To assess quality, the light guide (left) shines on a diffuse focusing screen; the resulting illumination image is recorded by a CMOS camera from behind the screen (images: Sumitomo (SHI) Demag)

Playing with Light

Injection Compression Molding. The optical properties of a part can generally be attributed to its geometry and material. A joint company project shed light on how the properties are influenced by the plant concept, process and processing parameters.

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With the birth of an optical part, it is important to focus not only on the design. It is also crucial to fill a mold with the appropriate material, using the right technology and the required precision. The key to success is knowing how much effort must be expended for a particular part geometry. The crucial factors are a profound basic knowledge and detailed understanding in various fields. To clarify the many open questions, a joint company project, "Optical Technologies", was initiated under the leadership of the Lüdenscheid Plastics Institute and ISK Iserlohner Kunststoff-Technologie GmbH, with a total of 16 participants.

The main purpose of the joint project is to define a possible test geometry that can clear up all the open questions and is very practically oriented. It includes selectively influencing the light distribution by thermoplastic lens systems and reflector surfaces. Using defined optical functions, it is possible to make a qualitative comparison with the properties actually determined. In addition, wall-thickness steps and intended functional and positioning elements are integrated into the optical part. Other requirements include economic production by injection or injection compression molding techniques with the appropriate measurement technology. The tester should have appropriate means for measuring the geometry.

! On the Topic

A movie about the production of the light guide by injection-compression molding on an all-electric injection molding machine, and the mold technology used for it can be found at the following link:
www.sumitomo-shi-demag.eu/solutions/optics/

Design for Optical Requirements and Plastic Materials

The light guide corresponds to a circular disc lens with a diameter of about

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54 mm and a weight of about 15 g (depending on the material). Using an optical simulation, developers have optimized the light guide to generate a relatively clearly defined 60° light cone **(Fig. 1)**. The light source is a white light-emitting diode (LED). The brightness distribution and spectral composition of the light cone on a screen are computed with the LightTools software (supplier: Optical Research Associates, Pasadena, USA). When simulating the total internal reflection and refraction, it is important to take into account all the optically relevant properties of LED light, the light guide material and the light guide. The image on the screen determined in this way is composed of light components that take different paths through the light guide. Measurement of the illumination image gives indications of the quality of the surfaces involved. The region shown in magenta is intended for reflection and would therefore act as a reflector.

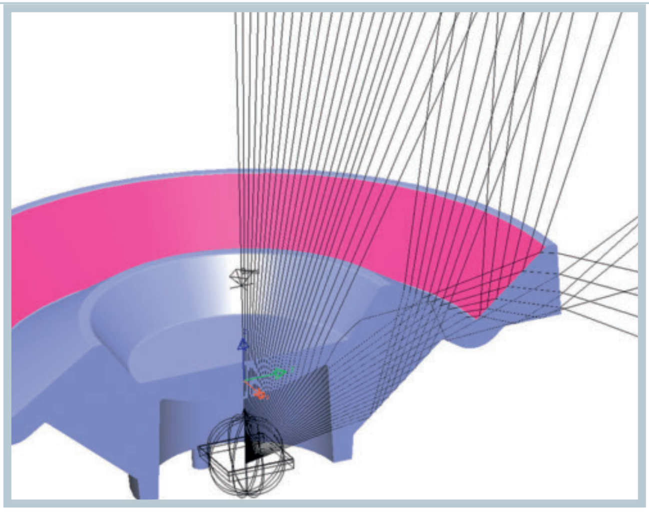

Fig. 1. The light guide has a distinctly delimited light cone of 60°; the light distribution of the cone was theoretically determined

An illumination image is based on the assumption of particular material properties. The refractive index influences the mode of operation of an optical part. The changes produced when a different material is used can be calculated in advance. It allows a universal test mold to be built for different materials.

