Precision Injection Molding

How to Make Polymer Optics for High Volume and High Precision Applications

Whether it is a cellphone camera or a head-up display – polymer optics is at the heart of many high tech devices and the market demand for such precision optical components is growing year by year. The main application fields are in the automotive industry, in the medical field (disposable optics), in sensor and information technology. Beside lightweight and economic advantages, polymer optics enables completely new solutions in optics. The key to all this is precision manufacturing.

Basic assessment of Precision Injection Molding

Injection molding is well known from the field of plastics production. The conventional injection molding technology is not accurate enough for optical parts production. To achieve the necessary precision, it is necessary to optimize the whole process chain.

After several years of continuous development, precision injection molding (PIM) became a technology that helps to satisfy growing market demands in reasonable priced but highly functional precision optics. Table 1 shows the differences in the process and the materials between conventional molding and precision injection molding.

Typical Features of Precision Injection Molding

Today, polymer optical components offer a number of unique features. Traditionally, they are particularly well suited for large production lots and low costs. But meanwhile they also offer some features, where they are clearly superior to glass optics: integrated optical or mechanical functionality is one example. The most important features will be discussed in the following.

- **Low weight**
  Optical polymers have approximately half the density of glass. Hence low weight designs are possible.
- **Low material cost**
  Optical polymers are within a range of 5…30 €/kg. Compared to optical glass this makes a notable difference.
- **Plain and fast mass production**
  Injection molded lenses are finished in one step to optical quality without the need for additional finishing steps, such as polishing. Compared to glass, the cycle times are very low which makes injection molding suitable for mass production.
- **High degrees of freedom in the design**
  With injection molding almost every surface shape (e.g. diffractive, freeform, nano structure) becomes feasible without extra costs. Hence this process is well suited for the mass production of demanding optical elements. Because of this advantage glass optics and polymer optics are sometimes combined (e.g. as an aspheric field lens) to improve imaging quality at reasonable costs.
- **Excellent automation possibilities**
  Modern injection molding machines are fully automated and computer controlled in every parameter. Together with an autonomous handling system and advanced process control, it is easy to set up flexible manufacturing cells. These cells are capable of running whole process chains like molding, testing, coating and packaging.
- **Integration of mechanical functionality**
  Injection molding enables the designer to incorporate mechanical mounts, like lens mounts, snappers and other fixture elements together with optical functionality into one part, which reduces the number of elements or may increase alignment accuracy of optical components.

Applications of PIM

Precision injection molding is developed to enable an economic mass production of precise spherical, aspheric, diffractive and freeform plastic lenses and mirrors with high accuracy and good to excellent optical surface finishing. Figure 1 briefly shows possible application fields.

THE AUTHOR

RALF MAYER

Dr.-Ing. Ralf Mayer attended University of Kaiserslautern and holds a degree in mechanical engineering. In 1997 he received a doctor´s degree in the fields of thin film coating and sputtering. After that he worked on the development of high speed scales at Wipotec and than joined SiemensVDO where he was responsible for the optical design of automotive head-up-displays. Today he in charge of Viaoptic´s development department. His main tasks are developing and designing optical systems from scratch for e.g. industrial sensors, LED lighting or automotive driver assistance systems like head-up-displays.

Dr.-Ing. Ralf Mayer
Viaoptic GmbH
Ludwig Erk Str. 7
35578 Wetzlar, Germany
Tel.: +49 (0) 6441/9011-35
E-mail: mayer@viaoptic.de
Website: www.viaoptic.de

Typical Part Specifications

Due to the manufacturing technology, polymer optical components have certain limitations in their dimensions. Precision injection molding allows for a lens diameter from 1 mm to 100 mm, lens thickness may be chosen between 1 and 30 mm. The diameter to thickness ratio should be in the range of 1:1 and 5:1. The optically used area may then be between 1 mm² and 50.000 mm². Technical tolerances for polymer optics are summarized in table 2.

