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# Hitting the Nail on the Head

Process Control



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Special reprint



The targeted control of the flow properties in the tool is the prerequisite for the manufacture of the same part on different machines

**Process Control.** The control of melt flow and viscosity via pressure and temperature sensors in injection molding tools is a major prerequisite for machine independent quality control of a molded part. Trials with nanostructures in a cavity show that apart from the strength and dimensions of a molded part previously difficult to describe parameters such as the reproduction accuracy of structures can also be controlled in a targeted manner.

# Hitting the Nail on the Head

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**T**hrough the combination of a pressure and temperature sensor melt flow and viscosity can be determined and controlled directly within the cavity of an injection molding tool [1]. In order to control the injection molding process and adapt this to various injection molding machines the basic parameters of the machine have to be adjusted so that the same flow conditions,

compression ratios and shrinkage conditions always apply. If, however, a mold is used on different machines identical conditions in the molded part can only be realized if they are set up using internal cavity pressure and mold wall temperature sensors. Depending on the machine, injection speed, melt temperature in the barrel of the machine or the hot runner manifold and tool surface temperature are then adjusted via the host computer interface until the target values in the cavity are achieved. In this way a mold can be used on different sized machines, with different screw diameters and different operating principles – e.g. hydraulic or electric – without los-

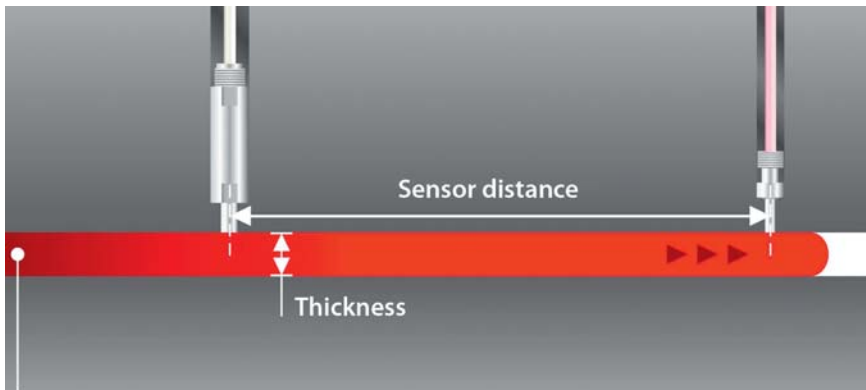
ing the initially optimized condition of the molded part.

## Control of the Flow Conditions

At first glance it seems obvious to combine the measurement of pressure and temperature signals; however, taking the measurements of both parameters at the same location has hardly any advantages in practice. A certain separation between the measurement points allows the determination of values that describe the melt flow – for example shear rate and shear stress and thus also the viscosity of the melt during production. To achieve this, a pressure and a temperature sensor were

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**Fig. 1.** Internal cavity pressure and mold wall temperature sensors are used for the automatic measurement and control of shear stress and shear rate in the cavity

installed in the direction of flow (Fig. 1) and then, using an automated process based on the average wall thickness and the spacing between the two sensors, both shear rate and shear stress could be determined directly in the cavity itself. The basis for the calculations was provided on the one hand by the acquired flow time of the melt between the two sensors and on the other by the internal cavity pressure measured at the time the melt reached the second sensor [2].

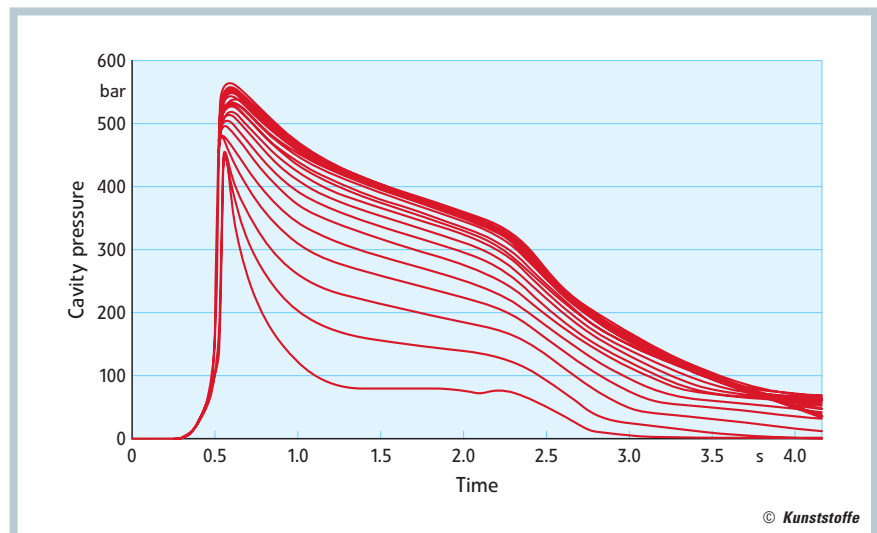
To do this it is necessary to detect the rise in the signal as close as possible to the moment at which the melt front reaches the two respective sensor positions. Since depending on the separation of the sensors and the velocity of the melt these can be very small time differentials in the millisecond range, the determination of the melt front via a switching threshold in the pressure and temperature signal is fundamentally unsuitable. Even with process control the melt flow would be so influenced that recognition of the melt front with simple switching thresholds would not be possible.

