprocating screw system has to be adapted to reach a constant filling volume of the cavity and therefore avoid burr formation or short shots. In this paper an approach for adaptive process control is introduced. This control loop is able to correct the set points of specific machines parameters online within the production cycle and therefore is able to avoid changes in the produced parts quality.

KEYWORDS: plastics injection moulding, injection moulding machine, adaptive control, quality control,
1. Background

Today’s injection moulding machines are equipped with very high precision drives. In particular, the translational motion of the reciprocation screws system for injecting the melt into the cavity is controlled precisely with a closed loop control. However, batch variations and start-up effects still have a negative impact on the produced parts quality \cite{1, 2}. Currently the method of choice is to stabilize part quality by keeping the machines set values in the narrowest range. Therefore temperatures, accelerations, velocities etcetera are kept constant over the production time.

There are two types of disturbances to the injection moulding process. Internal effects that result from manufacturing tolerances of the relevant processing technology elements, for example a not consistent closing behaviour of the non-return valve (on top of the injection screw) leads to deviations in displaced melt volume. External effects come to the injection moulding machine with the processed raw material and mainly result in a change in viscosity of the plastics melt. The change in viscosity itself induces more deviations while processing, for example the shear heating while injection is different. The different temperature of the melt in the mould leads to a variation in the molecular structure when cooling down to solid state again. These disturbances affect the process and the quality of the moulded parts (weight, dimensions, surface) in a negative way \cite{3, 4}.

Talking about changes in viscosity of the plastics melt the method of choice to correct the negative influence on the plastics part is to adapt the switch-over position from the speed controlled filling phase to the pressure controlled holding-phase. The target is to keep the degree of mould-filling at the position of switch-over constant. The different viscosity comes with different resistance to flow and therefore results in changed amount of displaced melt at identical injection stroke. Today this value is corrected by the machines operator intermittently after checking the parts quality. Thus the effects of changes are only corrected manually and on an incidental base, which may lead to a production of reject parts.

Comparable situations may occur within transient phases in injection moulding processes. In case of a pause due to failure or a planned mould change the thermal equilibrium state which developed over time is changed. The plasticized melt inside the barrel experiences a significantly different energy input since the process is stopped and time proportions are different. The quality (temperature and thus viscosity) of the processed resin is different. When starting the injection moulding process after a production interruption the results are significantly influenced. The task of an adaptive
process control is to correct the processing parameter in a way that the quality of the plastics part is constant. Mainly this is achieved by assuring a volumetrically constant filling of the cavity in each cycle. This is done first by the adaption of the switch-over position and second by adapting the holding pressure level based on the viscosity of the melt, details may be seen in /5/.

2. Plastics injection moulding process

The injection moulding process contains several process steps, where a thermoplastic based material is plasticized and injected into a cavity. The material is pressed into the mould and after cooling down ejected. There are furthermore many special processing technologies in injection moulding that have specific demands towards the process control.

The feedstock is brought into the injection moulding machine with the feed hopper, where the granular material directly flows down to the plastification screw. The material is now plasticised by the energy that is dissipated by the rotation of the screw as well as by the heat conducted from the tempered barrel. While plasticising the screw moves backwards and the plasticized plastic is stored in front of the screw for the next injection cycle. A non-return valve at the tip of the screw prevents the molten plastic form flowing back into the screw flights.

![Figure 1: Injection moulding process; a) mould closing; b) moving of injection unit; c) injection phase; d) holding pressure phase; e) plastification phase; f) mould open and ejection; based on /6/](image-url)
When the mould is closed the injection phase starts, the injection unit with the plastification barrel is moved towards the mould up to contact with the nozzle. Thereafter a speed controlled volumetric filling of the mould and a pressure and time controlled compression (holding-pressure) phase follows. Simultaneously the cooling of the injected plastics material takes place. The holding-pressure phase is mainly needed to compensate the thermal shrinkage of the material. While the formed part cools down the plastification of new material takes place. As the plastic part has reached its solidification temperature the mould can be reopened and the formed part is removed by an ejector system /7/.

