Process Control in Injection Moulding

Improved Part Properties. The process control presented here permits direct closed-loop control of the cavity pressure in both the injection and holding pressure phases. As a result, the process is more robust to disturbances and thus ensures improved quality constancy.

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Fig. 1. Allrounder 370 CMD. Computer-Monitor-Dialog: The computer was used for control and monitoring the machine, the monitor for displaying data and functions (1983) (Photo: Arburg)

The German plastics machinery industry is the world leader – not least because of the excellent basis created by German research institutes [1], which will continue in future. A considerable contribution to this was undoubtedly made by Prof. Dr.-Ing. Georg Menges, who taught and researched at the RWTH Aachen University from 1965 to 1988 as head of the Institute of Plastics Processing (IKV). Throughout these years, he was the driving force and inspiration behind the industry. He set standards in numerous areas of plastics technology, in particular in the field of injection moulding process control. His 80th birthday gives us an opportunity to recall the developments of previous decades, reflect on the present and cast an eye towards the future.

Process Computers Revolutionise Injection Moulding

When Professor Menges takes the helm of the IKV in 1965, injection moulding is already a firmly established production technology for plastics. At this time, the machine is characterised by a usually horizontal plastication unit, and it is only a few years since the reciprocating screw replaced the ram as an injection unit [2]. It is already possible to control the principal functions. The machines have comprehensive open-loop control boxes and programmable open-loop controls units are increasingly becoming established. The first closed-loop controls are emerging, often as external add-on units. At the IKV, work is beginning on analysing the injection moulding process with the aim of improving part quality [e. g. 3]. The knowledge that the quality of the products depends primarily on the temperatures and pressures prevailing in the process, and their time dependence, makes it necessary to acquire these parameters, particularly in front of the screw and in the mould, as functions of time. This is made possible by specific developments in metrology [e. g. 4]. Professor Menges formulates that the state of the melt after plastication and the progress of mould-filling – described by the pressure and temperature profiles in the mould – are crucial to the quality of the product and require the use of process computers for monitoring and controlling the injection moulding process [5]. While the relationship between the machine setting parameters and part quality has been considered in the past, leading in some cases to striking contradictions between experimental results, work at the IKV confirms the correlation between the part properties and thermodynamic state properties of the melt during the process. In this case the representation of the injection moulding cycle in the pvT diagram proves to be a basis for understanding the injection moulding process and optimising processes and the part quality [6, 7]. On this basis, Professor Menges developed strategies for controlling the injection moulding machines under variable production conditions and for optimising the operating point and automated data acquisition [8].

Control of Thermodynamic State Variables

To provide a basis for process control, process models are first formulated, which give a statistical-mathematical description of the relationship between process variables and part properties (e. g. shrinkage). For this purpose, shrinkage values are determined in the pvT diagram, with incremental and reciprocal variation of the influencing parameters (e. g. melt temperature), and ▶

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Fig. 2. Injection moulding machine with switch cabinet from the early eighties in the IKV pilot plant
(Manufacturer: Battenfeld)

then subject to regression. The result forms a polynomial, which describes, for example, shrinkage in dependence on process control for the process window and material under consideration. After computation of the local temperatures in the part as a function of time by means of a differential process, the setpoint pressure curve in the mould is determined and transmitted to the machine by means of corresponding control functions [9]. The very limited computing power is a source of much debate here. However, the emerging microprocessors promise dynamic developments in injection moulding machine controls. Measures such as closed-loop control of thermodynamic state variables (e. g. melt temperature), open-loop control of dynamic process steps (e. g. adapted screw advance rate) and the first steps towards open-loop control of the cavity-pressure profile help to make significant advances in product quality and reproducibility of the processes [10]. The limits are set by the methods and tools available to control technology at this time, relative to the high process dynamics, so that adaptation of the controller behaviour to the behaviour of the controlled system at the particular process state poses significant, in some cases insuperable difficulties [11]. Strategies are developed here to compensate for the lack of dynamics in the closed-loop control process. For example, changeover to holding pressure at the end of the seventies is subject to severe delays, usually taking 30 to 50 ms, modern machines only take about 15 ms. This leads to correspondingly high pressures in the mould with the consequences of overfed parts with flash or overloading of the mould. Menges counters this by using closed-loop control of the maximum pressure in the injection mould to improve the process reproducibility [12].

