

Focus on Precision

Injection Molding Optical Components. With above-average growth rates, optical technologies can be considered as setting the pace for the 21st century. However, the challenges when injection molding optical parts frequently differ from those encountered when injection molding conventional parts. In the face of international competition, the focus is shifting increasingly to innovative processing techniques.

Deciding to take on production of optical parts requires a clear understanding of the challenges (photo: Pillwein, Engel)

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Optical technologies are considered one of the most promising fields of the future. The opportunities for the plastics industry are to be found in automated production of high-quality optical components in large quantities [1, 2]. Injection molding of such components poses greater challenges than does conventional injection molding, specifically with regard to accuracy of surface replication and the level of molded-in stresses. Moreover, it is not unusual to have wall thicknesses as much as ten times greater than those typically encountered in injection molding (Fig. 1). When it comes to producing high-quality optical parts in a cost-effective manner, the conventional injection molding process quickly reaches its limits. For this reason, existing special processes undergo continual refinement and new approaches to processing are introduced:

- Injection compression molding is well-suited to produce molded parts with high replication accuracy and low molded-in stresses.

- Multi-layer injection molding can be used to increase replication accuracy as well. With thick-walled parts, it is further possible to reduce the cycle time [3].

- Variotherm mold temperature control is not limited to only improving the quality of replication of micro- or nano-structured surfaces [4].

Table 1 presents an aid to decision-making with regard to selection of the appropriate process. The individual processes are discussed in greater detail in the following.

Injection Compression Molding – a Well-established Process, Modern Machine Technology

The injection compression molding process has been used for several decades to successfully mold optical components [5]. In this process, the plastics melt is injected into an oversized cavity and subsequently compressed by moving mold elements during the compression phase.

For molded parts with a large flow length/wall thickness ratio, partial filling of the greatly oversized cavity takes place first. In this case, the shape is not formed until the compression phase; reduced mold filling pressure and thus lower molded-in stresses are the result. For thick-walled parts, it is useful to fill the

cavity during the injection phase and employ the compression stroke to simply compensate for shrinkage. Compared to conventional injection molding, the molded-in stress level and replication accuracy can also be improved in this way.

Depending on the geometry of the molded part, compression may take place over the entire surface or only over segments of the surface. To prevent the plastics melt from flowing into the parting line, sealing frames that enclose the cavity are often used. The necessary sealing force can be applied by spring elements or hydraulic cylinders (Fig. 2). To prevent the melt from flowing back into the injection unit, shutoff nozzles or slides must ▶

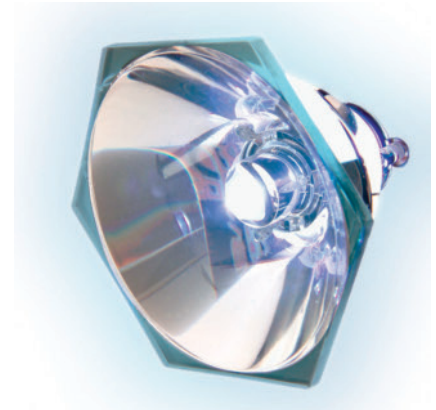


Fig. 1. Thick-walled LED lens for an OP lamp, molded from PMMA (photo: Trumpf Medizin Systeme)

