White Paper

Process monitoring with cavity pressure

Brief description

Zero-defect production, productivity gains and reduced costs: manufacturers of plastic parts are calling loudly for these requirements to be met, especially in the electrical and electronics sector, in medical technology and automotive engineering. Process-integrated quality assurance offers the only way of achieving these objectives. Detection of scrap at the earliest possible stage is a mandatory requirement for implementing lean production. Together with other measures, the sought-after goal of zero-defect production results in higher productivity thanks to better machine utilization and lower production costs.

Cavity pressure measurement has become established as a method for continuous monitoring of part quality in series production of complex plastic parts (1). The cavity pressure profile accurately mirrors the conditions under which the part is molded. Injection-molded parts which do not meet the required quality characteristics can be separated automatically. In addition to traditional quality assurance, cavity pressure opens up possibilities for efficient process optimization so that scrap can be minimized – if not eliminated altogether.

Of course, information from the cavity pressure signal can also be used to keep the process constant in a closed loop control. One method that has been used for a long time is switchover in response to cavity pressure, or automatic hot runner balancing. Other strategies for cavity pressure-based process control are known, but they are rarely used because of their high degree of complexity.

This White Paper demonstrates the potential of cavity pressure-based systems to optimize process efficiency and cycle time while also reducing quality costs. The key to attaining these goals is zero-defect production, which can be achieved through separation of scrap and process optimization based on cavity pressure, as explained here for practical use in injection molding.

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1. Introduction

Today's injection molders are confronted with challenges that are almost impossible to overcome. Requirements for quality are increasing, parts and processes are becoming more complex – but the prices that can be obtained for the articles are in continuous decline. As product life-cycles become shorter, it is now almost impossible to amortize long-term investments in process engineering and high-quality mold technology. Economic pressures are forcing injection molders to optimize their processes on a permanent basis, and avoiding expenses such as quality costs has become an essential requirement. In these circumstances, successful companies are investing in preventive quality assurance throughout the product life-cycle. Avoidance of quality costs in a highly optimized production facility is therefore a matter of absolute necessity.

In this context, process engineers are tasked with simultaneously optimizing numerous quality characteristics such as dimensional stability, surface quality and functional part characteristics, with the aim of producing under optimally cost-effective conditions. Disturbance variables originating from materials, the environment, peripherals and (by no means least) the operator can only be prevented to a limited extent, so it is essential to identify and compensate for them immediately. The most reliable method for this purpose is to integrate quality assurance into the process. To achieve the objective of zero defect production in injection molding with maximum cost-effectiveness, Kistler offers specialized sensor technology to measure cavity pressure. It is the most informative process variable, because it describes conditions immediately – while the molded part is actually being created. Sensors and systems based on cavity pressure detect whether or not a part is scrap at the earliest possible moment.

As will be demonstrated in more detail below, valuable process information can be obtained from the profile. As well as serving the purpose of monitoring, therefore, cavity pressure measurement can also be used to optimize the process. Visualization of processes in the mold delivers a range of benefits: improved quality of the plastic part, location and rectification of errors in the process, protection of molds, and also monitoring and documentation of part quality. Relevant parameters such as injection speed and holding pressure level, etc., have a direct influence on cavity pressure, so potential faults and errors can be identified from the pressure curve.

Cavity pressure-based monitoring and optimization of the process offer injection molders a solution to reduce quality costs and will protect them against the possibility of faulty parts reaching their customers. All efforts to achieve zero-defect output in series production focus on one goal: business success for the manufacturers.

2. Process monitoring methods

Every injection molding facility aims to achieve 100% quality in production. One efficient way of attaining this goal is to integrate quality assurance into the process. Quality assurance in series production uses various methods and measurands, which are presented in this section.

2.1 Different methods for process monitoring in injection molding

The methods range sampling to procedures for assessing the manufactured parts, as well as concepts that make it possible to use the injection molding process data for quality documentation.

2.1.1 Statistical process control

Statistical process control (SPC) is widely utilized throughout industry. It is used as the primary method for process monitoring and quality control (2). The method based on random sampling can be used to provide proof of the robustness of production. The results – mean value/range or mean value/standard deviation – are presented in the form of control charts. The random samples are taken from production at defined intervals, and within a defined scope; they are then measured according to a defined control plan. Due to the cooling that is required and the post-shrinkage that often occurs, there is usually a substantial time lapse between removal and testing of the part.

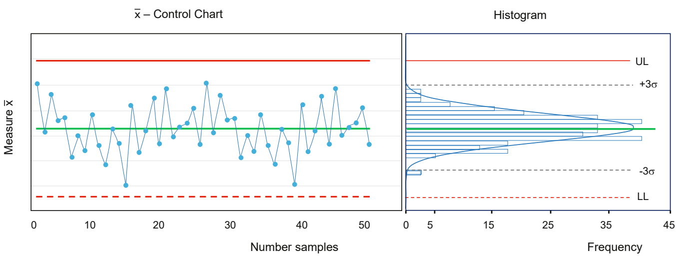


Figure 1: Control chart.

For these reasons, there are limitations on the suitability of this approach for the plastic injection molding process, with its short cycle times and high quantities. For correct determination of quality, control interventions in the process are only possible after a substantial delay; this can jeopardize the profitability of injection molded parts manufactured.

2.1.2 Process monitoring with key machine parameters

An alternative is offered by monitoring key machine parameters (2) (3). Instead of the part, this approach uses a process value from the machine. The evaluation criteria for manufactured quality are therefore based on actual values from injection molding machines and peripherals. Process data derived from screw displacement, hydraulic pressure and temperatures of tempering media are recorded as the basis for deriving informative key parameters. The statistically evaluated key parameters are displayed on the machines' central controls in graphic form (as a continuous control chart) or as lists. If individual or multiple key parameters violate defined limit values, an alarm is triggered and/or the produced parts are separated out from the production batch.