In general one should keep in mind that feasible tolerances are directly dependent on material properties and parts geometry. The polymer material also defines the optical properties. Today, the materials allow for refraction with n = 1.49…1.7 (1.9). The Abbe numbers can be between 28 and 58.

Limitations of Polymer Optics

Due to material properties, polymer optics are more sensitive to changes in the environmental conditions. Typical effects are: shrinkage, warpage (during processing), thermal and mechanical stress, water absorption, heat deflection. The parts service conditions are usually more important when dealing with polymer optics than with glass optics. Depending on the expected performance, the temperature range can be between –40 °C and 150 °C. Additionally, chemical impact (even in residual concentrations) may have a large impact on the lifetime of polymer optics.

Polymer Materials

The material properties are responsible for process capability and manufacturability of the products and hence for feasible tolerances. There are a wide variety of polymers available today. But if it comes to precision injection molding of optical components only a few are left, especially if the parts are to be coated with dielectric anti-reflex coatings.

Important material properties are e.g. viscosity, melt temperature, glass transition temperature, water take up and gas absorption. The latter are important parameters for thin film coating processes on polymers, because those coating processes are commonly running with process temperatures above 80 °C and require a water and residual gas free atmosphere.

Mold shrinkage is another important measure of a given material to accurately replicate fine product features and meet tight dimensional tolerances. Amorphous polymers typically exhibit lower shrinkage (0.3…0.8 %) than semi-crystalline polymers (1…3 %) [1]. Besides being a material specific feature shrinkage is dependent on process parameters and typically exhibits some batch to batch variations. Hence shrinkage prediction in injection molding is still a quite challenging problem and practical experience with material-behavior is irreplaceable. To improve the shrinkage behavior inorganic fillers like TiO nano particles are commonly used. Generalized: dimensional stability improves with a higher glass transition temperature and larger difference between service temperature and glass transition temperature.

Because of the above reasons VIAOPTIC prefer materials like COCs or COPs due to their low water take up and their temperature stability. Polycarbonate is not well suited for high precision applications because the relatively high water take up causes swelling which will spoil high tolerances immediately. Additional water vapor from the part is not very welcome during thin film processes.

For further reading on the mechanisms of dimensional instability in polymers appropriate literature such as [1] is recommended.

Premises for Precision Injection Molding

Looking at injection molding processes one can realize five different fields which are very important for precision injection molding.

Expert Knowledge

To achieve the tightest part tolerances one has to accept that precision injection molding already starts at the optical design of the parts. Further it is essential to consider the optical design, the mechanical design, the mold-process development and the mold-machine development as parts of an integrated design process with very strong interactions. You cannot do one without the other! Hence it is necessary to employ highly skilled and experienced design engineers who can understand and handle tasks like optical design, part design, tool design, finite element analysis and mold flow analysis.