There is a contradiction between the optical requirements and a design appropriate to plastics material. Depending on the function, the resulting geometry challenges the production technologies to manufacture precise and permanently reproducible parts. The effect of wall thickness distributions is already apparent during the filling simulation. The thick-walled regions cause a significant speeding up of the melt flow. Apart from the weld seam, which with some gating points cannot be avoided, the merging of the flow fronts results in an air inclusion in the region of the central lens surface **(Fig. 2)**. Uniform filling is produced by success adaptation of the wall thicknesses. The simulation further shows that the gating point and the thin-walled regions of the wave guide are frozen after only about 15 s **(Fig. 3)**. At this point, the volume shrinkage of the thick-walled regions is not yet complete.

Mold with Compression Plunger and Sensors

The test mold combines injection and injection-compression molding **(Fig. 4)**. Injection-compression molding takes place over the entire part surface and can be executed via the injection molding machine (machine compression) or via hydraulically operated cores (core compression). To investigate core compression, the mold is modified so that the stationary mold core is operated via a wedge slide. This does not change the shaping mold surface. In machine compression, it is modified into a frame mold. The melt backflow into the sprue system during the compression phase prevents shut-off close to the cavity.

The compression plungers are each fitted with a cooling system – conventional spiral-core cooling and conformal cooling. The conformal cooling circuit is introduced by LaserCusing technology. All the surfaces of the compression plunger are made of the same steel. This allows the mirror polish of the conformal cooling to be compared with spiral cooling. The mirror finishes were produced manually or mechanically and are another criterion for investigation **(Fig. 5)**. Mechanically speaking, ultraprecision diamond machining with monocrystalline diamond tools is used. Four compression plungers are thus available for the tests.

Compression and temperature sensors can measure additional local process parameters. To obtain detailed information about the mold in tests on the light guide, the following requirements are made on the sensors:

- The pressure gradient between the sensors close to and remote from the gate is displayed from shot to shot.
- Thick-walled zones are monitored, with the sensor front not leaving a

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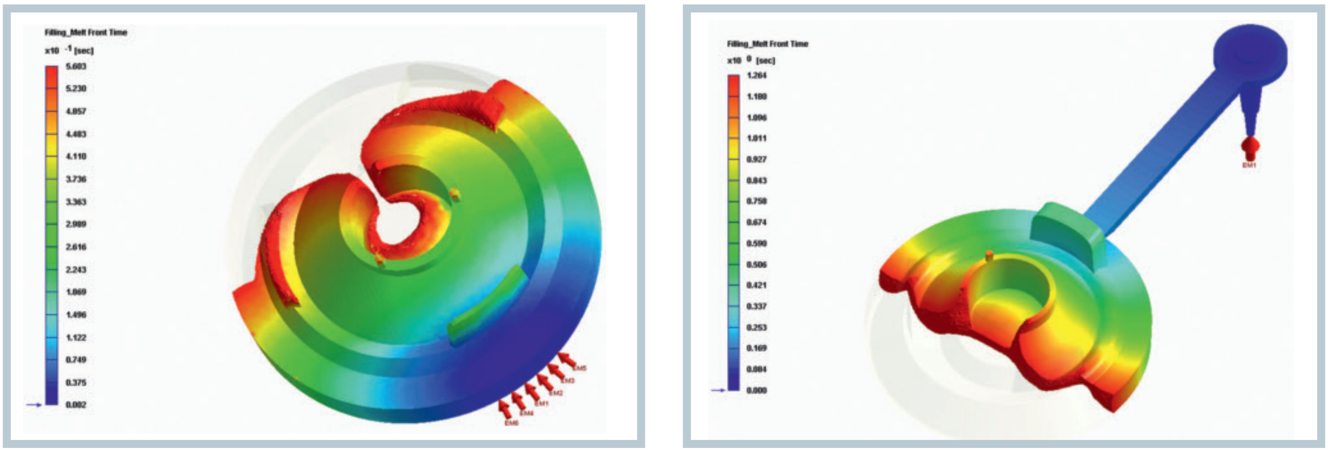

Fig. 2. In the filling simulation, the influence of the wall thickness distribution can be seen: left) faster advance of the outer flow fronts forms an air inclusion, right) after the wall thicknesses have been successively adjusted, the part fills uniformly

