# ADAPTIVE PROCESS CONTROL IN INJECTION MOLDING

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## ABSTRACT

Today's machine capability in injection molding is at a high standard and the variation of material properties are within a small range. Nevertheless variation in material properties and conditions influences the process- and product-quality. Examples are residual moisture or drying conditions by different material handling.

With respect to surface properties especially the injection-phase has a large influence on the part quality. By a recently developed process-adapted-pressure-control during the injection phase combined with control of the switch-over point and packing-pressure, the quality of the process can be improved. Process variations by, for example, varying residual moisture content of the material are compensated by this new control strategy.

## 1. INTRODUCTION

In automotive applications, consumer electronics and electrics, material combinations, high polished and refined surfaces are state of the art. High quality requirements go along with the increased machine capability and raw material quality. Nevertheless the material conditions variegate in a small range and influence the high product- and process-quality requirements. The actual process control is not able to compensate these influences and react to the process variations. Examples are residual moisture or drying conditions that affect the part weight and other quality criteria. Most of the time the defect parts are only identified after the processing. With respect to surface properties especially the injection-phase has an important influence on the part quality. The surface is defined at the first contact with the cavity wall.

Effects on the surface that correlate with different flow properties of the material are moisture streaks or different surface topography details. These defects are defined during the filling. Most of the time sink points or marks can be compensated during the packing by reducing the effects of shrinkage.

To reduce quality influences an inline detection and quality control to compensate the viscosity variations is necessary. Therefore it is necessary not only to reproduce the adjusted process parameters but to adapt the processing to the actual conditions. The target figure is always the product quality with demands as geometry, surface quality or mechanical properties. The quality criteria for the product have to be matched with quality parameters for the process to be detectable. These parameters have to be controlled to adapt the processing to assure a constant product quality.

## 2. RELATED WORK

The production machines need to be able to detect changes within the processing, refer these variations to the quality criteria and adapt the process parameters to assure the process quality. Several different approaches have been developed to secure a good quality production by an inline process control within the last years.

A lot of quality criteria go along with a constant part weight which is used as a quality parameter easy to measure [1]. As the machine capability, good maintenance of the machine parts and static energetic supply can be taken as standard for high quality productions, still the non-return valve affects the processing. The closing characteristic of the valve variegates from one shot to another, influenced by different positioning of the valve in the plasticizing unit (relative to the barrel and the screw) and the material viscosity. A second influence to the injection process is added by the switch-over strategy, also amplified by a varying viscosity of the plasticized polymer material [1, 2]. A third influence can be described by a material flow that streams into the screw antechamber after the decompression during the plasticizing phase [3]. The material flow variegates by homogeneity, temperature and therefore viscosity. Today`s advanced control strategies try to compensate these effects by adjusting the switch-over process based on referenced curves and referenced process control values. If the filling pressure curve differs from the reference, the switch-over point is adjusted. Possible characterization parameters are differences between the pressure reference and the actual pressure or the pressure development as an integral over the screw stroke. These strategies have a positive effect on a constant part weight [2, 3, 4].

Other strategies control the process by the cavity pressure. As additional sensors within the cavity are necessary, the direct link to party quality criteria like part weight is well known [5, 6]. Advanced control strategies correlate the cavity pressure profile with the process and material condition by measured pressure and temperature. A specific gradient of the cavity pressure is realized during the injection phase. In a second step the cavity pressure is optimized during the packing according to the material specific pvT-behavior [6]. In [8] the implementation of the cavity cooling system into a self-optimization injection molding process by the pvT- and cavity pressure control is mentioned.

The control system is implemented by neuronal networks that have to be taught to work properly [6, 7]. Neuronal networks are also used for other control strategies that correlate the process parameters directly to quality parameters. In this case, the process is described by defined parameters like maxima, average and integral values [9]. The recorded parameters are connected by the control systems neuronal network structure to quality parameters. Recommended process adaptions are made automatically if taught to the system [10, 7].