Machine manufacturers have integrated processes of this type into their controls. In many cases, process monitoring with key machine parameters based on actual values enables detection of disruptive external influences. This makes it a suitable method for monitoring the quality of the process.

2.1.3 Process monitoring with sensor technology integrated in the mold

Nevertheless key parameters from machines and peripherals are often not sufficient to monitor the process and the quality of the manufactured parts with adequate accuracy. To obtain a full picture, processes in the mold – including manifolds and cavities – must be taken into account as many effects and disruptive influences only arrise in the cavity. For example, effects due to the hot runner, or flow differences which occure in multi-cavity molds, cannot be captured from the machine. (3)

To ensure reliable process monitoring, sensors in all cavities of the molds are therefore the preferred solution. Relevant variables can be captured exactly where the part is being formed. In most cases, the variable used is the pressure in the cavity ("cavity pressure"). In recent years, combined recording of cavity pressure and contact temperature has also become an established method. (4)

2.1.4 Quality monitoring with process models

Quality monitoring with process models represents an extended form of process value monitoring, because the correlation of the key process values to the specified part characteristics is mapped in a model. (5)

As compared to monitoring based on process variables, the method based on quality models has the advantage that part characteristics can be calculated directly and compared with the specifications.

This method requires appropriate models that allow accurate calculation of the part characteristics – mostly on the basis of values for cavity pressure and contact temperature. These models are defined in advance of production, for example during the mold trial phase. For this purpose, process knowledge as well as knowledge about the influence exerted on quality characteristics by machine setting parameters is taken as the basis for initial trials, with the help of statistical test planning (Design of Experiments, DoE). When the tests are carried out, the process data is measured and the quality of the produced parts is determined, taking account of the relevant boundary conditions (e.g. post-shrinkage and crystallization). The procedure with a DoE has proven to be more efficient and to deliver better performance than continuous observation of random samples (6) (5).

Generation of the process models, i.e. calculation of the relationships between process data and part characteristics, is based on a mathematical analysis. Provided that their accuracy is adequate, these models are used for online quality monitoring (7). Several advantages become possible: calculation of the relevant quality characteristics, 100% documentation of manufactured quality, separation of scrap and the possibility of near-real-time quality control. At the same time, this approach guarantees that process knowledge is built up systematically, with efficient mathematical quality optimization.

2.2 Physical variables used to monitor the plastic injection molding process

The inner properties are based on the melt's pvT behavior: this describes solidification behavior and, therefore, shrinkage. In this model, the measurable variables – pressure and melt temperature – describe the behavior clearly. At present, measuring the melt temperature in the cavity is a complex and costly procedure, and the temperature also varies greatly over the cross-section; in practical applications, therefore, cavity pressure has become a very important factor in describing the processes in the cavity. A distinction is drawn between two types of in-cavity temperature measurement: the method using IR sensors (which will not be discussed in more detail here), and measurement with a thermocouple, although this can only supply a contact temperature.

2.2.1 Cavity pressure

Cavity pressure provides a complete description of the part formation conditions across all phases. It is the most informative process value for injection molding because it provides insights into the mold where the plastic part is gradually being formed.

During the injection phase, influence is mainly exerted on the surface characteristics, and on orientation and crystallinity in the outer layers. The compression phase follows after the switchover point: the cavity contours are molded. The progression of this phase determines factors such as flash and, therefore, possible damage to the mold. During the holding pressure phase, the principal influence is exerted on the shrinkage and weight of the molded part, but the degree of crystallization and the orientation of the macromolecules inside the part are also influenced. After the gate freezes (the "sealing point"), no further material is transported into the part.

	Injection	Compression	Back Pressure
Quality	Surface, Warpage, Crystallinity, Orientation outer layer	Fill status, Surface forming, Flash, Weight	Weight, sink marks, shrinkage, warpage, voids, orientation core

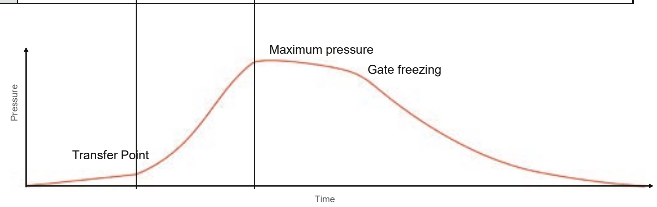


Figure 2: Ideal cavity pressure curve with correlating part characteristics (3) (7).

Information about cavity pressure can be used as the base line for monitoring the process and optimizing production. Cavity pressure correlates with quality-relevant part characteristics such as dimensional accuracy, surface, weight or accurate filling. Knowledge of the fundamental physical correlations makes it easy to evaluate and interpret the cavity pressure curve (3).

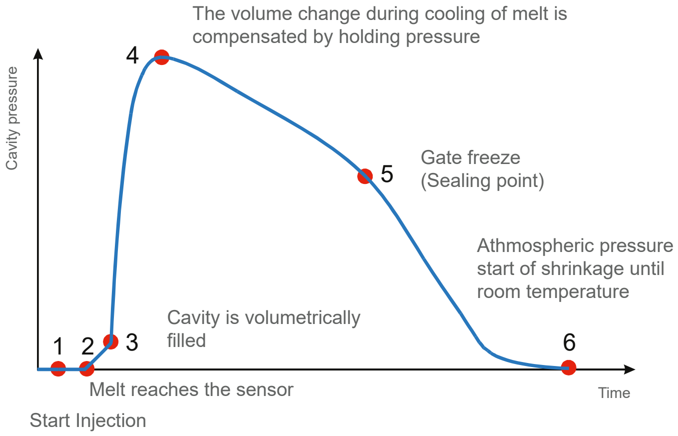


Figure 3: Cavity pressure curve.