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Process	Injection compression	Variotherm mold temperature control	Multi-layer injection molding
Molded part properties			
Thick wall (> 4 mm)	<div>+</div> High replication accuracy by applying holding pressure via compression stroke; no thick sprue/gate needed <div>+</div> Fewer molded-in stresses due to uniform holding pressure	<div>+</div> Reduction of jetting marks <div>+</div> Cooling time reduction possible	<div>+</div> Cycle time reduction possible <div>+</div> Improved replication accuracy, as subsequent layers compensate for shrinkage <div>+</div> Less risk of jetting <div>-</div> Stresses at interfaces and warpage possible
Thin wall (< 4 mm)	<div>+</div> Lower filling pressure when injecting into oversized cavity <div>+</div> Reduced molded-in stresses due to lower pressure gradients during filling and holding pressure phase	<div>+</div> Lower filling pressure due to slower cooling of melt <div>-</div> Longer cycle time to be expected	<div>!</div> Negligible benefits with thin walls
Large wall thickness differences	<div>+</div> Compression over partial surface increases replication accuracy <div>-</div> Compression over entire surface: thin regions limit duration of compression	<div>!</div> Limited heating options	<div>+</div> Improved replication accuracy, as subsequent layers compensate for shrinkage
High flow length / wall thickness ratio	<div>+</div> Lower filling pressure when injecting into oversized cavity <div>+</div> Reduced molded-in stresses due to lower pressure gradients during filling and holding pressure phase	<div>+</div> Lower filling pressure due to slower cooling of melt <div>!</div> Warpage with variotherm temperature control on one side	<div>-</div> Further increase in flow length / wall thickness ratio, thus higher filling pressure, more molded-in stresses
3-D geometry	<div>-</div> Compression motion has less effect on angled surfaces	<div>!</div> Limited heating options	
Microstructures, nanostructures	<div>+</div> More uniform replication along the flow path	<div>+</div> High replication accuracy due to slower cooling of melt	
	<div>+</div> Benefit	<div>-</div> Drawback	<div>!</div> Limitation

Table 1. Aid to decision-making for processors: benefits and drawbacks of selected processing techniques compared to conventional injection molding

(source: Engel)

be installed as a blocking mechanism [6]. These should be positioned as close to the cavity as possible to minimize movement of the mass and the molded-in stresses produced as a result.

In addition to mold design, the machine and controls are essential factors in successful production of optical parts. Because of its similarity to the injection and holding pressure phases, a newcomer quickly becomes familiar with the injection compression software developed for the all-electric “e-motion” Series (manufacturer: Engel Austria GmbH, Schwertberg, Austria). The operator interface is organized into the steps

- speed-controlled compression, transfer,
- cavity-pressure or force-controlled compression and
- position control (isochoric cooling) corresponding to the typical process sequence (Fig. 3).

During the speed-controlled compression phase, the cavity is filled volumetrically and the melt compressed. The operator can trigger transfer optionally via position, time, compression force or cavity pressure, with the compression force or cavity pressure profile being variable as required by the application. While the part continues to cool to the ejection temperature, the molded-in stress level is determined primarily by

the pressure gradients present and the extent of material movement. A high level of molded-in stresses adversely affects the optical characteristics of lenses, among other things, and can cause cracks to form in subsequently applied coatings [7, 8].

Isochoric cooling prevents material movement and helps to reduce the molded-in stress level [9]. The compression gap – and thus the volume of the cavity – is kept constant. For this purpose, a position sensor is attached to the mold and used for position control.

The Accuracy of Electric Injection Molding Machines

Surface replication accuracy requirements are especially high for optical components. Dimensional tolerances of less than $\pm 20 \mu\text{m}$ are quite common. For this reason, all relevant machine movements

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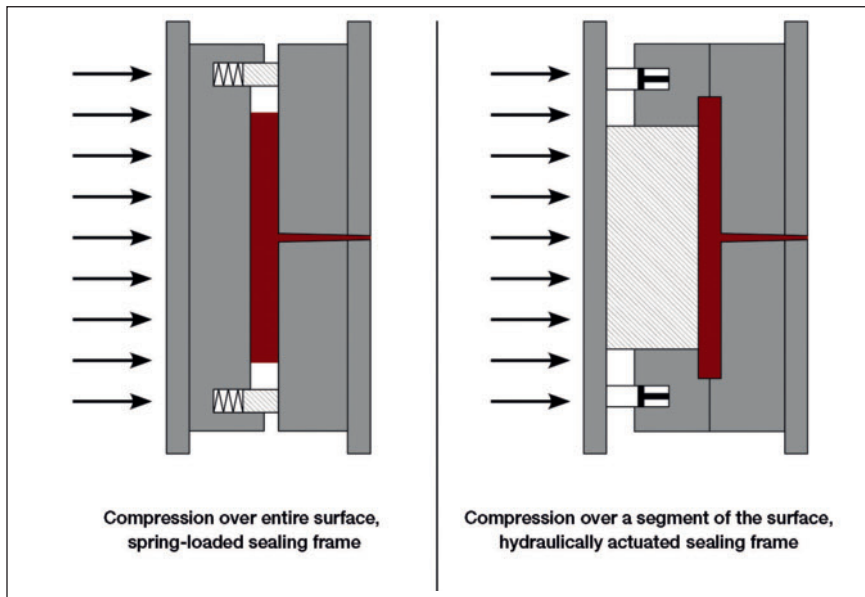