The related control strategies still do not completely compensate possible process disturbances. The cavity pressure is limited by the shifted response time in the injection phase of the pressure sensor and needs a very precise detected pvT-diagram. For quality criteria linked to the injection phase like the closing behavior of the non-return valve and differing material properties the control effect is limited. The neuronal network can only react to quality parameters and connections that are trained and as a black box system need very precise installation.

By control strategies shifting the switch-over point a good compensation of the closing behavior can be achieved. But the strategies are also limited by varying material viscosities that influence the filling process and the definition of surface properties.

## 3. VISCOSITY VARIATIONS

The material handling, raw material properties or charge mainly influence the viscosity next to the processing conditions. In addition to the initial conditions, the handling of the material has a major influence on the viscosity and therefore the process quality. As generally known, technical polymers like polybutylene terephthalate (PBT) or polyamide (PA) tend to absorb humidity during storage and have to be dried before the processing [11]. Because of the complex measurement methods for residual moisture in polymeric materials, the drying process is done at a standard setup without a control system. Varying transportation ways to the injection molding unit and residence times are a critical source of error that lead to different residual moisture levels and therefore viscosities and quality variations. Figure 1 shows the viscosity of a PA 6 material and different residual moisture contents. The viscosity reducing effect of the moisture content is pointed out by a Carreau-model-fit of the measurement spots.

The results are combined measurements of oscillatory and stationary analysis at a rotation rheometer and a high pressure capillary rheometer.

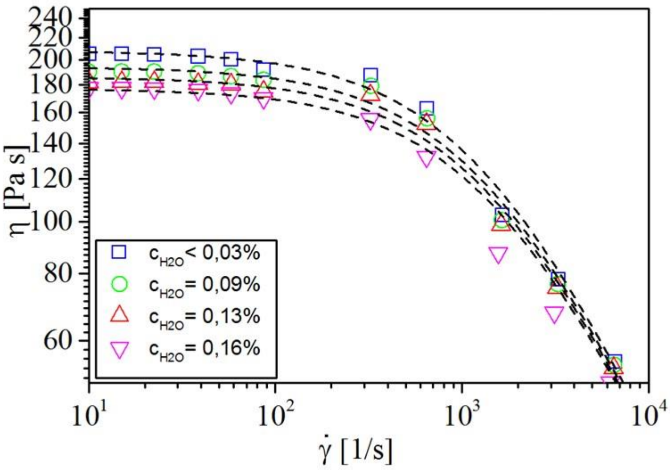


*Figure 1. Influence of high moisture content variations on the material viscosity of PA 6*

The residual moisture has the physical effect of a lubricant and reduces the viscosity. It may also increase the chemical degradation reactions [12]. During the processing, the different effects of time, temperature, residual moisture and processing (shearing) superimpose. With respect to quality parameters, changes in the viscosity directly influence the part weight [13], residual moisture has an additional effect on the surface quality [14]. So during the processing these effects have to be detectable on the one hand and compensated by adapted filling or packing parameters. Examples for surface defects are streaks or different reflecting spots and can be detected at parts with deflectometric surface inspections [15] or image based measurements.

## 4. QUALITY INFLUENCES

The material used for the investigations was polyamide 6 (Durethan B30S). The material was dried and conditioned to the residual moisture levels by storage to controlled laboratory environment. The experimental setup was a full electric driven injection molding machine KM 180-750 AX with a high bandwidth measurement setup connected to the machine software.
Within this investigation PA 6 material with a different residual moisture contents was examined. Processing different material condition, after changing to material with a residual moisture that exceeded the recommended content, streaks occurred on the surface as quality defects. Possible effects on the process and part quality are shown in Figure 2. To show the very high influence on this surface, a relief-filter can point out the resulting streaks on the surface.