Now that the basic work on understanding the injection moulding process is well advanced and the first closed-loop control strategies have been developed, the eighties are characterised by new opportunities opened up by the rapid developments in microprocessors (Figs. 1 and 2). Efforts to improve part quality increasingly focus on part shrinkage. This can be seen from the pvT diagram in principle, and is linked to the closing of the gate, i. e. when the 1-bar line is reached in the pvT diagram [13]. The intensive developments for closed-loop control of part quality focus on a reproducible and planned approaching of a defined point on this 1-bar line by means of corresponding closed-loop control of the cavity pressure in the holding pressure phase [14] and eventually result in so-called pvT optimisation [15]. Here, the holding pressure profile is modified from cycle to cycle in dependence on measured variations of the melt temperature or the mould wall temperature. In a new concept to further improve the reproducibility of the part properties, in particular the part weights, the effects of process variables are registered in a learning phase and saved in a characteristics map. This characteristics map is then used for closed-loop control of isobaric holding pressure time in the subsequent production phase. This method, which has become known as the pmT concept, has helped to make significant improvements in the reproducibility of the injection moulding process [16]. In parallel with this, Bourdon develops a concept for speeding up the setting of injection moulding machines by using the process data obtained from process simulation, which is also highly developed, for offline programming of the important process steps [17].

Statistical Process Modelling for Optimising Part Quality

Development work continues, now after Prof. Menges' departure from active service but still strongly influenced by his pioneering efforts. It is characterised by the use of statistical methods for describing the system behaviour of injection moulding processes. Gierth develops the first completely statistical process models, which describe the relationship between part properties and the manufacturing process, no longer based on thermodynamic state variables but by means of so-called characteristic data, to which the process parameter profiles (temperatures, pressures, etc.) have previously been compressed. The operations necessary for this are integrated into the modular software under the name Promon, so that, for the first time, a fully functioning tool for measurement data acquisition and processing and for predicting part properties solely on the basis of process data is available [18]. On this basis, and supplement-

Typical flow

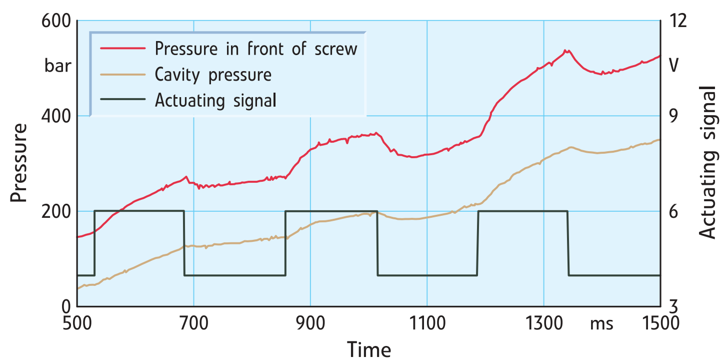


Fig. 3. Response of the cavity pressure to steps in the actuating signal

ed by the use of neural networks for forming process characteristic parameters and for direct processing of process curve profiles, concepts are developed for closed-loop control of part quality based on this process model, which automatically compensate for process disturbances and ensure constant part properties [19]. This demonstrated that closed-loop control of part quality by means process models is by all means possible. Supplementary to this, a part-oriented quality assurance system was developed, which automates the laborious experimental design and the complex development of process models and significantly simplifies data management [20].

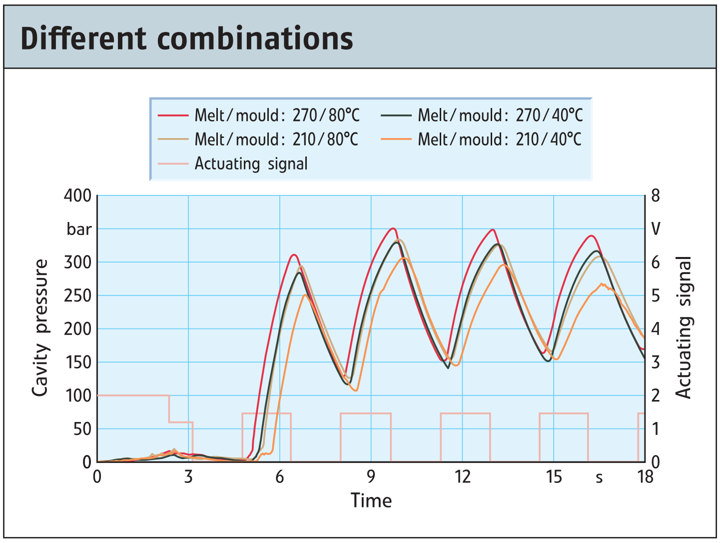
While a methodology for prediction of part properties based on statistical process models has since become established on the market, the closed-loop control of part quality based on process models has not been able to prevail because of the extremely high complexity of the systems and difficulties in handling.