Fig. 2. Schematic illustration of possible mold concepts in which the compression stroke is executed by the clamping unit (illustration: Engel)

must be highly accurate and reproducible [6, 8]. All-electric injection molding machines are very well-suited for production of precision optical components, since the position sensors in the servo motors permit very high positioning accuracy in conjunction with the kinematics of the toggle mechanism. In the course of trials to investigate reproducibility, the compression gap was observed prior to the start of injection with the aid of an inductive position sensor. In the all-electric "e-motion" Series of injection molding machines, the variation was less than 5 μm .

In addition to its high reproducibility, this machine line is characterized by the high dynamics of the clamping unit. These dynamics can be exploited, for instance, for thin-walled molded parts with a micro-structured surface by first forming the structure through an abrupt increase in compression force and subsequently achieving a low molded-in stress level.

Better Replication with Variotherm Temperature Control

With variotherm mold temperature control, the surface of the cavity is heated prior to each injection cycle and then cooled again. Compared to conventional mold temperature control, this produces a higher contact temperature between the plastic and cavity wall that delays solidification of the melt. Depending on the geometry and surface of the molded part, it is possible to improve different characteristics in this way (Table 1). In addition

to fluid-based variotherm mold temperature control using water, steam or oil, additional methods such as induction, infrared radiation or electric resistance feeding are known [4]. Cooling generally takes place with water.

Variotherm mold temperature control permits establishment of independent temperatures that have been optimized for the respective process step. During the cooling phase, the water supply temperature can be considerably lower than is normally the case with conventional mold temperature control. This makes it possible to reduce the cooling time when producing thick-walled optical parts.

In a simulation of temperatures used to mold an 11 mm thick LED lens from PMMA with both conventional and variotherm temperature control, a constant supply temperature of 75°C was assumed in one case, while the temperature was varied between 125 and 25°C in the other case. In this example, the cycle time savings was 15 % (Fig. 4).

The benefits of variotherm temperature control are obvious: it improves molded part quality and can – under certain circumstances – shorten the cycle time. As drawbacks, the relatively high investment, depending on the type of temperature control, and increased energy consumption have to be mentioned.

Improving Quality by Layers

Multi-layer injection molding, sometimes called overmolding, is a process that is still relatively new to the field of injection molding of optical parts and which can help improve the quality of thick-walled lenses [3]. The process involves first molding a preshot and then subsequently overmolding one or more layers of the same material. A machine with a rotary table or a mold with an indexing plate is generally needed; a physical transfer is also conceivable. The major benefit of the process is that the overmolding step can correct or compensate for sink marks or other flaws in the surface of the preshot. A lens on which an obvious surface flaw was created for demonstration purposes can serve as an example (Fig. 5). This lens is overmolded with a 2 mm thick layer of plastic. This ▶