The melt enters the cavity at the start of the injection phase (1). The pressure can be measured as soon as the flow front reaches the sensor (2). The pressure should show an almost linear increase as the fill time increases. The end of the injection phase (3) is reached on volumetric filling of the cavity. The melt will be compacted during the compression phase to guarantee molding of the part contours. The holding pressure phase starts after the maximum cavity pressure has been reached (4). This phase compensates for the high shrinkage of the plastic material – i.e. the reduction of its volume due to cooling – by adding material. When the melt freezes in the gate (5), the pressure in the cavity drops to ambient pressure level due to continued thermal contraction (6).

2.2.2 Contact temperature

Measuring the temperature on the cavity wall also supplies process information from cavity.

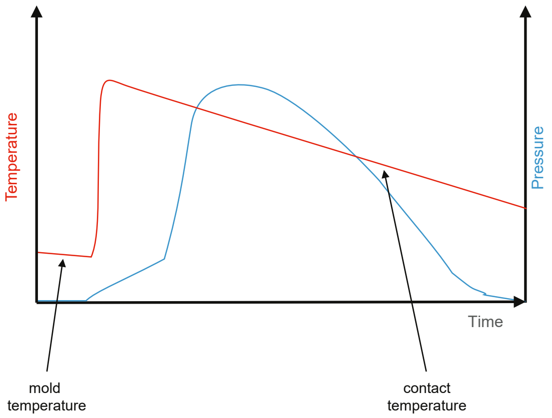


Figure 4: Temperature profile in the cavity.

At the start of the measurement, the temperature profile shows the mold temperature in the cavity because the melt has not yet reached the sensor. As it flows over the sensor, the temperature rises sharply by approx. 30 – 40 K. The maximum temperature does not correspond to the melt temperature, because the solidifying melt in the outer layer causes a massive reduction in thermal conductivity.

The profile can therefore be used to monitor the mold temperature and to detect the melt front precisely in the process. The technical process information that can be obtained from the curve profile as such is limited.

3. Cavity pressure sensor technology

The processes that take place in the mold determine the quality of the molded parts. This section focuses on sensor technology and methods for reliable cavity pressure measurement.

3.1 How cavity pressure sensor technology works

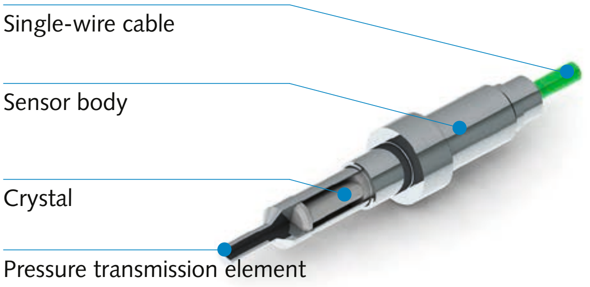


Figure 5: Direct pressure sensor.

Exact and interpretable pressure measurements from high-precision cavity pressure sensors increase process reliability. Measurement of pressure and temperature during injection molding calls for reliable and durable measuring technology with high resolution and no need for maintenance. Measurement systems that meet these requirements cover a melt temperature range of up to 450° Celsius and, even under pressure conditions of 2,000 bar, they must capture and read the smallest pressure fluctuations.

These requirements are only met by piezoelectric sensors, in some case with special crystals. The measuring principle is based on the piezoelectric effect, which allows measurements of highly dynamic pressures and forces (7).

The directed deformation of a piezoelectric measuring element creates an electrical charge. The charge signal, which is proportional to the pressure, is converted into electrical voltage using a charge amplifier.

In practice, the plastic melt that flows into the mold exerts a mechanical load on the sensor as soon as it reaches the sensor's front. This causes deformation of the quartz element in the sensor which, in turn, produces an electrical charge. The charge signal is fed via a connecting cable to a charge amplifier that converts it into a voltage signal from 0 to 10 volts. The individual signals behave proportionally to one another, which means that the measured voltage is proportional to the cavity pressure. This value can be picked up from the charge amplifier and used for the purposes of measurement, monitoring or closed loop control.

3.2 Direct, indirect and contact-free measurement

With the direct measuring method, the sensor contacts the melt in the cavity to measure the pressure directly and without losses. In most cases, the front of the sensor can be adapted to the surface of the cavity, which means that only minimal marks can detected on the part. Direct positioning of the sensor equipment is independent of the orientation of the mold axis, and it supplies an unfalsified measurement value (4).

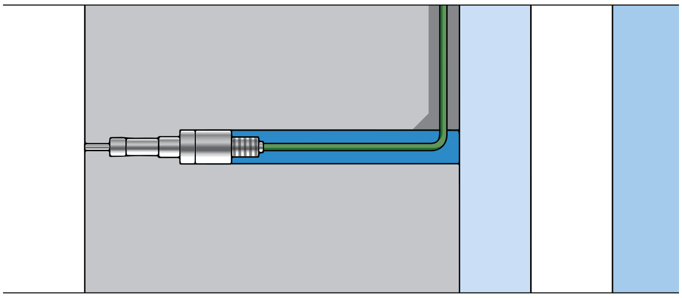


Figure 6: Direct measurement: the melt pressure acts directly on the front of the pressure sensor.

Indirect positioning of the sensor offers an alternative. In this case, a force sensor is positioned behind a static pin or an ejector, pin. The force flow therefore proceeds from the melt onto the front surface of the ejector pin, which passes the force on to the sensor. When calculating the pressure value, the effective front surface area of the ejector pin must be taken into account. The sensor is usually installed in the mold axis. The indirect measuring method is recommended if there is not enough space for a direct-measuring sensor.