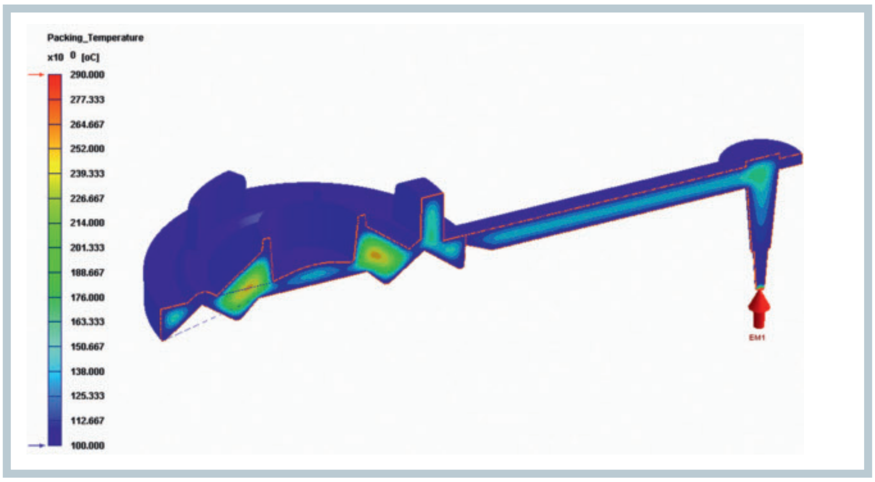

Fig. 3. Gating and thin-walled regions are already frozen after 15 s, while the thick-walled regions continue to shrink significantly

mark in the optically relevant mold region.

- Depending on the sensor, switchover to holding pressure is performed depending on the cavity pressure.
- Imaging of the contact temperatures should be possible.

Based on this, pressure-temperature sensors (type: 6189A, manufacturer: Kistler Instrumente AG, Winterthur, Switzerland) with diameters of 2.5 mm are positioned close to and remote from the gate, outside the optical functional zone. A strain measuring pin (type: 9247A, by the same manufacturer) is used for contactless measurement of the cavity pressure in the thick-walled zones (**Fig. 6**).

Taking an Integrated Approach

Manufacturing products cost effectively in high quality requires a detailed understanding of the individual process steps in many areas. Besides precise manufacture of key components such as mold inserts and ensuring product-related design of machine and mold technology as an integrated unit, it is also crucial to specify process-relevant parameters and their tolerance limits. The latter is extremely difficult and therefore determined in practical tests with flexible recording of the measured values. The system technology, comprising sensors and electronics, permits a more precise interpretation of the individual processes taking place in the mold. To keep the effort and costs within reasonable limits, it also helps to concentrate on key parameters in the quality testing of optical functions of the plastic part.

The question of which machine platform generates what optical precision is both difficult to answer and product dependent: all-hydraulic systems generally offer a solid basis for thick-walled optical parts with long holding-pressure times. Hybrid concepts are the correct platform in the thin-walled range. The oil-operated hydraulic injection molding machines, by comparison, have a significantly longer holding pressure application at a high level, and greater injection performance. All-electric machines permit precise movements for very accurate optical parts with small shot weights of medium wall thickness. The axes generally move faster by an order of magnitude and can realize parallel machine movements, which is particularly important for simultaneous compression via the clamping unit. The mechanical force transmission of the spindle and clamping system maintain the selected position very stably.

Ultimately, it makes sense to perform a product-based comparison of possible machine concepts. In the case of the light guide, an all-electric machine (type: IntElect 100 Performance, manufacturer: Sumitomo (SHI) Demag Plastics Machinery GmbH, Schwaig, Germany, **Fig. 7**) is chosen because of the large wall-thickness steps in the medium thickness range, which required a compression study.

The precisely designed stroke utilization of the plastication unit permits very accurate control of the injection velocity. The filling, compression and metering zones have their length, flight depth, pitch and compression ratio adapted to the requirements of the materials to be processed. The moving end of the machine is additionally equipped with an integrated simultaneous compression control and additionally with parallel core-compression functions via an internal hydraulic unit. A laminar flow box (manufacturer: Max Petek Reinraumtechnik, Radolfzell, Germany) ensures consistent cleanliness of all components in the mold area. All the important process data are externally processed via a data interface.