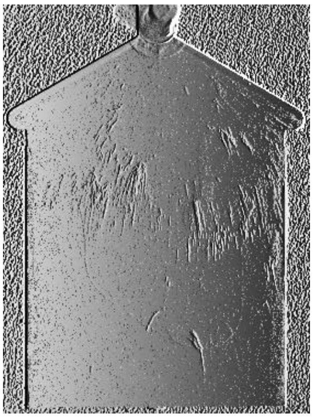

*Figure 2. Influence of high moisture content variations on the part surface*

The high residual moisture content influences the filling process by the changed material viscosity and therefore the surface quality. In Figure 3 the resulting equivalent injection pressure, calculated by the measured force at the screw shank, is shown for different residual moisture content. The filling was characterized at a constant injection speed $v_S$, and constant plasticizing parameters. The material was changed during the processing to the different conditioned residual moisture contents and added to the hopper. Characteristic cycles after a short transition during the material change are shown in Figure 3.

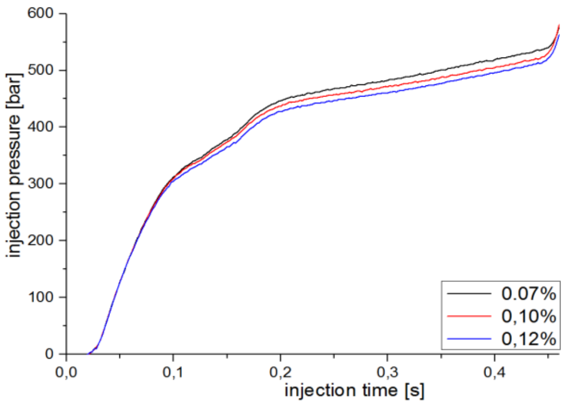


*Figure 3. Influence of high moisture content variations on the filling pressure*

As shown in Figure 3, the material variations lead to different pressure behaviors during the filling at constant injection speed profiles. The viscosity reduction directly influences the loss of pressure. The reduced pressure leads to a delayed overflow of retention bars and areas of high flow resistances in the cavity. The surface is formed with less pressure and bounded residual moisture can gas out and damage the surface. Today´s machine control cannot compensate the changing process condition by reproducing the machine parameter setup. An adaptive quality control is necessary to adapt the process to the changing conditions.
With respect to surface properties, especially the fast filling process is of interest. The surface is defined at the first contact with the cold cavity wall. Only sink points or marks can be compensated during the packing by reducing the effects of shrinkage. Effects on the surface that correlate with different flow properties of the material are flow marks and moisture streaks or different molded surface topography details. Process simulations have also shown high mass temperature variations by varying material viscosities at constant injection speeds [16]. These variations of the pressure and temperature influence the quality criteria defined during the filling and lead to different pvT-parameters at the switchover to the packing.

## 5. Model for quality control

By referenced plasticizing parameters and stable processing, the plasticizing torque can be used to set up a quality model and to prognosticate filling parameters like the integrated pressure over the screw stroke or the maximum pressure during the injection phase. For a quality control after the processing, the detected variations can support a 100%-control and critical parts can be sorted out. Nevertheless to secure a constant quality an adaption of the process parameters is necessary.

Adjusting the filling process to control the quality is the important next step. For quality requirements like surface properties especially the filling speed and pressure curve are important. At the institute for product engineering a new control strategy for the filling during the injection molding process has been developed to control the quality during the processing. Before the process can be controlled, a reference setup has to be saved for comparison. The necessary parameters are the injection speed, pressure profile during the filling, switch-over point and packing pressure profile. This setup needs to be referenced to a good quality production point that matches all quality requirements. To compensate influences of material viscosity variations, the velocity controlled filling is superimposed by a pressure control. By controlling the pressure during the filling and reproducing the reference pressure profile, the injection velocity is no longer a constant value. If the viscosity of the material changes, differences in the resulting pressure compared to the reference are controlled by an adapted injection velocity. So the effects of reduced viscosity in the processing are compensated by a pressure profile adapted injection speed. If the viscosity of the material is reduced because of i.e. different drying conditions, the injection speed is increased to adjust the pressure profile to the reference.