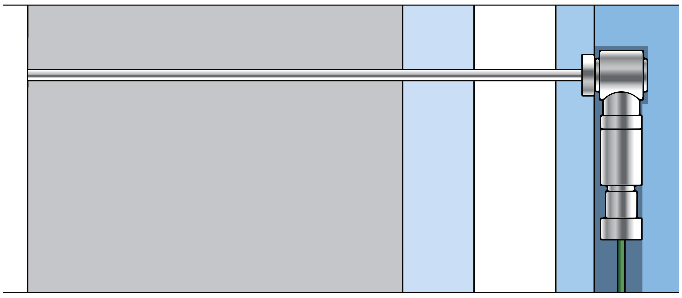


Figure 7: Indirect measurement: the ejector pin transmits the pressure to a force sensor.

Optical components – such as lenses or light conductors and parts with Class A surfaces for automotive applications – must not show any marks left by the sensors. The cavity pressure for these applications can also be measured contact-free with measuring pins.

These sensors measure the elastic deformation of the mold steel caused by the cavity pressure. The measured value can be used as a reference for the pressure load at this position (4).

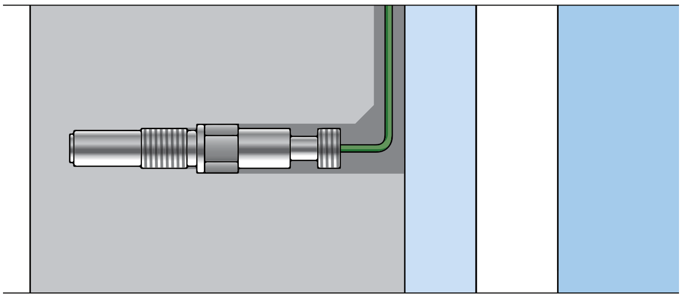


Figure 8: Contact-free measurement: measuring pins capture the mold compression caused by the pressure.

4. Positioning of pressure sensors

The positioning of the sensor in the mold is just as important as the sensor itself. CAD data simplifies identification of the ideal installation positions for one or more sensors in the mold. The basic knowledge required for this purpose is presented in the following sections.

Correct positioning of the cavity pressure sensor is important in order to obtain meaningful measurements. Particular attention must be paid to the position of the sensor relative to the flow path of the melt and the wall thickness of the part at the installation point. To position the pressure sensors ideally, the points where the melt freezes first and last must be estimated correctly. For cavities with several gates, the measurement should be taken in critical areas of the part.

The purpose of sensor equipment is particularly relevant for the positioning of the cavity pressure sensor. Depending on the position of the sensor in the flow path, certain advantages will be gained both for the use of the signals and for subsequent evaluation. The table (Figure 9) shows some examples of optimal sensor positioning for different types of use. Combinations are deployed for applications with multiple areas of use.

Use	Position in flow path
Process optimization in general	1/3
Scrap separation of incompletely filled parts	Close to the critical area, usually end of fill
Scrap separation of parts with sink marks	Close to the critical area
Automatic switchover (SLP)	1/3
Automatic hot runner balancing	1/3

Figure 9: Basic rules for optimal sensor positioning.

A sensor position at the end of the flow path is recommended when monitoring short shots. For larger parts a sensor near gate and a second sensor end of fill can be usefull to obtain all possible faults.

4.1 Measurement near the gate

The pressure progression in the mold will be captured during the injection phase as soon as the flow front of the melt reaches the sensor. The ideal position for the cavity pressure sensor is close to the gate. A sensor positioned nearer to the gate will deliver proportionately more process information.

A meaningful and more sustained measuring result is usually obtained near the gate and in the area of the greatest wall thickness. This is because thick-walled points are the last to solidify.

4.2 Measurement away from the gate

The further from the gate the measurement is taken, the later the flow front of the melt will reach the sensor. Pressure measurement only begins at a late filling stage. Therefore, the injection phase cannot be described until the sensor is reached. During a measurement at the edge of the part – i.e. away from the gate or at the end of the flow path – typically the measured signal will rise steeply in the compression phase.

Measurement positions end of fill offer benefits if special quality problems need to be monitored at the end of the flow path. For example, these might include unfilled part contours, weld lines or diesel effects.

4.3 Critical sensor positions

Sensors should only be positioned in the gate or cold runner manifold in exceptional cases, because only limited information can be collected in this area – especially after the melt has solidified in the gate. Injection molding of micro-parts is an exception, because there is insufficient space in the actual cavity to install a sensor.

Sensors should never be positioned exactly opposite the gate point, in order to prevent superimposition of a dynamic force component on the measurement of the cavity pressure signal; this would lead to falsification of the measurement.

Caution is also required with an installation parallel to the parting surface. This can lead to problems with demolding the part if the sensor was not installed flush with the cavity wall. Additional risks are posed by deformation of the mounting bore due to compression of the mold (clamping force). This can cause the sensor to become jammed in the bore, leading to disruption of the sensor's correct function. If the sensor is mounted parallel to the parting surface, it is therefore essential to ensure that there is an adequate distance from the parting surface and that the mold structure is solid (4).

5. Structure of the measuring chain

The measuring chain used to evaluate a pressure signal essentially comprises the sensor, the connecting cable and the measurement amplifier. The amplifier converts the charge signal into a proportional voltage which is then used to assess the pressure profile in the cavity. The voltage signal can be processed either by the injection molding machine itself, or with an external monitoring unit. Standardized sensor connections fit both evaluation units. (8)

5.1 Connection technology (cables and connectors)

Increasing numbers of cavities and more complex cooling concepts are increasing the complexity of the mold. The connection technology for pressure and temperature sensors has undergone continuous development, and it offers various technical solutions for the challenges that are presented.