3. Function of the adaptive process control concept

The adaptive process control method is introduced with the help of exemplary processing parameters from a standard thermoplastic injection moulding machine. In the first step the viscosity of the plasticized polymer melt is characterized by a defined key indicator in the injection phase. The corresponding process variable is to be measured in a suitable way. For hydro-mechanically driven machines this is done by measuring the driving hydraulic pressure. The pressure is converted to plastics melt pressure with the area ratio between hydraulic cylinder and screw diameter. The position of the screw is measured by an appropriate external position sensor. An injection work equals the displacement of the molten plastic volume flow against a resistance. Similarly to a viscometer, the work is measured during injection phase as an integral of the injection pressure over screw stroke. For integrating over time the result is an injection energy instead of a work (1) /3/.

\[ MI = \int_{t(s=MI_{pos1})}^{t(s=MI_{pos2})} p(t) \, dt \]  

MI stands for the range of the screw stroke in which the pressure integral is to be calculated (Figure 2). This range must be chosen in a way that no dynamic effects (e.g. pressure oscillations) in the displaced melt have a negative impact on the measurement. In order to eliminate effects of a differing closing behaviour of the non-return valve (NRV) the measuring range has to be determined specific for each cycle. The measuring interval position is then shifted based on the deviation in the closing point of the NRV. The evaluation of the pressure gradient at the beginning of the mould filling gives the actual closing position of the NRV and the range of MI is shifted accordingly (Figure 3).
Figure 2: Melt pressure and screw displacement during the injection- and holding phase. The viscosity index (VI) is formed depending on the closing behaviour of the non-return valve. The filling index (FI) describes the volumetric filling of the cavity and is similar to the injection work.

Figure 3: Shift of the measurement interval MI to avoid measurement failures due to unsteady closing of the non-return valve.

Plastic melts are shear viscous and the volume flow rate has a big influence on the resulting viscosity. For this reason, the characteristic flow resistance is furthermore scaled to the mean of the injection speed $v_{MI}$. For characterizing the quality of the melt, this normalized characteristic parameter may now be used: viscosity index (VI).
This key figure is measured online in the injection phase. An additional scaling may be added with the correction constant $K_1$ (2).

$$VI = MI \cdot \frac{K_1}{v_{MI}}$$  \hspace{1cm} (2)

Also a filling index (FI) is calculated which describes the active cavity filling from the position where the return valve closes $s = CP$ until switch-over $s = COP$ (3) (Figure 2).

$$FI = \int_{t(s=CP)}^{t(s=COP)} p(t) \, dt$$  \hspace{1cm} (3)

During the injection phase the filling index is calculated. The integral starts when the non-return valve is closed (closing position) and ends at the switch-over position.

The approach of an adaptive process control now uses a key ratio for characterizing the process. A moulded part volume equivalent (MPV) is calculated. The filling index is set at a ratio to the viscosity index. This ratio describes the displaced volume of plastic melt at a given individual flow resistance of every single injection moulding cycle (4).

$$MPV = \frac{FI}{VI}$$  \hspace{1cm} (4)

Rearranging the equation the value of FI may be determined. With a fixed (reference) value of MPV and a cycle-specific value of VI one can calculate the target value for a constant melt displacement. Hence the injection process is stopped, when the value FI reaches the target value. The reference values are extracted based on a running process inside the quality tolerances. In this manner, the volumetric filling of the cavity may be kept constant (within limitations) independently of viscosity variations induced by the processed resin.

The holding pressure phase starts after switch-over in order to compensate the thermal shrinkage caused by the decrease of the specific volume of the plastic. Therefore a holding pressure is applied to deliver the needed volume. Depending on the used polymer, the cavity geometry and process parameters used the holding pressure has to be chosen.

$$p_{packP} = p_{packL} \cdot \left(1 + \frac{V_{IP} - V_{IL}}{V_{IL}} \cdot K_2 \right)$$  \hspace{1cm} (5)

In general, the higher the holding pressure is applied, and the longer it is applied, the more melted resin is pushed into the cavity. In order to correct the effects of changing
viscosities it is needed to adopt the holding pressure level. This is done in accordance to the above shown variables characterizing the melt (5).