Direct Closed-loop Control of Cavity Pressure

An alternative for increasing the quality constancy is offered by closed-loop control concepts aimed solely at the cavity pressure as the parameter determining the quality of the part. Only with online closed-loop control of the cavity pressures is it possible to respond to current process states and compensate disturbances during the injection moulding cycle.

Thanks to developments in microelectronics and drive technology, it was possible to take the initial steps towards direct closed-loop cavity pressure control [21], However, the PI and PID controllers used did not produce satisfactory results. Only the use of self-adapting controllers permits effective online control of the cavity pressure in the injection phase.

Fig. 4. Response of the cavity pressure to steps in the actuating signal



Dynamic Behaviour of Cavity Pressure

The process model, which is essential for a predictive controller, can be determined by analysis of the system behaviour. For this purpose, input and output signals of the system are recorded and evaluated. The model's input signal is formed by the actuating signal for the hydraulic valve or the servo motor for the screw advance. The output signal is the cavity pressure. Fig. 3 shows a typical profile of the two parameters for a square-wave input signal with constant flow-channel cross-section for the injection phase. It is clearly visible that the behaviour is highly non-linear with much dead time. Depending on the degree of cavity filling, the cavity pressure profile undergoes different changes for the same step sizes. A similar behaviour occurs in the holding pressure phase. In Fig. 4, the cavity pressure profiles as a response to the series of steps are recorded for different combinations of melt temperature and mould temperature. It can be seen that both the amplitude of the cavity pressure and the dead time are affected by the changes of both temperatures.

The non-linearity of the controlled system against time can be explained by the cooling process since the sprue freezes and pressure losses are consequently higher.

The data recorded in the step tests are fed to the model formation routine, which represents the behaviour in the form of a differential equation system. The process model that is found, however, only applies to the operating state under consideration, so that a separate model must be generated for each change in the operating point.

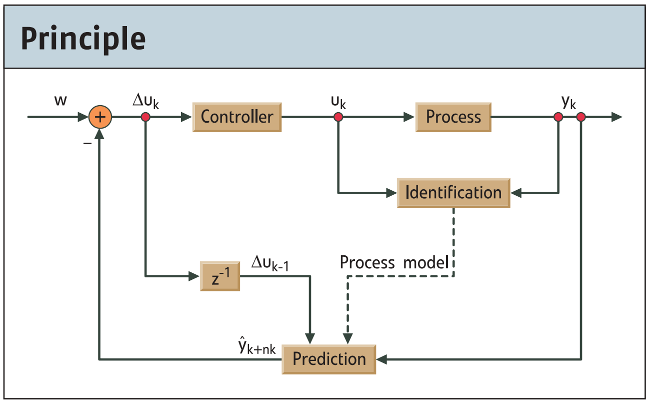
Model-predictive Control Algorithm Compensates Dead Time

The model-predictive control algorithm according to [22], on the basis of the process model, makes a prediction of the guide parameter from the current to the future point in time (Fig. 5). It is thus possible to consider the dead time in the controlled system. To allow the control to adapt itself to a changing process, an adaptation unit is superimposed on the controller. The adaptation ensures that the control system is always ideally adapted to the process. After each cycle, a recursive identification takes place to determine a new process model. If the model found is better than the one previously used, then it is adopted. Fig. 6 plots the controller deviation after a disturbance over several cycles. By adaptation to the process model, it decreases continuously until the model describes the process again.