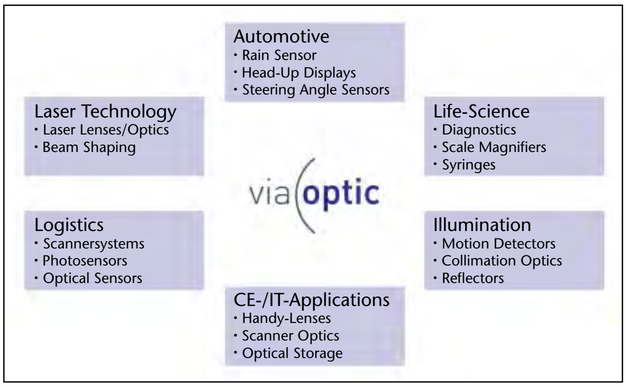

FIGURE 1: **Applications for precision polymer optics.**

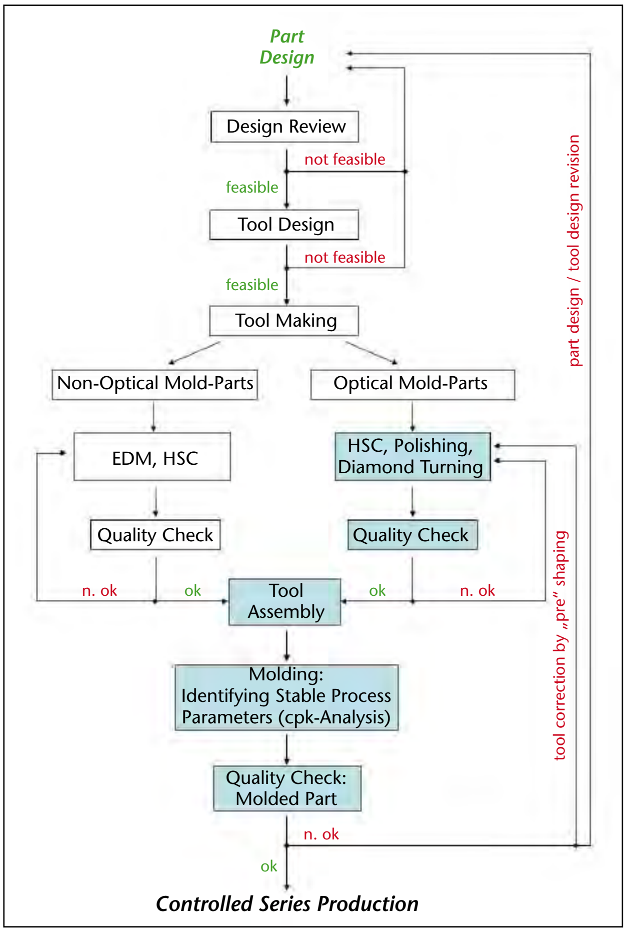

FIGURE 2: **From Design to part: High Precision injection molding starts with parts design and ends with the molded part.**

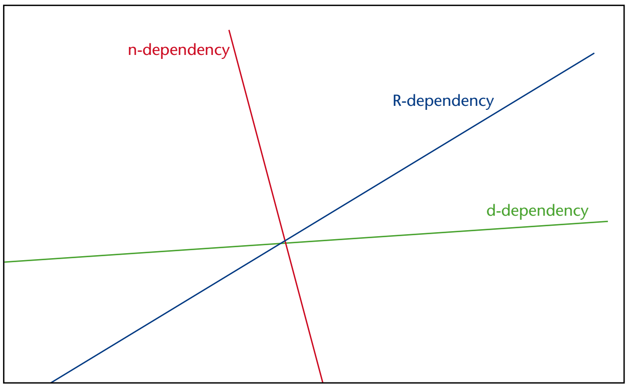

FIGURE 3: **Comparison of the impact of n-index tolerances to dimensional tolerances.**

FIGURE 4: **MOORE Nanotech 250UPL diamond turning a freeform lens.**

Even if most operations during injection molding processes are fully automated and controlled by computers today, the presence of skilled and well educated operators is still essential. High precision injection molding processes are operating on the edge of the capabilities of injection molding technology. Typical are tide process windows and therefore a demand for continuous monitoring and manual adjusting critical process parameters and that is where the human factor is very important.