Actually there is no direct pressure controlled filling available at injection molding machines. The pressure control is set up at an external system with a direct link to the machine control. With a pre-controlled PID-controller a defined pressure curve during the injection phase can be used for the process management. The PID-controller uses available pressure curves as reference date and adapts the command variable injection velocity. Because of the external setup and indirect control of the velocity, there is still a switch-over between filling and packing. The switch-over point needs to be adapted to the material condition and therefore the necessary velocity correction to adjust the pressure reference. The controller design is shown schematically in Figure 4.

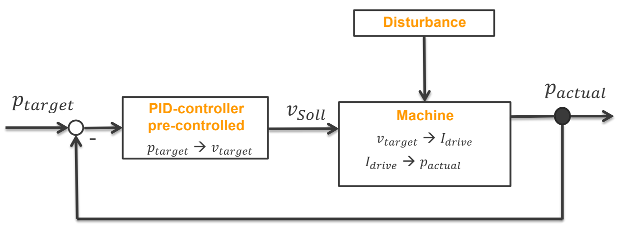


*Figure 4. Controller design for pressure controlled filling*

With a pre-controlled PID-controller a defined pressure curve during the injection phase can be used for the process management. The PID-controller uses the available pressure profiles as reference date and adapts the command variable injection velocity. The pre-control velocity is adapted to the actual process condition before the injection phase starts to secure a good accuracy of the controlled values. The adaption is setup by a process characterization of the previous cycle by the average necessary injection speed. In Figure 5 the process control, reference pressure profile and reproduced pressure curves for different viscosities is shown. To exclude influences on the control system by acceleration processes and the non-return valve, the injection movement is started by the pre-controlled speed. After a pressure criterial of 100 bar, the non-return valve closed and the pre-controlled speed is superimposed by the PID-controller the reproduce the pressure reference.

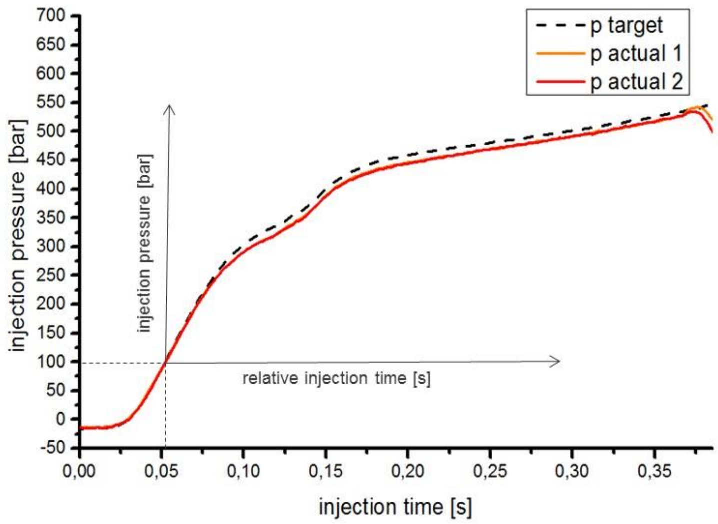


*Figure 5. Quality control model during the filling process*

Important for the quality model is an additional adaptation of the switchover point according to the viscosity, injection speed and the closing behavior of the non-return valve. Because the closing behavior of the non-return-valve is very much speed and viscosity dependent, an adaption of the switchover criteria is necessary to secure a constant filling process and process conditions at the beginning of the packing.

The switchover point is adapted to the closing behavior of the non-return valve to secure constant filling properties. Therefore a pressure control criteria during the acceleration process and therefore closing of the non-return valve at the beginning of the filling process is integrated. The necessary time and screw way so build up a pressure reference of 100 bar (specific for this cavity) is detected. In the following, the pressure profile reference is adapted to the time differences and reproduced with relative time axis. Therefore the pressure profile is reproduced unaffected by the closing behavior and time to the pressure reference. To secure a constant filling volume, the screw way and therefore volume differences at 100 bar compared to the reference cycle is used to adapt the switchover criteria. This combinations enabled constant pressure conditions and a constant filling volume at the switchover point.