The shear rates and shear stresses – and thus the viscosity of the melt – have to be controlled because they have a major influence on the quality of the finished parts. Differences in flow conditions lead for example to differences in the boundary layers formed with semi-crystalline materials, to differences in weld lines, varying reproduction accuracy of surface structures up to and including sporadic under-filling of parts. Batch to batch variations of materials are an additional reason for variations in the flow conditions, which have to be recognized and compensated for.

### Controlling Compression

In order to ensure that a molded part is always produced with the same compaction conditions, i. e. strength, similar

varies from machine to machine. At the same time the internal cavity pressure has to be controlled in such a way that the influences of injection and holding pressure can be separated from each other. It is therefore not particularly sensible to use only the maximum value of the internal cavity pressure as a basis, since this can result not only from the holding pressure, but also from (too) high injection speeds. Multiple superimposed internal cavity pressure curves show how the packing of a molded part can be optimized and controlled via variation on the holding pressure settings (Fig. 2).



**Fig. 2.** Multiple superimposed internal cavity pressure curves were automatically adjusted to the target values via the holding pressure stages of the injection molding machine (compression control)

cavity pressures in the molded part have to be guaranteed. Since, however, depending on the process conditions the pressure conditions in the cavity change, the same holding pressure settings on the same machine do not necessarily lead to the same compaction in the part. This has to be measured using the internal cavity pressure and, where appropriate, adjusted.

In order to achieve the same compaction on different machines several factors have to be monitored and controlled. On the one hand the starting points of multiple holding pressure stages have to be correctly interpreted and adjusted since both the number and logic of these

### Controlling Shrinkage

The same prerequisites apply to the shrinkage conditions of a molded part: It has to be ensured that the same conditions always apply to the part itself, independent of the type, size and settings of the injection molding machine used. In the case of shrinkage this would seem obvious as it is not a machine parameter but rather in particular the mold surface temperature in the cavity that has to be controlled, which ideally and for the sake of simplicity should be carried out by the host computer interface of the machine. Since the shrinkage of a molded part – and thus its final dimensions – can be explained by its  $p, v, T$  behavior, these physical laws are used as the basis for the control process. Therefore the surface temperatures are not only controlled to a defined value, but rather they are also controlled to a defined value when the internal cavity pressure reaches atmospheric pressure again.