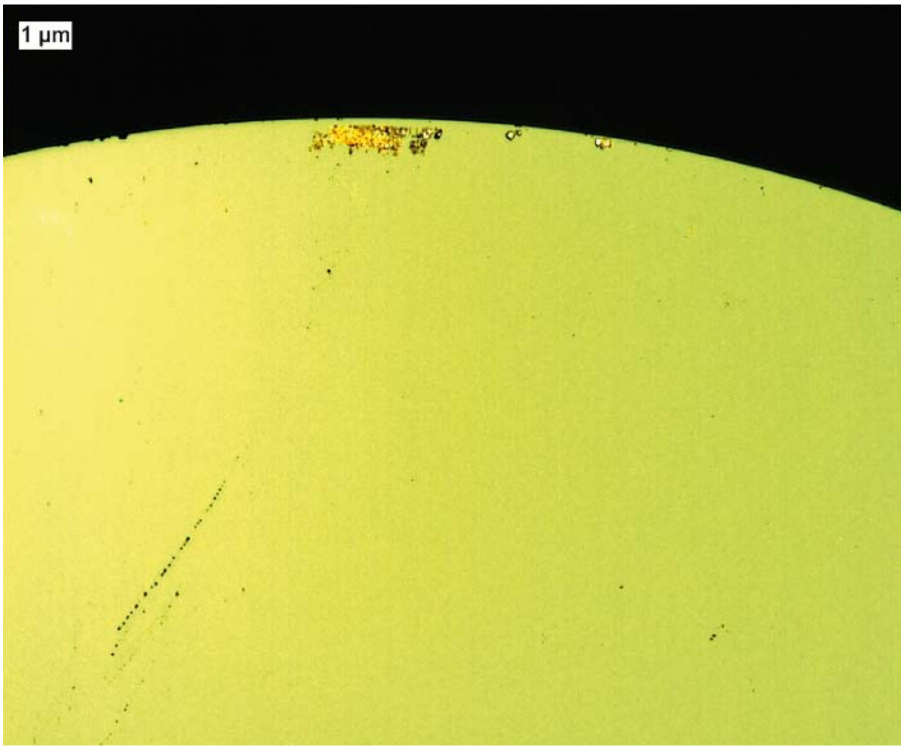

FIGURE 5: **Worn out diamond tool tip.**

Design Experience

To obtain maximum part performance with minimum parts tolerances the part design is very important (see figure 2). The part design decides about the feasible tolerances. Some common design rules from our experience are:

- preferably constant wall thickness in parts
- no wall-thickness leaps, smooth transitions
- keep a reasonable minimum wall thickness (material dependent)
- no holes etc. near optical active surfaces because of resulting flow lines
- avoid material accumulations, they are prone to sinkmarks.

THE COMPANY

Viaoptic GmbH
Wetzlar, Germany

VIAOPTIC GmbH is a professional partner in the development and manufacture of optical components, mechanical parts and sub-assemblies made of plastic material, with advanced competence in: Selection of materials, Design of individual parts and sub-assemblies, Prototyping, Tool design, Tool fabrication, Manufacturing with injection moulding, Sub-assembly Fabrication and quality assurance.
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Furthermore, one has to keep in mind that the refractive index of polymer lenses is less accurate than with glass lenses. From our experience you cannot expect more than the 2nd to 3rd decimal of stability of the refractive index under standard environmental conditions. Let's look at the sensitivity of some lens parameters in comparison:

The focal length of a spherical lens with 2 radii R ½, center-thickness d and refractive index n is defined by:

$$f = (n-1) \cdot \left(\frac{1}{R_1} - \frac{1}{R} + \frac{(n-1) \cdot d}{n \cdot R_1 \cdot R_2} \right)$$

One can easily derive the sensitivities Δ to radius changes thickness changes and refractive index changes from:

$$\Delta_n = \frac{\partial f}{\partial n}, \ \Delta_R = \frac{\partial f}{\partial R}, \ \Delta_d = \frac{\partial f}{\partial d}$$

Looking for example at a lens with n = 1.5, d = 3 mm, $R_1 = -R_2 = 10$ mm the nominal calculated focal length will be 10.52 mm. Graphically one will get the dependencies shown in figure 3 for a parameters change from –1 %…to 1 %.

From Figure 3 one may obtain a different significance of mechanical tolerances and it should be clear that it is worthwhile to think twice about tight geometrical tolerances in a design, which may become a problem during injection molding.

Tool design is of the same importance as part design. The tool directly defines the achievable product quality. Product tolerances in the micron range require tools which are dimensionally stable within the sub micron range. There is no common wisdom in tool design and there are a lot of successful tool concepts but there is one important thing to mention: Dimensional stable tools require a high rigid design and adequate material choices with an adequate heat treating. The importance of the latter is often neglected. Hardened steel for example tends to change its dimensions in the sub micron and micron range even without load if the microstructure change during austenite to martensite transition is not totally finished or stopped, by e.g. cryogenic treatment [2].