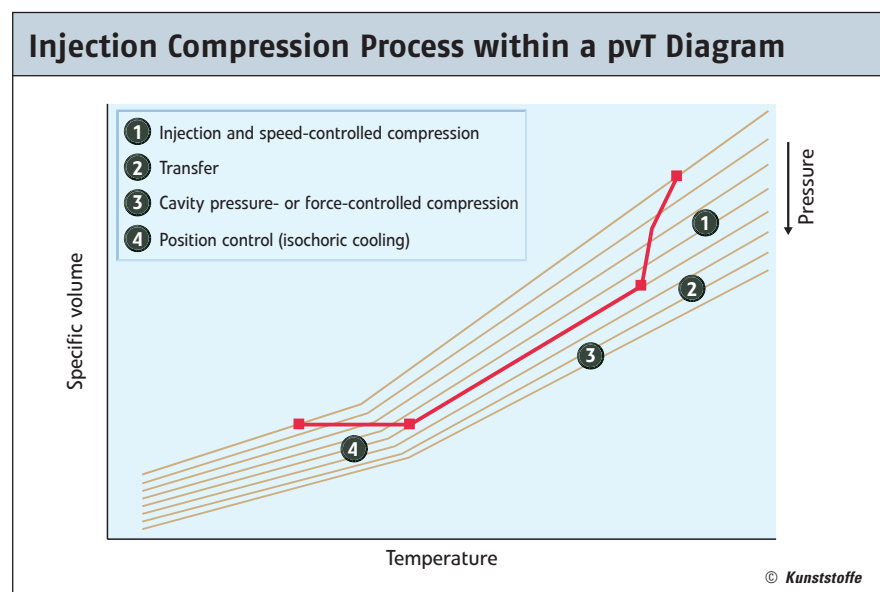


Fig. 3. The operator interface for the injection compression software is organized into the four steps typical of the process sequence (illustration: Engel)

process can thus correct even severe flaws in the surface.

The often-discussed question as to the possible cycle time savings associated with multi-layer molding cannot be given a generally valid answer. The potential savings depend largely on the part geometry, the relationship between the layer thicknesses and the mold temperature control requirements.

When using a rotary table, the general constraint is that the time required for the individual steps should be as close to identical as possible. Since the preshot is in contact with both sides of the mold, while subsequent molded layers are cooled largely from only one side, the conclusion drawn is that subsequent layers should be approximately half as thick as the first layer. In the case of two layers, the relationship between the layer thicknesses should be 2/3 to 1/3; in the case of three layers, 2/4 to 1/4 to 1/4 etc. These

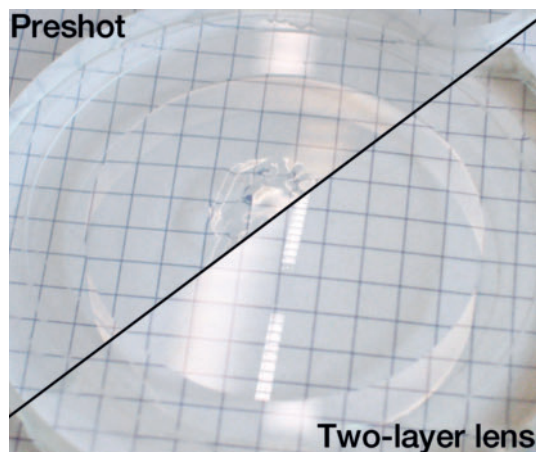


Fig. 5. Preshot with surface defect before and after overmolding of a 2 mm thick layer of plastic (mold: IKV Aachen)

relationships apply exactly only for a flat plate, but can be taken as a rule of thumb for the layer thicknesses with simple part geometries.

Ideally, each station of the rotary table should have independent mold temperature control. Care must be taken to ensure that the outer surfaces essential to the optical function are temperature-controlled as necessary to satisfy quality requirements. For the inner surfaces, the supply temperature can be lowered to reduce the cooling time.

To obtain useful information about the cooling time, a thermal simulation based on the actual part geometry is required. Simulations were conducted under various constraints for a 30 mm thick, plano-convex polycarbonate lens. These simulations compared 1-, 2- and

3-layer molding processes, with two variations for the three-layer approach: The three layers can be molded in succession, or an initial preshot can be overmolded on both sides simultaneously. It is assumed in the simulation that the inner surfaces are cooled more intensely (60 instead of 90°C). Compared to molding a single-layer lens, the various approaches to overmolding multiple layers in conjunction with appro-

priate temperature control shorten the cooling time (Fig. 6).

Overall, the multi-layer molding process can not only improve surface quality considerably, but also reduce the cooling time as well. This is especially the case when the inner layers are cooled more intensely. For the lens investigated here, the possible cooling time reduction amounted to as much as 35 %. The processor must, of course, take the additional investment costs for the more complex equipment (rotary table, indexing plate etc.) into consideration when investigating the economic viability of any particular approach.