The measuring chain between the sensor and connector on the mold can be realized with two different types of cable. The most suitable cable must be chosen, depending on the application and the mold structure.

In Single-Wire technology, the cable consists of just one conductor with a very small cross-section, and a special high-insulation covering. In this case, shielding of the sensitive charge signal against external influences is provided by the mold itself. Single wire technology offers the advantage of simple connections by means of cut-and-grip contacts, and the possibility for customers themselves to shorten the cable to the required length. Any possible damage can easily be repaired. However, it is important to ensure that no live lines (e.g. for heating elements) are installed in the same cable channel.

On the other hand, coax cable has its own insulation and it provides reliable shielding even in difficult installation situations. The disadvantage here is the larger diameter, which makes it more difficult to use in molds with large numbers of cavities. Also, users cannot adapt the length of the prefabricated cable, so they have to specify the length and the connector in advance. Repairs are usually impossible on account of the multi-layer structure.

For complex and modular molds, contact elements connect cables in different mold elements inside the mold. Contact surfaces in both elements establish the electrical connection.

Another option is the use of conductive spacer sleeves. If the installation is not angled, the spacer sleeve can be screwed to the sensor instead of a cable; this alternative significantly simplifies drilling of the mounting bore and installation of the sensor. A contact element will be installed on the opposite side to guarantee secure transmission of the charge.

A multichannel connector and a special cable are generally used to connect the mold to a process monitoring system. In this multichannel connector, four or eight measuring channels are combined and connected via one plug.

As standard, the multi-channel connector on the mold is equipped with a chip to allow automatic mold detection. The measurement and analysis system automatically detects the mold and uses the relevant sensor and system settings. This prevents errors and allows significantly faster mold changes.

5.2 Process monitoring systems

Process monitoring systems perform far more functions than process monitoring as such. They are also used for cavity pressure-based analysis, optimization, documentation and control of injection molding, even including automatic detection and separation of faulty parts.

Modern process monitoring systems are expected to be compact and suitable for industrial purposes; it must be possible to integrate them flexibly into diverse production environments,

Figure 10: Installation of a process monitoring system based on cavity pressure.

and they must have a process-oriented operating concept. Systems of this sort have up to 32 inputs for piezoelectric cavity pressure sensors, and up to 20 analog voltage inputs for temperature and machine signals (screw displacement, machine pressure, etc.) (4).

Networking of multiple devices transfers process- and quality-related production data for live and completed orders together in one database, providing the basis for detailed analytical options and statistical evaluations across all historic and actual production runs.

Central storage of production data provides an overview of the status of each injection molding machine, as well as making it possible to monitor production. Machines can therefore be compared to one another, so process fluctuations can be detected rapidly. Storage and management of all mold settings are also integrated into the central system. Data can be accessed at any time via a web browser – and also from a mobile device.

Modern process monitoring systems operate independently of the injection molding machine that is used, making them suitable choices for flexible use and for facilities equipped with multiple machine technology.

As an alternative to external process monitors, most machine manufacturers offer the option of transferring the signals into their own machine control via integrated charge amplifiers. Basic functions such as visualization, certain monitoring functions and simple switchover in response to cavity pressure are also available as options on the machines.

6. Process optimization based on cavity pressure in injection molding practice

As already described in the previous sections, the cavity pressure profile offers excellent insights into the progression of the overall process and the processes in the cavity as the part is formed. It provides an instrument for optimizing the process, because important effects that influence the quality of the part become transparent and visible (8) (11). The individual phases in the process – the injection phase, and the compression and holding pressure phases – can be clearly identified, and common sense criteria can be applied to optimize them on the basis of the cavity pressure curve. Some relevant aspects are explained below.

6.1 Switchover point

The switchover point marks the end of the injection phase which, on all commonly used machines nowadays, is controlled in relation to the screw displacement speed (i.e. control dependent on volume flow). With volumetric filling of the cavity, the switchover point marks the transition from speed-oriented process control to pressure-controlled mode in the compression and holding pressure phases. There are numerous methods of determining the switchover point, both in practice and in the literature; only the switchover method based on cavity pressure is explained here.

During the injection phase, a continuous and mostly linear increase in pressure due to flow resistance can be seen in the cavity pressure curve. Once the mold is completely filled, a sharp increase in pressure is apparent due to the limited compressibility of the melt. This produces a kink in the pressure curve that indicates volumetric filling (Figure 11)

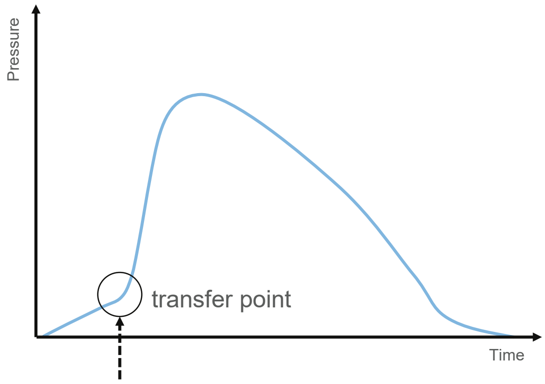


Figure 11: Switchover point after volumetric filling.

If the selected switchover point is too early, the mold will not be completely filled and the melt flow stopps; this can be identified in the curve as a pressure drop. Interruption of the continuous melt flow can result in freezing of the melt front, which negatively impacts part quality. Possible effects include short shots, poor weld lines, sink marks (especially away from the sprue), flow marks, surface defects and weight fluctuations (Figure 12).