**Figure 4** below shows the pressure profile of the injection- and beginning of holding-phase of two polymer melts. A reduction in viscosity of the plastics melt form Example A to B leads to lowered injection pressure. Regarding (4) a lower FI is needed for a correct volumetric filling of the cavity. In that case the switch-over will take part at an earlier state (position). Also the holding pressure level is reduced accordingly to the ratio of $V_{IP}$ to $V_{IL}$ in (5).

![Figure 4: The melt pressure curves for a plastic melt A and B. Hatched shown are the FI’s to the corresponding materials. Material B has a lower viscosity than Material A, so that less injection pressure is needed to fill the cavity, therefore, it is switched-over on an earlier screw position from injection- to holding pressure phase.](image)

4. **Validation of the adaptive process control concept**

In order to evaluate the effectiveness and robustness of the adaptive control concept an extensive field test program was conducted. Representative for the test program two processes will be shown in detail. First reference is a trial using a hydraulically driven injection moulding machine (KraussMaffei KM35-180CX) with a clamping force of 350 kN and an injection screw diameter of 28 mm as shown in **figure 5**.
The machine was equipped with the adaptive process control in order to compensate viscosity deviations induced by admixing regrind feedstock. Using regrind feedstock is today commonly applied in injection moulding to reach ecological as well as cost objectives. Due to a thermal degradation a plastic is undergoing when processed the admixing of regrind feedstock will result in a lowered viscosity.

**Figure 6** shows the resulting parts weights as measure for the parts quality and the viscosity of the plastics melt. It can be seen that the amount of regrind admixed has a substantial effect on the plastics melt viscosity (green). Increasing the amount of
regrind from 0 % to 100 % lowers the viscosity by 20 %. When the machine is operated with a constant injection stroke a change in parts weight of 0.187 g (0.480 %) takes place (red). Running the adaptive process control with the reference set to the 0 % regrind the effect is marginal; the deviation in parts weight is reduced to 0.030 g (0.077 %). Figure 7 shows two screenshots from the machines control with the corresponding pressure curves. One is without adoption of the process; one is showing the pressure curves with automatic adaption of switch-over position and holding pressure level.

Figure 7: Screenshots from machines control, left: resulting difference in pressure curves without adaption of process, right: pressure curves with adaption of switch-over position and holding pressure level.

Second representative process is running in a two component injection moulding machine (KraussMaffei KM500-2000/750CXZ) which is producing a radio cover for the automotive OEM market in back-injection technology. First a transparent PC component for the display is injected.

Figure 8: left: KraussMaffei KM500-2000/750CXZ injection moulding machine with peripheral equipment / right: produced plastic part “radio cover” in 2-component back injection moulding process.

Then the mould rotates and black PC-ABS for the case body follows in the same cavity in the second step while the other cavity is already being filled for the next display. This
all takes place on the back of a PC film with scratch-resistant coating and decorated in black that is inserted into the mould. The production cell based on the injection moulding machine and the part produced can be seen in Figure 8.

**Figure 9:** Resulting part weights for 24 h without adaption (left) and 24 h with adaption (right) of the process, the standard deviation of the part weight was reduced from 0.16 g to 0.03 g

In this trial again the part weight was chosen as the representative parameter for the parts quality. In order to compare the robustness of the moulding process with and without the adaptive process control here 48 hours of series production were evaluated. Figure 9 shows the resulting part weights as well as the switch-over position. The first 24 hours of production the adaptive control was not used e.g. the switch-over position is constant. The resulting standard deviation of the part weight was 0.16 g within the control samples. With the activation of the adaptive process control the standard deviation was brought down to a value of only 0.03 g in the 24 hours of production.

### 5. Conclusions

Injection moulding machines, which are operated with the introduced adaptive process control, are able to compensate negative effects on part quality like they are caused by viscosity changes in the feedstock. Since the characterization of the actual value of the polymer melt viscosity takes place in the first part of the injection movement an online correction within the same production cycle is possible. This is an important advantage compared to prior approaches and helps to effectively control starting up and restarting injection moulding processes. In case of changing conditions induced by the raw
material the adaptive process control helps to stabilize the produced parts quality by reducing the deviations to a minimum.

6. References


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