Tool Shop Capabilities

Besides design considerations the tooling is a very important part of injection mold processes. The molds have to be machined and assembled to very tight tolerances because what you give away here in terms of tolerances is hardly retrieved later in the injection mold process and/or will for sure further narrow the process window. Important for precision tool making is a temperature controlled environment. From technology point of view precise high speed multi axis milling machines are thought to replace EDM technology more and more. But from our point of view you need both in very high qualities. When it comes to the quality of the optical mold inserts VIAOPTIC relies on a MOORE

Nanotech 250 UPL (see figure 4) for single point diamond turning for ready to use tool inserts (without the need for polishing).

A big disadvantage of diamond turning today is that there is no process to cut directly into ferrous materials, such as steel, that would wear out the diamond pretty fast. You always need a nickel coating on the steel inserts which may be an additional risk in terms of durability. Currently VIAOPTIC joins a research project developing a heat treatment process for some tool steels to enable single point diamond turning in optical quality. The initial results look very promising.

The availability of high precision tooling machines is only half the truth. The other part is the cutting/milling tool itself. E.g. for single point diamond turning high precision and accurate grinded monocrystalline tool-tips are needed. At VIAOPTIC we pay much attention to the surface and edge finish of this tools. Even the tiniest defects (see figure 5) in the cutting edge will be seen later on the molded part.

For high precision machining you need high precision data formats. *.iges and *.step files proved not to be accurate enough (figure 6). This is why the authors use direct surface descriptions, e.g. using the mathematical polynomial of if that is not feasible NURBS.

Injection Molding Machinery

The injection molding machine is of course another important element of the process chain. Within the machine the polymer is melted and reproducibly injected into the mold. This requires a precise control of all process temperatures, the displacement volume, the injection speed, the cavity-pressure etc. Product quality in the micron range requires micron precision machinery!

TABLE 1: **Differences in the process and the materials between conventional molding and precision injection molding.**

Process Features	Precision Injection Molding (PIM)	Conventional Molding
critical phase	post filling	filling
mold temperature	high	low
polymer temperature	high	low
cycle time	long	short
packing pressure	high	medium
injection velocity	low	high
major difficulties	sinkmarks, warpage, shrinkage	short shots, flash
thin walled parts	easy	difficult
thick walled parts	difficult	easy
Material Features	**Precision Injection Molding (PIM)**	**Conventional Molding**
glass transition temperature	high	medium
water uptake	very low	NA
stiffness	high	NA
melt viscosity	low	low
compliance	low	NA

TABLE 2: **Typical tolerances of optical components made of polymers.**

	Low Cost Quality	Standard Quality	State of the Art
Focal Length	+/– 3…5 %	+/– 2…3 %	+/– 0.5…1 %
Curvature Error	+/– 3…5 %	+/– 2…3 %	+/– 0.5…1 %
Irregularities (@ 25 mm diameter)	6…10 fringes	2…6 fringes	0.5…2 fringes
Geometry Error (arbitrary surfaces)	20…50 µm	5…20 µm	0.5…5 µm
Surface Quality (scratch/dig)	80/50	60/40	40/20
Roughness Ra	10…15 nm	5…10 nm	2…5 nm
Centering Accuracy	+/– 3 min	+/– 2 min	+/– 1 min
Center Thickness	+/– 0.1 mm	+/– 0.05 mm	+/– 0.01 mm
Diameter	+/– 0.1 mm	+/– 0.05 mm	+/– 0.01 mm
Reproducibility	1…2 %	0.5…1 %	0.3…0.5 %