## 6. Results and conclusion

A first test of the control strategy was calibrated with dried material with a residual moisture of 0,07 % and therefore within the recommended processing range. The referenced injection velocity profile is adjusted with a target velocity of 60 mm/s (constant) till the switch-over.

After the calibration to the referenced parameters the material was changed to higher moisture content and added to the process. With activated injection pressure control, the material change was compensated during the filling process. As shown in figure 5 the reference pressure profile $p_{target}$ (--) can be very good adjusted by the control unit for the two exemplary cycles to $p_{actual}$ (-,-). The added material had a considerably higher moisture content than the reference. The needed velocity adaption during the filling underlines the analysis. As shown in figure 6 the needed screw advance speed is adapted to the viscosity changes to adjust the referenced pressure profile. After the acceleration the target has a constant reference velocity $v_{reference}$ (--)

of 60 mm/s. The control system adjusts the injection speed according to the process conditions to $v_{actual}$ (-,-) for the two exemplary cycles.
To adjust the reference pressure profile with different material conditions, an adapted velocity of more than 65 mm/s is necessary. Because the pressure reference and target have a small difference during the main part of the controlled way, the velocity continuously increases during the controlling. This is optimized by referring the pre-control speed of the next cycle to the actual necessary average injection speed. The accuracy and reaction time of the control system are therefore considerably increased.

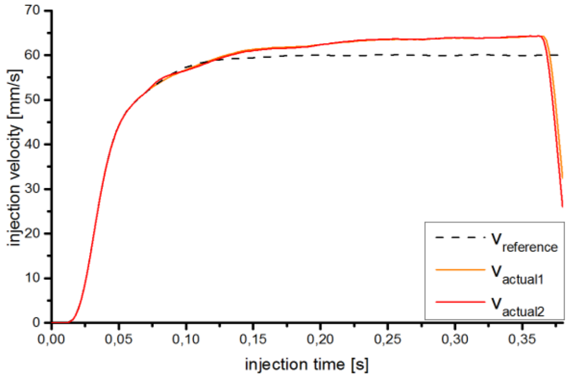

Figure 6. Injection speed with injection pressure controlled filling

In a second investigation a wide range of different material conditions was added to the controlled processing. As shown in Figure 7 the average injection speed characterizes the process and material condition very well. Pressure differences are compensated by an increased injection speed if the material viscosity is lower according to the reference or by a reduced injection speed for higher material viscosities. If the control system is deactivated, the reference injection speed of 60 mm/s is reproduced.

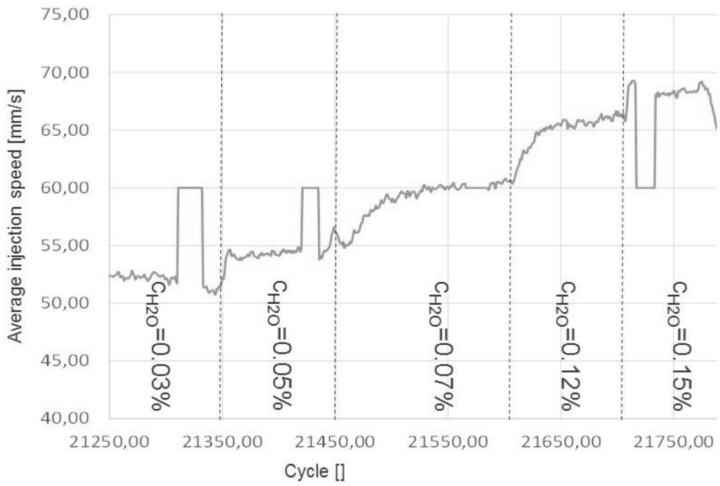

Figure 7. Average injection speed with injection pressure controlled filling

The combination of the pressure controlled filling with an adapted switchover point secure a constant filling energy input and filling rate that supports the part quality of the surface and morphology. First investigations of the defects have shown a good response to the strategy. As shown in figure 8, the streaks on the surface that occurred at stable process conditions after the material change (0.15 % residual moisture content) can be prevented. The surface quality is increased considerably, most of the streaks are eliminated.