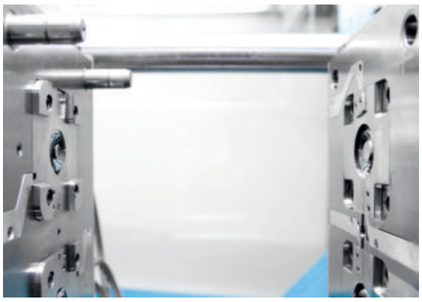

Fig. 4. With the test mold, the parts can be produced by injection molding and injection-compression molding; injection-compression can be performed either via the machine or via hydraulically operated cores

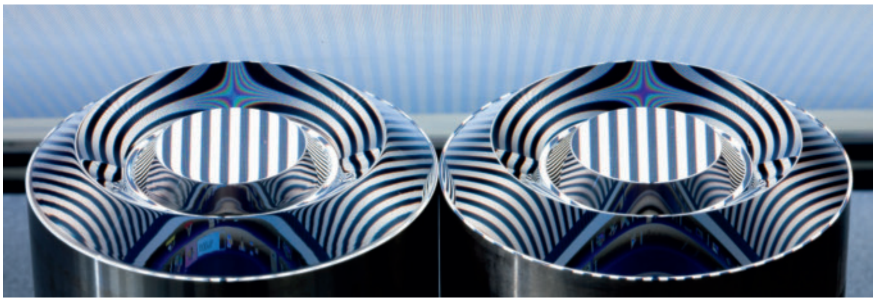

Fig. 5. To determine how the mirror finish influenced the quality of the test sample, two inserts – one polished manually (left) and one by machine (right) – were produced and tested with a strip reflection

Power Reserves and Problem Zones

In injection-compression molding, the volume of the cavity can be very finely adjusted. It allows the properties of the optical parts to be directly influenced. Compared to injection molding, the dimensional stability and warpage can also be improved, along with lower melt stressing as a result of reduced material shearing, less orientation and sink marks, and easier deaeration.

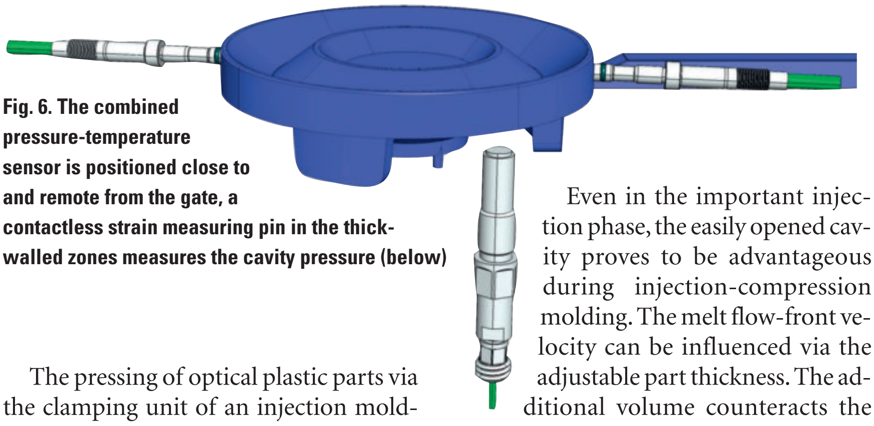

Fig. 6. The combined pressure-temperature sensor is positioned close to and remote from the gate, a contactless strain measuring pin in the thick-walled zones measures the cavity pressure (below)

The pressing of optical plastic parts via the clamping unit of an injection molding machine provides a substantial power reserve. Machine compression is particularly advantageous for asymmetrical filling processes, complex geometries, long flow paths, high pressures and rapid compression movements. Mold compression versions with hydraulic plungers permit a very good pressure transmission over a comparatively long time. The compression plunger is a particularly suitable system for parts with small problem zones, such as very thin-walled chip regions of credit cards (localized compression) and relatively large part thicknesses, such as magnifying glasses. For the light guide, it is very difficult to predict which effect will be produced by which version of pressure transmission. More information can be ascertained from a comparison of the two compression techniques: what pressure level is transmitted over what time, and what shrinkage compensation – an important quality criterion – the injection molded part experiences.