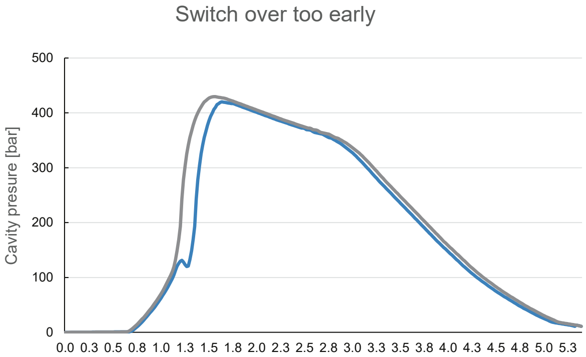


Figure 12: Cavity pressure if switchover point is too early.

Setting the switchover point too late causes excessively peak pressure, because the specified screw speed is maintained although the cavity is already completely filled, so the injection pressure is increased to its maximum. This results in a pressure peak during the compression phase, accompanied by flashing.

If the mold is pressed apart due to high local pressures, this can result in permanent deformations on the sensitive parting surface (Figure 13).

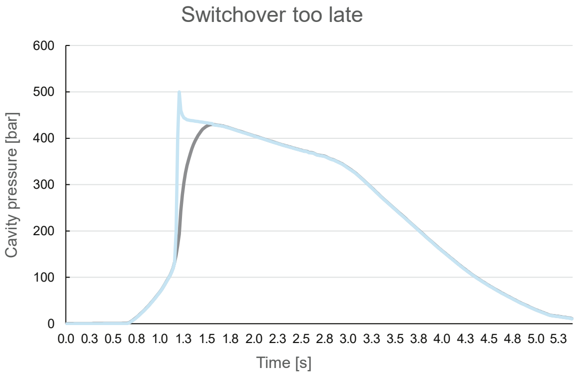


Figure 13: Cavity pressure if switchover point is too late.

During setup, part fill studies are therefore undertaken to determine the optimum switchover point. This procedure is greatly simplified thanks to visualization of the cavity pressure profile (9). The cavity pressure curve is shown on the screen in real time, so the switchover point is visible as a kink.

The option of optimizing the switchover point with cavity pressure can be utilized for various switchover processes. Switchover based on the screw position, or by means of hydraulic pressure, has become established as the most common method. If cavity pressure is used as the measurand for switchover, it becomes possible to compensate for numerous material- or machine-related influencing parameters that are reflected in the pressure curve. As well as the classical method of defining a threshold value, there are methods for fully automated kink detection and switchover. This method, which has been patented by Kistler (ComoNeoSWITCH or SLP), allows process control that adapts automatically to changed boundary conditions such as changes in viscosity.

6.2 Injection speed

Injection and melt front speed are variables that significantly influence cavity pressure. During the injection phase, the objective is to keep the melt front speed constant throughout the entire flow path.

A change or increase in injection speed is apparent in the cavity pressure curve as a change in the gradient of the pressure rise during the injection phase. Injection time and (in some cases) injection pressure change under the given circumstances, which will lead to an in-or decrease of the pressure gradient.

In terms of production, an increase in the injection speed of the melt in the nozzle-sprue-gate system and as it flows through the part geometry means increased shearing of the melt, with a corresponding increase in temperature and a reduction in viscosity. In extreme cases, increased injection speed can cause the melt temperature to rise to such an extent that thermal damage to the plastic occurs as a result. Correlative optimization is possible based on the cavity pressure curve.

If filling of the cavity is too slow, the result may be that the melt freezes and the part is not completely filled.

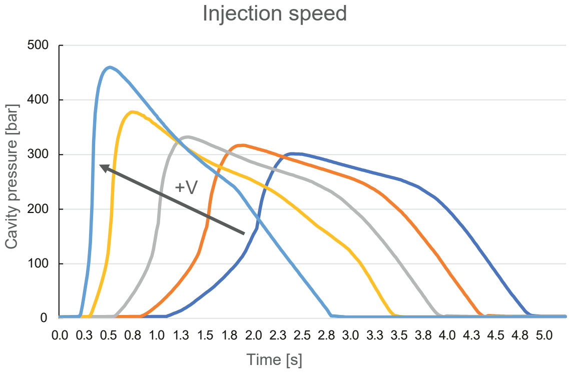


Figure 14: Influence of injection speed on the cavity pressure curve.

Since cavity pressure correlates directly to melt front speed, changes in wall thickness can be clearly recognized and located, so they can be compensated by adjustments to the injection profile.

6.3 Holding pressure

In the holding pressure phase, material shrinkage is compensated and additional melt is fed into the cavity under pressure control.

The holding pressure can be increased if the holding pressure time is long enough. This positively impacts dimensional stability, orientation near the gate, the weight of the molded part and the strength of the weld lines. An increase in holding pressure also reduces sink marks, blowholes and shrinkages. If, however, the selected holding pressure profile is too high, the results to be expected include increased difficulties with demolding, residual pressure and flashing (flash shot). The melt is increasingly compacted so that, in extreme cases, the mold may even open sligtly.

The objective of process optimization is to determine the best possible profile for the cavity pressure. According to the commonly used method to achieve this, the pressure level is increased on the basis of the material specifications and part characteristics until the molded part is free of defects. The goal is achieved quickly, and more easily, with the help of visualized cavity pressure measurement: this goal is the "ideal" cavity pressure curve, without major pressure drops and with gentle transitions (Figure 11).