Due to the various process conditions this can very much occur at different

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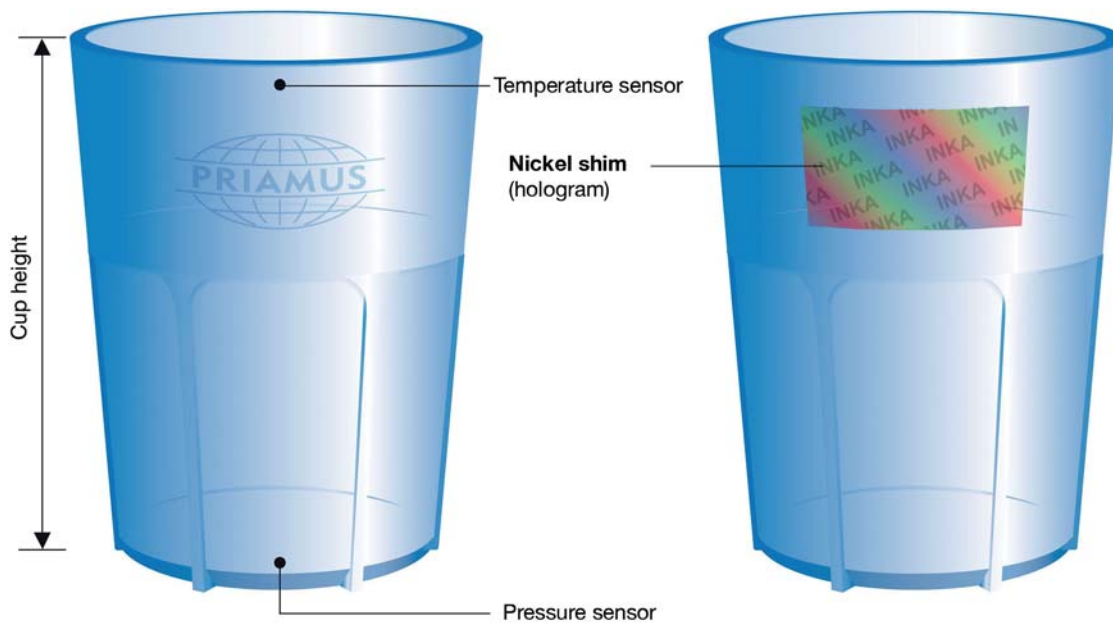


Fig. 3. A cup made from PC with holographic and diffractive features reproduced from a nickel shim. The reproduction of the surface was automatically controlled with a pressure and temperature sensor

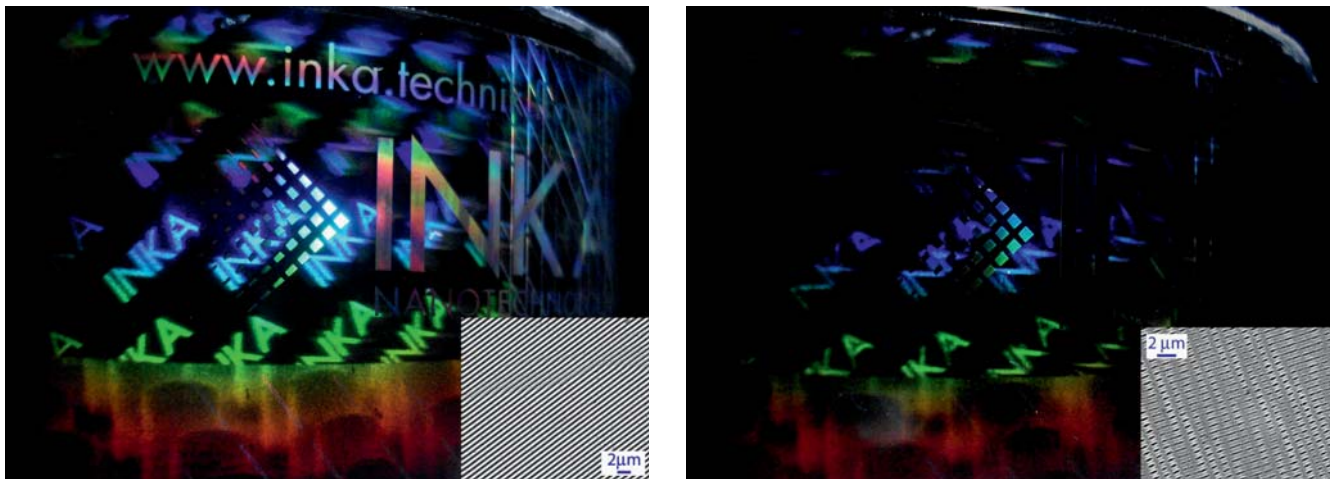


Fig. 4. Reproduction quality of the nickel shim under optimal (left) and deliberately chosen unfavorable process conditions (right) including respective SEM images of the nanostructured diffraction grating

times, which means that control of the mold surface temperature in no way guarantees the same shrinkage behavior. If one assumes that different thermal control units have an effect on the temperature control behavior – e.g. the flow of the cooling medium – the initial settings have to be systematically altered until the same conditions apply to the part itself.

### Reliable Replication of Structures

The reproduction of micro and nanostructures by injection molding requires accurate control of processing parameters. Replication, in particular with high aspect ratios in the structures to be reproduced, is dependent to a significant degree on the mold wall temperature and the flow behavior of the polymer, as de-

termined by the viscosity which is in its turn dependent on temperature and shear rate. Control of these parameters therefore offers an ideal basis for the precise reproduction of micro and nanostructures on the molded part surface.