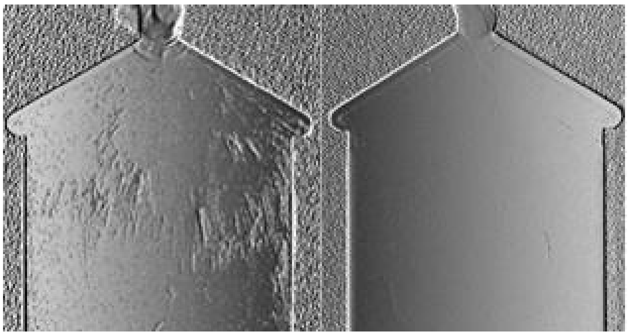

Figure 8. Reduced surface defects by adapted filling in comparison to conventional injection molding process control (residual moisture 0.15%)

In addition an adaptive pressure control during the packing process can ensure a constant part weight. The adaptive pressure control can be referenced to the new available process characterization parameter. The necessary average injection speed is significant to the process condition and necessary control process and therefor utilizable for the packing pressure adaption.

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## 8. Keywords

Injection molding, quality control, surface quality, pressure controlled process

## REFERENCES


[1] R. Schiffers, PhD Thesis, University of Duisburg-Essen, Duisburg, Germany, (2009).
[2] S. Kruppa, et al.; *29th Proceedings of the Polymer Processing Society*, Nuremberg, Germany, (2013).
[3] G. Pillwein, J. Giessauf, G. Steinbichler; *Kunststoffe,* 09/2012, 31, (2012).
[4] D.O. Kazmer, et al.; *Polymer Engineering and Science*, **50**, (2010).
[5] W. Michaeli, J. Gruber, *Journal of Plastics Technology*, (2005).
[6] W. Michaeli, A. Schreiber, Ch. Lettowsky, *Journal of Plastics Technology*, (2008).
[7] M. Al-Haj Mustafa, PhD Thesis, University of Essen, Aachen, Germany, (2000).
[8] W. Michaeli, Ch. Hopmann, A. Reßmann, *SPE European Technical Conference*, Barcelona, Spain, (2011).
[9] E. Schmidberger, J. Neher, *QZ - Qualität und Zuverlässigkeit*, **49**, 67, (2004).
[10] E. Schmidberger, J. Neher, *X-Press*, **3**, 16, (2005).
[11] J. Wortberg, T. Schroer, *Kunststoffe,* **10/2003**, 149, (2003).
[12] F.A. Heinzler, J. Wortberg, *Advances in plastics technology (APT`13),* Sosnowiec, Poland, (2013).
[13] J. Wortberg, R. Schiffers, *23rd Proceedings of the Polymer Processing Society*, Salvador, (2007).
[14] F.A. Heinzler, J. Wortberg, *29th Proceedings of the Polymer Processing Society*, Nuremberg, Germany, (2013).
[15] J. Macher, D. Gruber, G. Berger, W. Friesenbichler, *Proceedings of the Austrian – Slovenian Polymer Meeting*, Bled, Slovenia, (2013).
[16] F. Heinzler, J. Wortberg, Modeling of moisture effects on the rheological behavior of polymers and influences on the injection molding process, *Society of Plastics Engineering Annual Technical Conference (SPE Antec)*, Las Vegas, Nevada (USA), April 28-30, (2014)
[17] F. Heinzler, J. Wortberg; Quality improvement by enhanced pressure controlled injection molding, *Society of Plastics Engineering Annual Technical Conference (SPE Antec)*, Las Vegas, Nevada (USA), April 28-30, (2014)


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