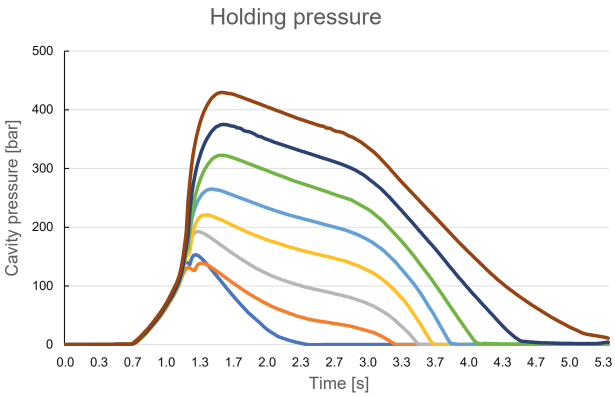


Figure 15: Influence of holding pressure level on the cavity pressure curve.

Insufficient holding pressure leads to sink marks and dimensional problems. This is caused by insufficient shrinkage compensation or even by material flowback into the runner system (lower curves in Figure 15). If the holding pressure is too high, the mold is overfilled.

6.4 Holding pressure time

During the holding pressure time, the melt cools down and there is a reduction in the liquid flow channel. When the gate has frozen after the "sealing time", no more melt can reach the cavity.

The goal of process optimization is therefore to maintain the required holding pressure for as long as possible, and to feed melt into the part without unnecessarily extending the cycle time.

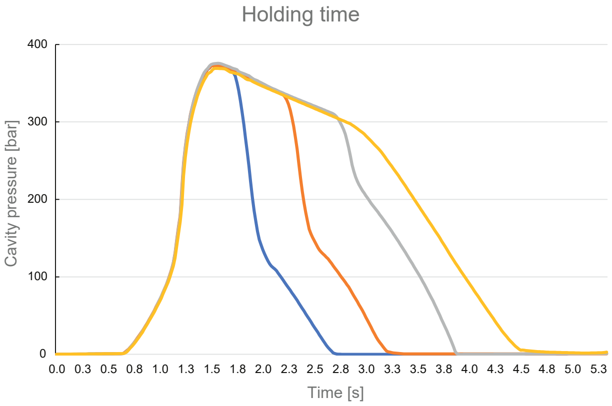


Figure 16: Influence of holding pressure time on the cavity pressure curve (3)

If the holding pressure time is too short (i.e. the holding pressure ends before the gate is frozen), this can be recognized as a pressure drop in the cavity pressure curve (Figure 16). A too long holding pressure time will not have a direct impact in the cavity pressure curve. After the gate freezes, the material in the cavity can no longer be influenced. The correct holding pressure time setting is reached when the pressure curve is not changing at longer holding pressure times.

6.5 Mold temperature

Mold temperature has very little influence on flow during filling and compression. For cooling of the melt in the holding pressure phase, however, the situation is different: cavity temperature plays an important part here because the higher temperature slows down cooling in the molded part.

As the mold temperature rises, cavity reproduction accuracy increases. There are also improvements to mechanical properties thanks to the more homogenous structure of semicrystalline plastics, and weld lines are less clearly visible. The disadvantages are a longer cooling time and therefore longer cycle time.

For process optimization that should favor complete filling of the parts, the mold temperature can be adapted as appropriate; it should be noted here that the cycle time changes in accordance with the significantly longer cooling time.

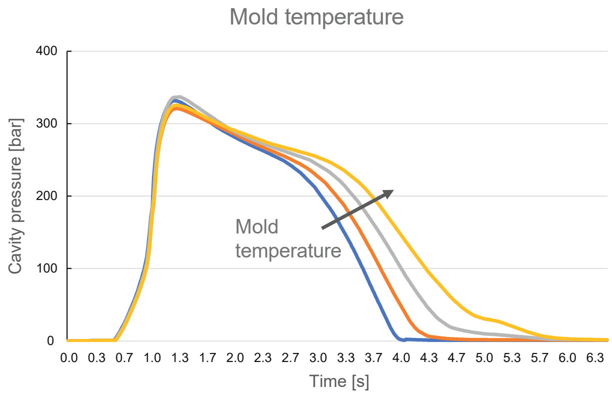


Figure 17: Influence of mold temperature on the cavity pressure profile.

6.6 Melt temperature

A higher melt temperature has a positive impact on the molding precision and the visibility of the weld lines. However, there may be an increase in the occurrence of shrinkages and thermal degradation of the melt.

For process optimization of the melt temperature, the provided material datasheets are usually taken as the basis. Within these limits, the melt temperature is either reduced with the aim of reducing the cycle time, or is increased with the aim of lower viscosity.

The influence of the melt temperature is shown schematically in Figures 18 and 19. Changes in the melt temperature can easily be recognized from the cavity pressure curve because the melt temperature directly impacts material viscosity: the higher the temperature, the lower the viscosity will be. This has an impact on the flow behaviour as well as the pressure conditions in the cavity: A lower melt temperature (with higher viscosity) results in higher pressures during filling becauseof the increased flow resistance over the whole flow path. However the maximum pressure will be lower as the pressure transmission though the gate is reduced. (Figure 18, dark blue curve). A higher melt temperature (with lower viscosity) will result in lower pressures in the filling phase, as the melt flows easier through the contures of the cavity. The lower flow resistance will lead to the reduced pressures. The easier flowing melt also allowes a better pressure transmission through nozzle and gate system, therefore the maximum pressures in compression and holding phase will be higher (Figure 19, light blue curve).

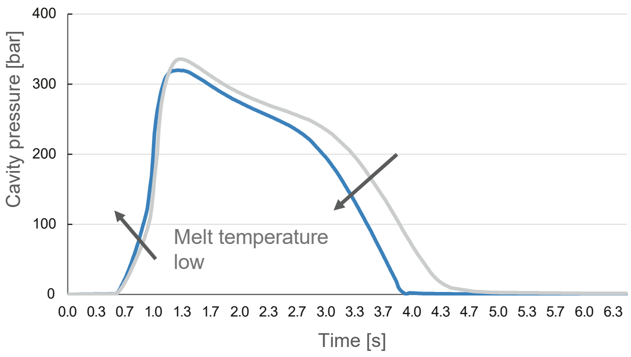


Figure 18: Cavity pressure curve if melt temperature is low.