Even in the important injection phase, the easily opened cavity proves to be advantageous during injection-compression molding. The melt flow-front velocity can be influenced via the adjustable part thickness. The additional volume counteracts the material shrinkage. The shrinkage compensation takes place much earlier, and not solely via the plastic core **(Fig. 8)**. While, in injection molding, this compensation is generated hydrodynamically via the melt by an applied holding pressure, the compression movement presses the material virtually hydrostatically and evenly **(Fig. 9)**.

Appropriate Material Selection

A specially designed questionnaire oriented to the project participants ought to clarify which materials can be preferred for which light guide systems. The aim is to produce an independent and statistical relationship between the material, test geometry, part size and manufacturing tolerance. Based on the quoted materials and the effects on the light guide, fifteen materials were shortlisted. Besides the typical polymers polycarbonate (PC) and polymethylmethacrylate (PMMA), polymethacrylmethylimide (PMMI), cyclopolyolefin copolymers (COC), styrene acrylonitrile (SAN) and polyamide (PA) are also tested.

Material	Refractive index	Transmission [%]	Abbe number	Critical angle [°]
PC	1.58	89	30	39.3
PMMI	1.54	91	53	40.5
PMMA	1.49	92	59	42.2

Table 1. Comparison of optical properties: Polycarbonate (PC) has a high refractive index for plastics, this results in low transmission; in the case of polymethylmethacrylate (PMMA), the opposite is the case, and polymethacrylmethylimide (PMMI) is roughly in the middle

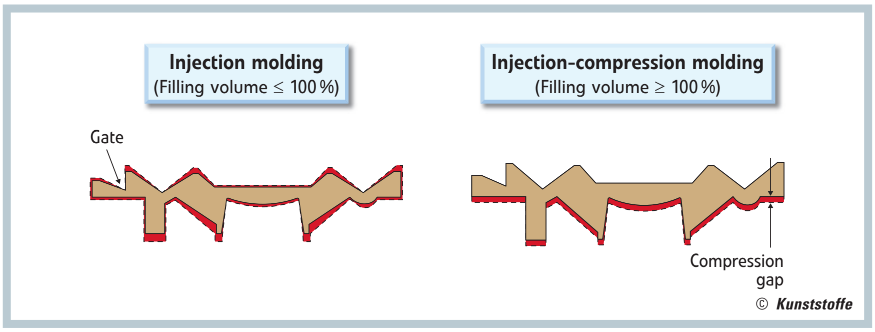

Fig. 8. The material shrinkage is expressed differently in injection molding than in injection-compression molding, consequently the final part volumes are different

To investigate the shaping fidelity, a simple plate geometry (wall thickness 2 mm) is chosen as test geometry. The mirror finish surface of the test mold is provided with pyramidal notches of different depths (DIN hardness test, HV 10, 20 and 30). The defined position of the notches permits comparative measurements between the material forming and mold insert.

The test samples are measured with a chromatic white light sensor, which reproduces the plastic surface three dimensionally, and the roughness values R_a and R_q are determined. The results can be displayed in a 5-axis network diagram as percentages of the roughness values and the heights of the pyramids **(Fig. 10)**. The degree of reproduction is a measure of the reproduction accuracy of the materials investigated.

Fig. 7. The test machine is an all-electric injection molding machine with integrated simultaneous compression control

Two PC grades and one PMMA and one PMMI grade each show the best results for reproduction accuracy. They are selected for further studies. High-impact PC, scratchproof PMMA and high-temperature resistant PMMI have different optical properties **(Table 1)**.

Three Test Series, Two Evaluation Strategies

The test series can be classified into three areas: how the flow-front velocity is influenced by the stepped velocity profile and compression gap, comparison of injection molding and injection-compression molding processes, and how the polishing and cooling concepts affect the surface of the light guide.