Cavity Pressure-controlled Injection

Direct control of the cavity pressure offers the possibility of specifying a pressure ▶

Fig. 5. Adaptive and model-predictive controller



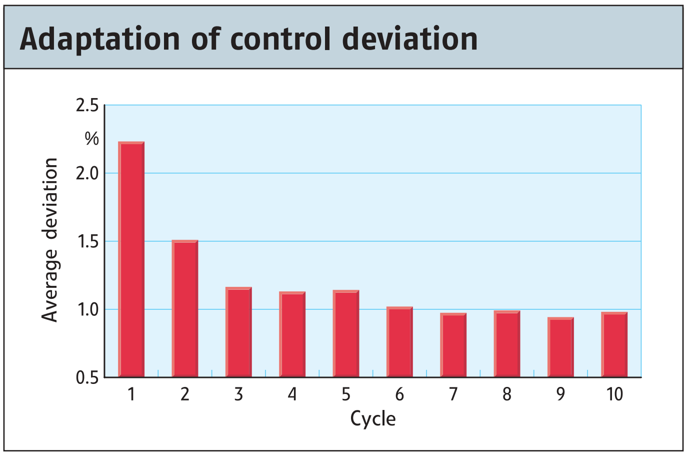


Fig. 6. Adaptation of the process model to a change in the system behaviour

sure phase. The advantage of this procedure over methods covering all the machine cycles is that the optimisation is carried out with data from the current process.

The effect on part quality is considered by means of a sheet geometry with 3.5 mm wall thickness. This mould is also equipped with a piezoelectric cavity pressure sensor close to the gate. The temperature of melt and mould are varied to investigate the effect of cavity pressure control on the part forming process and the quality of the parts produced.

profile during injection. The effect of geometry changes along the flow path on the profile of cavity pressure, and thereby the flow-front advance is compensated by the control system. For analysis of the control algorithm during injection, a mould is used containing a long flow path (l = 880 mm) with constant rectangular flow-channel cross-section (b = 20 mm, h = 3 mm). By means of cavity inserts, it is possible to locally constrict or enlarge the flow channel and thereby achieve different steps in wall-thickness. The mould is equipped with a piezoelectric cavity pressure sensor, which is 20 mm from the sprue. A reference curve for the cavity pressure is specified, which represents a defined linear ascent through the gradient.

Fig. 7 shows the specified and actual profile of the cavity pressure for a local reduction of the flow-channel height from 3 to 2 mm plotted against time. The red curve shows the cavity pressure when a constant screw advance rate is specified. The different gradients of the cavity pressure for the regions of different wall thickness can be clearly seen. The beige curve was implemented with the cavity pressure control system. It is clearly visible that the use of the cavity pressure controller allows the specified constantly increasing cavity pressure profile over the entire flow path to be achieved independent of geometrical changes in the flow channel.

According to Kudlik [23], the constant increase of cavity pressure results in a uniform flow-front advance rate, which provides a uniform outer layer orientation and therefore uniform part properties over the flow path. The studies have shown that precisely this is achieved by the use of cavity pressure control. The maximum deviation of the degree of orientation is reduced by from 8 to 16.5 % compared to the previous process control, which depended on the injection rate and the specified cavity pressure.

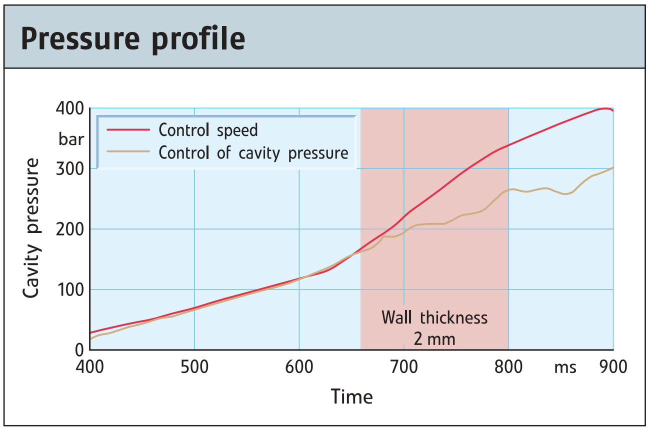


Fig. 7. Temporary narrowing of the flow cross-section from 3 to 2 mm

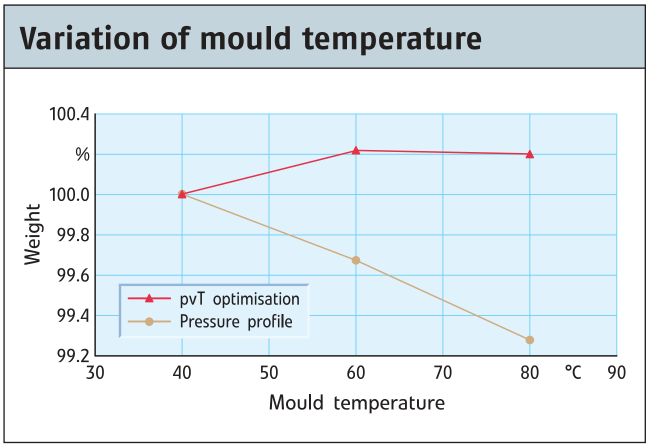


Fig. 8. Influence of the mould temperature on the part weight can be greatly reduced by the control system