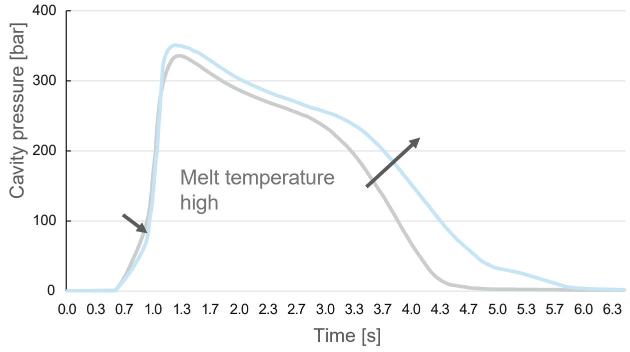


Figure 19: Cavity pressure curve if melt temperature is high.

Therefore, the cavity pressure curve also indicates changes in temperature, so effective monitoring is achieved.

7. Fully automated process monitoring

One aspect of fully automated process monitoring that is important for production is the control and documentation of the process with separation of good and bad parts. Integrated process monitoring solutions that are independent of the machine control (such as those from Kistler) are suitable for these application areas.

Systems such as ComoNeo from Kistler make it possible to follow the cavity pressure profile in real time; process conditions can easily be understood thanks to intuitive visualization.

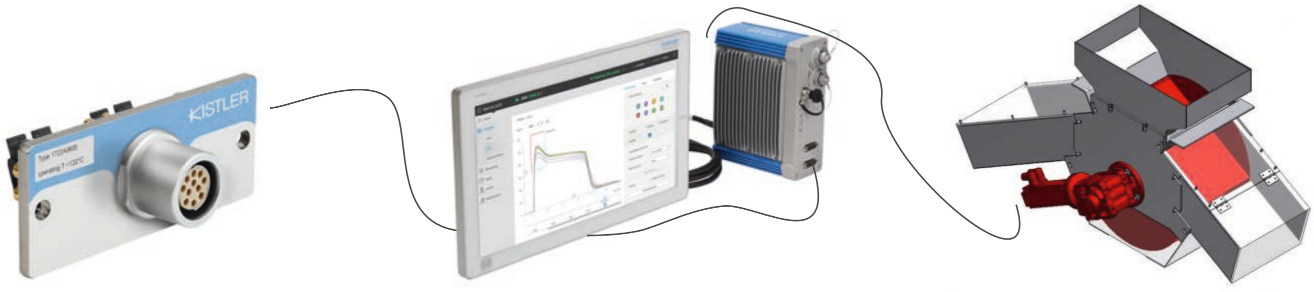
In addition to observing and optimizing the process parameters, the part quality in the running cycle can be assest with so called evaluation objects. So part quality can be evaluated even before the part is demolded. Manufacturers of precision parts and producers of other critical high-quality components benefit from this tool, which gives users 100% in-process prediction of all quality features.

Real-time thresholds enable automatic process control or effective protection of molds in case of unwanted process conditions.

Further options make it possible to continue optimizing the injection molding process for complex plastic parts. For example, fully automated control of the hot runner parameters can effectively optimize the balancing of multi-cavity molds. The input data is supplied by the cavity pressure curve in the individual cavities.

As opposed to machine-integrated solutions, external process monitors make it possible to store complete curve profiles for the entire injection molding facility in one database. In this way, past production runs can be compared with the reference curve at any time, and the validated process can be proven in case of a complaint.

Together with external devices, fully automated cavity pressure monitoring performs functions such as mold trials, process analysis and optimization, process and production monitoring, process and production documentation, and also process control, i.e. closed loop control of hot runner controllers and of the switchover point.



Cavity Pressure Measurement
in the Injection molding process

ComoNeo for process
Monitoring & control

Seperation of
bad parts

Figure 20: Structure of a monitoring system.

8. Summary and conclusions

All injection molding facilities aim to produce as cost-efficiently as possible. Reducing quality costs is a continuous effort. Process monitoring based on cavity pressure can play an important role here.

The cavity pressure signal reacts sensitively to process anomalies, and can indicate deviations at an early stage. Random influences that lead to problems such as short shots are reliably detected, and faulty parts are separated out. This avoids secundary costs in the production facility – and after parts have reached the customer – at the earliest possible point.

Thanks to cavity pressure measurement, greater transparency is achieved not only for process optimization but also for mold trials – leading overall to a reduced time effort. Intelligent software assistants are available to optimize the startup process and set up the monitoring criteria; thanks to these assistants, less experienced users can also achieve transparent results (9).

High scrap rates caused by incomplete part filling can be avoided, as this White Paper clearly explains.

Fully automated process monitoring sets the course for the future, because processing of the data is constantly becoming more important. Cavity pressures measured during production clearly reflect the quality of the manufactured parts, so they can be used to provide documented proof of quality: a benefit that is equally appreciated by manufacturers and their customers.

As a leading manufacturer of sensors and systems for quality assurance in the injection molding of plastic parts, Kistler pioneered the fundamental development work in the 1970s. In the future, too, Kistler intends to retain the trust that molders all over the world place in its expertise and experience. The company aims to strengthen its position as the technology leader with further innovations for process monitoring in the plastics segment, in demanding industries such as the electrical and electronics sector, medical technology, aerospace and automotive engineering.

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