The evaluation is based on two different strategies. First, the relevant process parameters are directly recorded and controlled. On the other hand, a downstream

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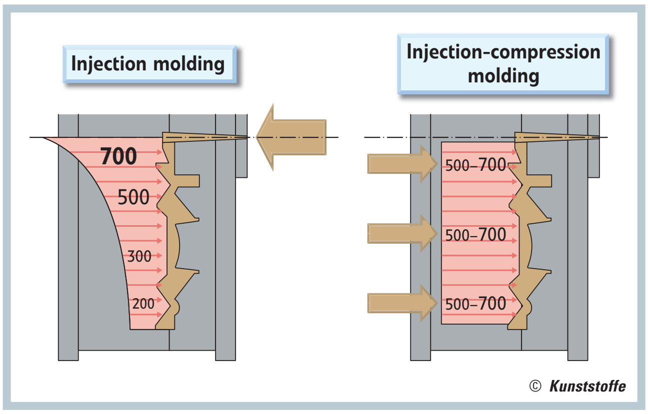

Fig. 9. Theoretical cavity pressure behavior in injection molding, the holding pressure is hydrodynamically (200–700 bar) applied via the melt, in compression, via a plunger over the surface and approximately hydrostatic (500–700 bar)

optical measuring bank determines the quality parameters and their dependencies. The optical part radiates onto a diffuse focusing screen **(Title photo)**. A CMOS (complementary metal oxide semiconductor) camera records the illumination image on its reverse side. To evaluate the illumination distribution, characteristic lines are defined, converted into a gray value distribution curve and compared with a reference curve.

Pressure Transmission Affects Quality

The flawless introduction of the materials requires a sensitive injection profile. Inaccurate positioning during changeover to holding pressure leads to filling problems of the small foot. The compression gap favors mold filling when it reaches about 5 % of the average wall thickness of the lens. The thick-walled regions of the reflector ring and foot (**Fig. 11**, item 2) are located behind the cold runner gate (item 1). They are directly followed by the thin-walled edge (item 3) of the inner, very thick main reflection surface (item 4). The inner lens region (item 5) is also thin walled. The injection unit of the machine must be capable of achieving the necessary velocity changes at the individual points rapidly, precisely and reproducibly, and so eliminating surface defects such as flow lines.

The accurate contour reproduction of the optical surfaces is a prerequisite for the functioning of the light guide. During injection molding, in all test series, the holding pressure transmission falls off rapidly, independently of the set pressure level. After about 20 s, all the cavity pressure signals fall below 200 bar **(Fig. 12 left)**.

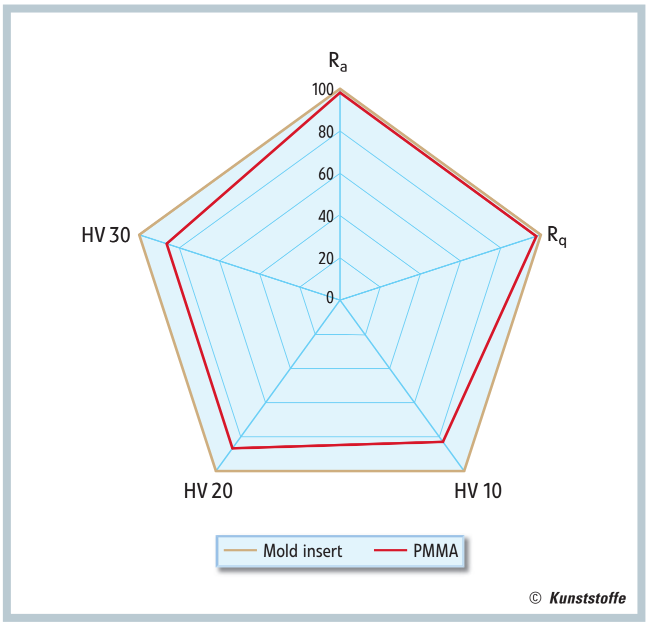

Fig. 10. The notches additionally introduced into the mold, and roughness values could be used to determine the demolding degree in percent of polymethylmethacrylate (PMMA)