The influence of various machine settings on the dimensions as well as the part weight of a molded cup (Fig. 3) made from polycarbonate (grade: Lexan Resin 123R, manufacturer: Sabic Innovative Plastics) was documented in a series of tests together with the signals from a pressure and a temperature sensor in the tool. In addition, a nickel shim is integrated into the mold cavity. It contains a series of holographic and diffractive elements that react with different sensitivity to changes in the process parameters. The holographic elements have a rather low structure depth (aspect ratio of 0.5 and less),

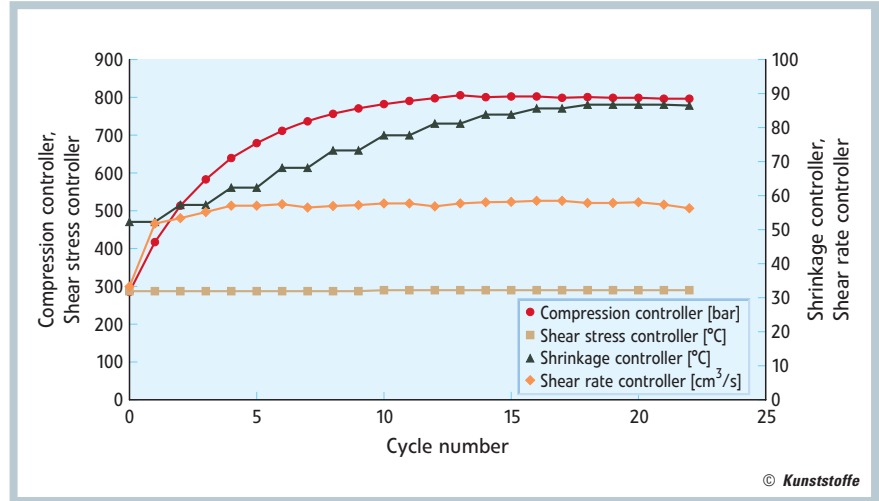
whilst the diffractive elements depending on their position on the shim have a structure depth of up to 0.5 µm.

In order to reveal the dependence of the reproduction quality of the nickel shim on process conditions, part of the cup was cut out and photographed under equivalent lighting conditions (angled to the white light coming from above). Striking differences in the interference effects occurring can be seen in the images taken of the moldings made under optimal and deliberately unsuitable process conditions – this can also be seen in the associated scanning electron microscope (SEM) pictures of the nanostructured diffraction grating (Fig. 4).

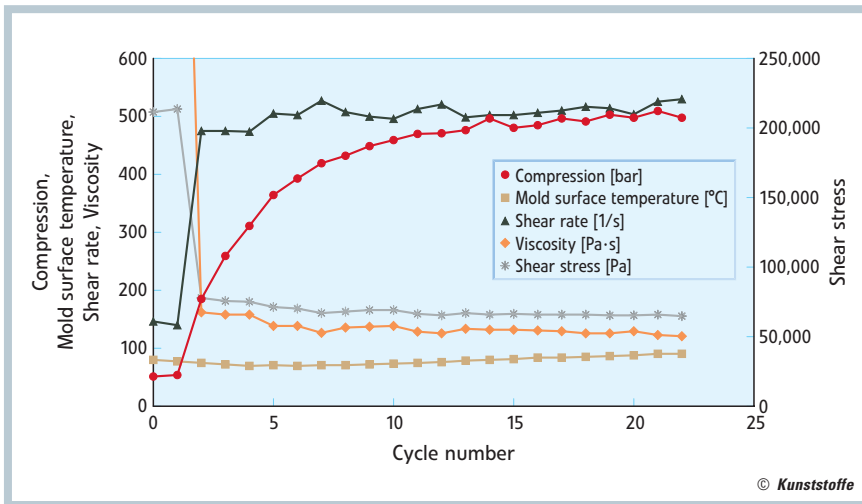
As expected the holographic image is in both extreme cases still clearly visible. This is due to the extremely low depth of the structure of around 200 nm in this

area of the nickel shim and demonstrates that the near surface holograms can be realized without extensive effort in injection molding processes. In this area of the nickel shim SEM imaging shows barely any differences between the two extreme conditions.