Online Optimisation of the Holding Pressure Takes into Account the Material Behaviour

As from volumetric filling, the holding pressure phase is controlled on the basis of the pvT behaviour of the material used. Unlike the pvT optimisation concepts previously used, here there is no computation of the machine setting parameters holding pressure level against holding pressure time [15]; online control during the cycle is performed instead. For this the required pressure is computed in real time by means of the pvT diagram of the polymer used during the holding pres-

The specific volumes when the 1-bar line is reached in conventional injection moulding show a clear dependence on the disturbance variables, in particular the mould temperature. Thus, with a change of moult temperature from 40 to 80 °C, the specific volume increases by about 1.24 % when the 1-bar line is reached. Where cavity pressure control is used, this dependency on mould temperature can be almost entirely compensated. pvT optimisation computes the necessary pressure profile, so that the 1-bar line is always achieved at a constant specific volume. The part weight, which is influenced predominantly in the holding pres-

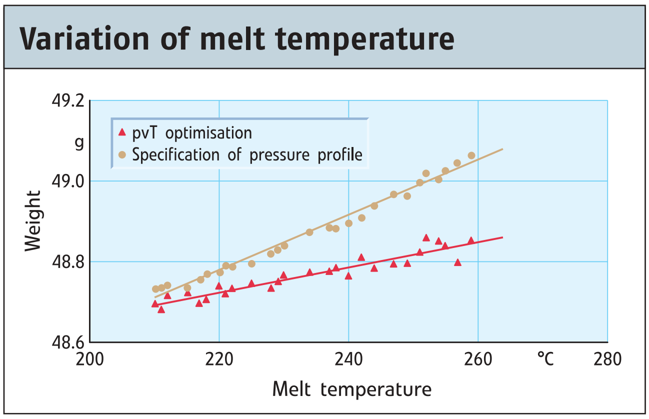


Fig. 9. The average melt increase of the parts is less than for conventional processes

sure phase, is used as the quality feature. The part weights obtained with variation of the mould temperature are shown in Fig. 8. It is clear that the influence of the mould temperature on the part weight can be greatly reduced by the control system. The weights obtained by variation of the melt temperature also show a compensating effect of the cavity pressure control on the part-forming process (Fig. 9). Although the average weight increase with increasing melt temperature cannot be completely compensated, it is lower on average than for parts produced by conventional processes.

Summary

The process control presented here permits direct control of the cavity pressure in both the injection and holding pressure phases. As is shown by the studies conducted, the control has the required speed and stability. During the injection phase, a specified pressure profile can be followed. This minimises fluctuations in the outer layer orientation. In the holding pressure phase, an online optimisation is carried out based on the pvT behaviour. The resulting process flow ensures that the 1-bar line is continually reached at a given specific volume. This directly results in greater process constancy. It is possible to respond to process and material fluctuations in real time during the entire process. High quality and process stability are thus achieved. Whereas the controller can compensate short-term influences during the cycle, the adaptive control concept can automatically adapt to changing process conditions and thereby compensate for long-term influences. This capability of the controller greatly simplifies setup and adjustment work on the injection moulding machine, which were previously performed by the operator based on empirical data.

With his work Prof. Menges laid the foundation stone for the modern understanding of the process and set strategies for quality control during injection moulding. The drives of modern injection moulding machines and progress in control technology have made many things possible that Menges already thought out 30 years ago. Much has now been implemented, some of it remains as challenges for future work, such as automation of the start-up process [8] . ■

Dedicated to Prof. em. Dr.-Ing. Georg Menges, former head of the Institute for Plastics Processing, Aachen/Germany, on the occasion of his 80th birthday

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LITERATURE

The extensive references list can be found on the internet at www.kunststoffe.de/A010

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