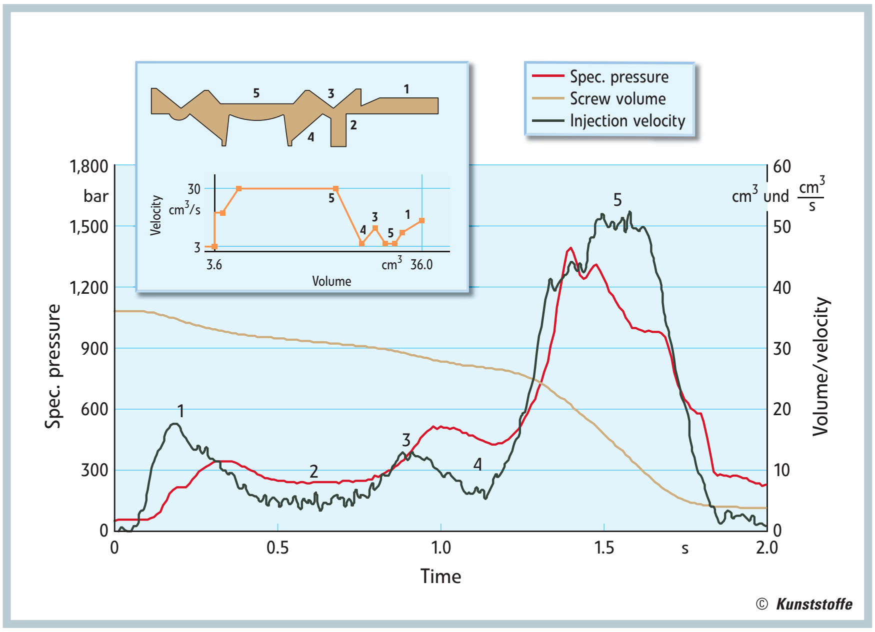

Fig. 11. To avoid stress cracking, gramophone record effects or air inclusions, a sensitive injection profile is established; the actual curve on the machine with polycarbonate as material

The failure in the holding pressure inevitably causes sink marks, which seriously alter the desired illumination distribution. Compression via the hydraulic plunger also doesn't provide adequate cavity pressure values.

Machine compression, on the other hand, provides significantly better results. With an "ideal" setting, the internal pressure level is still sufficiently high, at about 500 bar after about 90 s **(Fig. 12, right)**. For the optical quality, it is important for the internal pressure to settle at a constant high level after about 30 s during machine compression. Moreover, the starting point of compression is of crucial importance. If the compression stroke starts too early, too much material is forced back out of the cavity. If it starts too late, very high pressures are generated in the mold, since the thin-walled regions are already frozen. The part has significantly greater internal

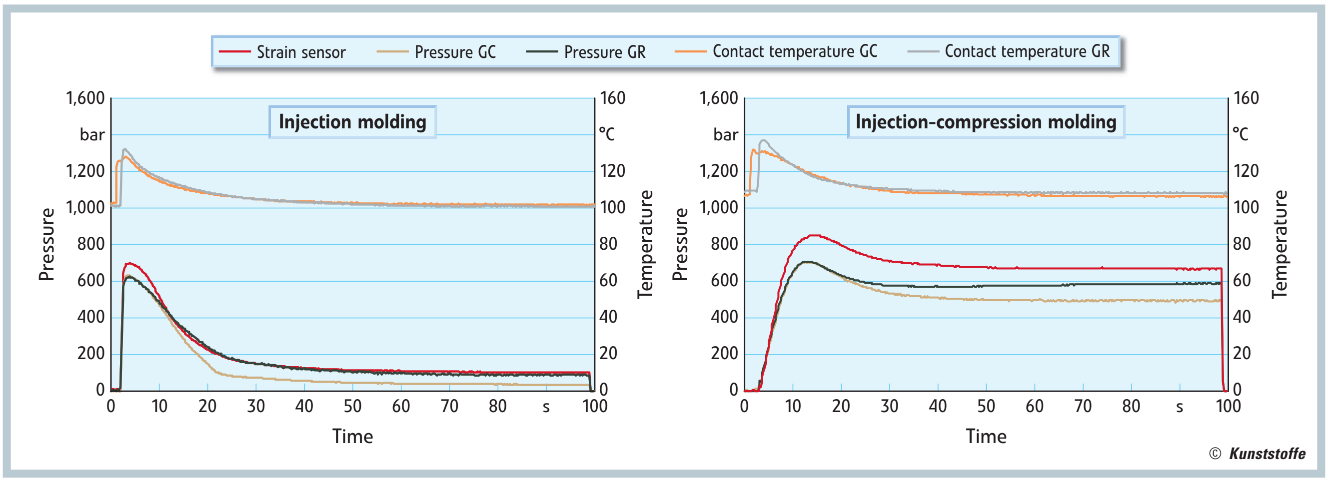

Fig. 12. In injection molding, the built-up pressure (left) falls within the first 30 s to below 200 bar; in injection compression (right), the pressure remains at about 500 bar both close to (GC) and remote from (GR) the gate

stresses and in the worst case is damaged during demolding.