The most impressive differences are seen in the area with large horizontally running letters which are composed of diffraction line gratings (400 nm line width, 800 nm pitch). These line gratings have high aspect ratios (structure depth > 0.5 μm), which is why worse reproduction is achieved under poor process conditions. This is also reinforced by the SEM images, in which the reproduction difficulties under poor conditions (in this case high viscosity from low injection speed) lead to both interrupted lines and a low surface depth.



**Fig. 5.** The individual controllers automatically adjust the set values of the machine – injection and holding pressure profile as well as mold surface temperature – until the target value in the cavity is achieved. For fine adjustment a hot runner balancing control system can be added



**Fig. 6.** Target values – for example from a previous process optimization – are achieved after just a few cycles. Starting values: Mold surface temperature: 50 °C, melt temperature: 280 °C (zones 1–3), injection speed: 10 cm<sup>3</sup>/s, holding pressure: 150 bar (first stage); target values: mold surface temperature: 90 °C, shear stress: 65,700 Pa, shear rate: 510 s<sup>-1</sup>, holding pressure: 500 bar at the sensor position

**Fully Automatic Process Control**

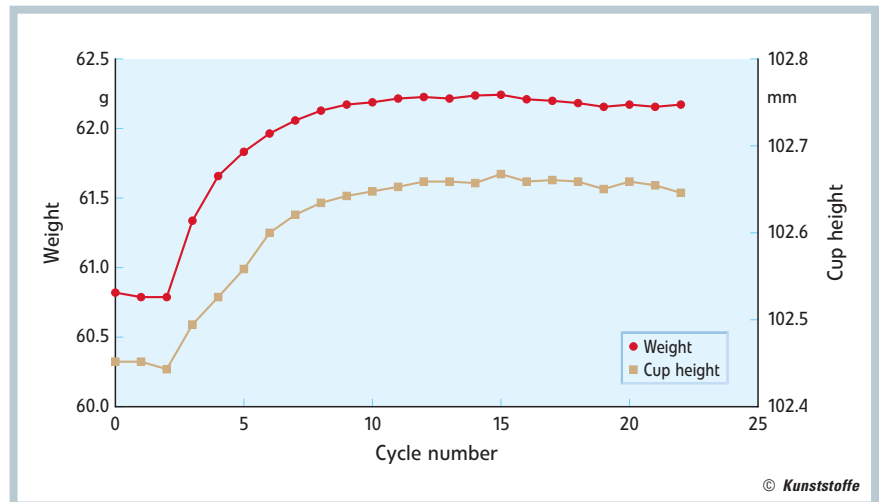
The structures produced in these trials all have a relatively small aspect ratio (max. 1.5), which is why the melt and mold temperature only have a minor influence. In this case the melt viscosity is the deciding process parameter for reproduction quality, which could in particular be seen at low injection speeds. The substantial increase in viscosity caused by this resulted in a negative influence on the reproduction of the nickel shim.

In practice the target values for the flow, compression and shrinkage of a molded part have to be automatically controlled in order to be able to use a mold on different machines. In trials the injection and holding pressure profiles as well as the melt and mold temperature were auto-

matically adjusted via the host computer interface of an all-round injection molder (420S 800-350 from Arburg GmbH + Co KG) until the target values were reached. The individual controllers changed the set values on the machine slowly, however, particularly in the case of the injection speed the set values rapidly approached the end values (Fig. 5). The target values measured and controlled in the mold cavity were reached within only a few cycles (Fig. 6). For comparison both the cup height and weight were determined and could be reproduced at any time with the help of the control system (Fig. 7).

**Outlook**

The investigations have shown that apart from the parameters that can readily be measured such as strength, molded part dimensions and weight the reproduction accuracy of micro and nanostructures can



**Fig. 7.** Weight and height of the cup can be reproduced on different machines (figs.: Priamus)

be influenced and controlled in a targeted manner. Besides subtle control of the compression and shrinkage behavior particularly control of the flow properties is important in this respect. It can be assumed that the surface quality of molded parts can be influenced in a similar manner with other processes such as the variotherm technology.

In general the use of machine independent quality control will be beneficial when the process optimization and the actual production are conducted on different machines or at different sites. Unlike DoE based systems that require a great deal of time and technical know-how in order to describe a particular state of a molded part, the control system described here is comparatively simple to

implement. For the first time using this approach a mold is available with which values previously optimized with a finite element simulation can be realistically and automatically replicated. ■

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