Variotherm Cycle Time Reduction

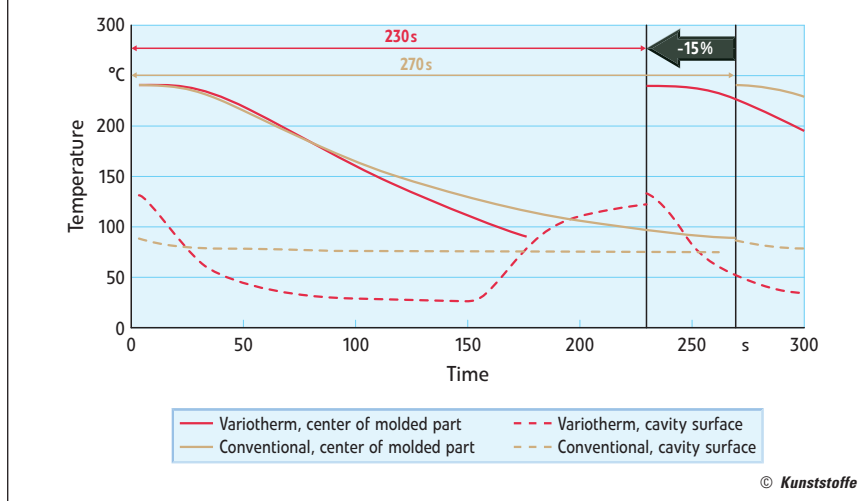


Fig. 4. Calculated temperature curves from the moment of mold filling with variotherm and conventional mold temperature control for an 11 mm thick LED lens molded from PMMA. Reheating of the cavity starts already during the first cycle after about 150 s (illustration: Engel)

Multi-layer Injection Molding

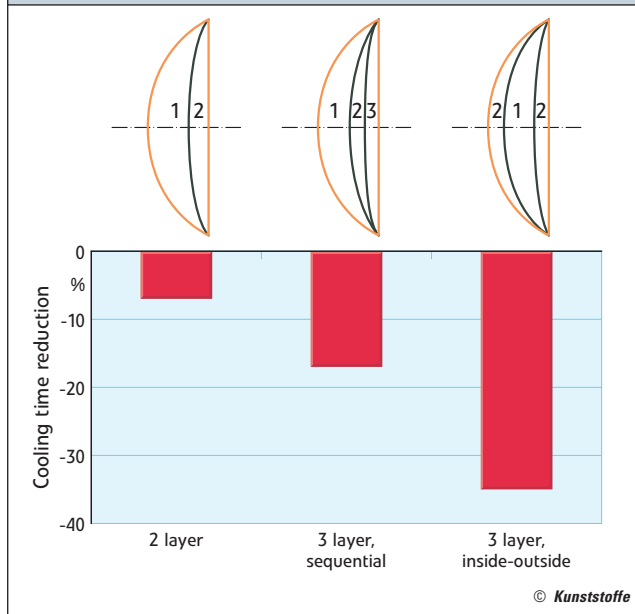


Fig. 6. Simulation results for various molding sequences: compared to the single-layer approach, the multi-layer process reduces the cooling time considerably. The cavity wall temperatures are color-coded (black: 60°C, red: 90°C) (illustration: Engel)

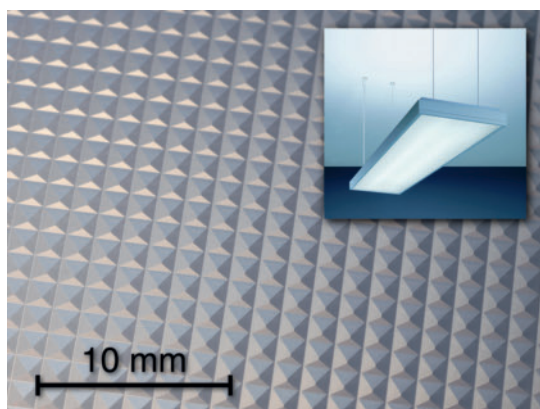


Fig. 7. Structured optical component for glare-free light: The micro-pyramids with a base of $1.5 \times 1.5 \text{ mm}^2$ are produced by means of injection compression molding in conjunction with variotherm mold temperature control (manufacturer: Zumtobel Lighting)

Beneficial Process Combination

The variety of requirements that a plastic optical component must satisfy may require a combination of several processes. A structured optical component (Fig. 7) that permits glare-free office illumination may, because of its high flow length/wall thickness ratio, require use of injection compression molding on the one hand, while on the other the precision needed for the angles of the micro-pyramids can be achieved only with variotherm mold temperature control. This combination of processes has been adopted in actual practice.

The outcome was positive and should encourage injection molders: the examples presented in this article show that improved quality and economics are indeed compatible with one another where optical parts are concerned. ■

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