Illumination Image as a Quality Characteristic

The type of polishing is not found to influence the optical quality, for the same test set up, either in the illumination image or in the light distribution. In the cooling concepts, it is found that the use of spiral core and LaserCusing also generates the same illumination images and light distributions. Quality is only affected by the mold temperature: Too high feed temperatures, as a result of the greater thermal contraction, lead to insufficient reproduction fidelity, irrespective of the raw material used.

The photographed illumination images illustrate the quality differences very accurately. The theoretical illumination image is schematically composed of two regions: a circular area in the center, superimposed with a circular ring somewhat further out **(Fig. 13, left)**. In all injection molded optical parts, the circular ring has illumination maxima at the inner and outer edges **(Fig. 13, center)**. One cause of these are sink marks in the thick-walled regions, which divert the light rays towards the inside and outside. The uniform pressure transfer in machine compression and the improved mold filling, with a slightly enlarged cavity, lead to an illumination image **(Fig. 13, right)** that approximately corresponds to the simulation of the optical design.

Outlook

Provided that all influences are adequately understood, complex optical parts can already be manufactured in good quality. Modern processing and mold technology offer some interesting approaches. Injection-compression via the clamping unit of the machine, combined with precise mould technology, increases the reproduction accuracy of the parts, and therefore the illumination function. Proper evaluation of the influencing parameters requires ascertaining a meaningful relationship between the produced quality and optical function.

There is still plenty to do in the future, and therefore a new joint company project "Optical Technologies 2" was started in February 2010. The main issues are the integration of diffractive structures into optics, the possibilities for state-dependent demolding and the influence of variotherm temperature-control technology. Furthermore, the possibilities of LSR processing will be investigated for their suitability for manufacturing highly transparent optical parts. This project has already started with thirteen participants; others can still join at a later point. ■

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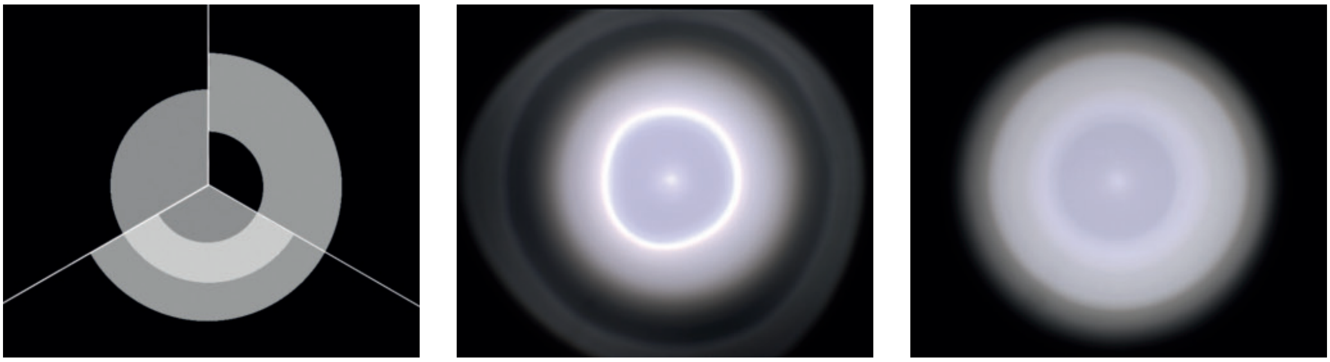

Fig. 13. The theoretical illumination (left) is schematically composed of two regions; the injection molded part has an illumination maximum (center) at the inner and outer edge; the uniform pressure distribution during compression reduces the illumination maxima (right)