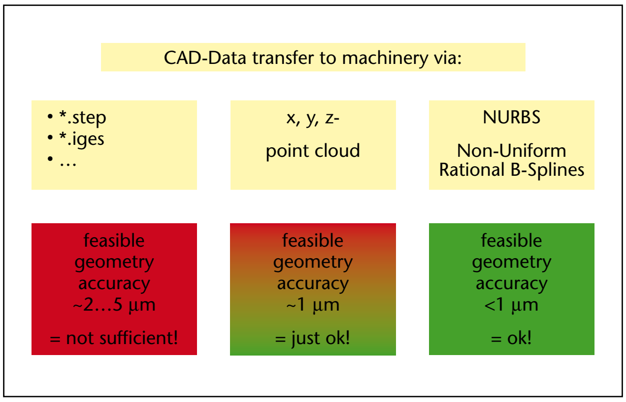

FIGURE 6: **Data formats in brief comparison.**

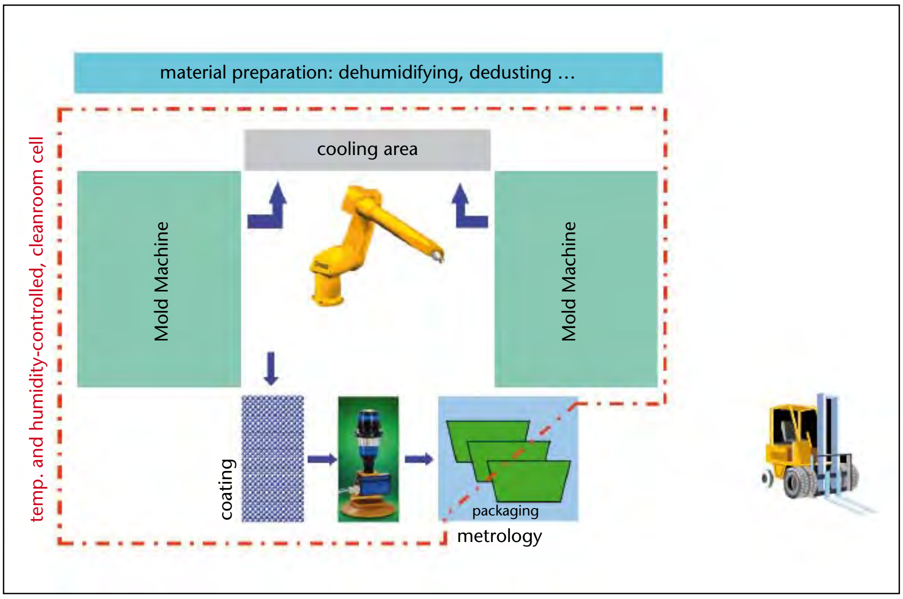

FIGURE 7: **Manufacturing Cell (schematic).**

Mandatory for PIM machines is controlling those parameters within a closed loop. Furthermore, all process relevant mechanical movements of the machine should be of highest precision (e.g. parallelism of mold mounting plates) and all relevant machine parts of high stability. Due to their drive concept electrically driven injection molding machines have clear advantages in terms of accuracy and reproducibility and should be preferred for PIM.

Another important point are the environmental conditions in which the parts are molded. For parts with tolerances in the low µm range a climate controlled, de-dusted, dehumidified environment is mandatory. This is particularly true if the parts should be coated afterwards. The manufacturing cell should than be set up according to the customer's specification for "reference-conditions".

Because there are different customer specifications and because climacontrolling and dedusting large areas is expensive, setting up an appropriate manufacturing cell is a good alternative (see schematic in Figure 7).

Further common requirements for a "clean" manufacturing cell are:

- thermo controlled environment according to customer's specifications
- constant humidity according to customer's parts specification (water absorption)
- to the highest standard cleaned and dried process-air (no condensates)
- local granulate dryers and dedusters
- local granulate degassing processes and prompt use
- automated part handling systems: for part handling during and after injection and for packing and measuring parts as well
- special devices to cut sprue without dust or debris
- as less human interaction as possible

Injection Molding Process

The injection molding processes can be classified into two types: conventional injection molding and injection-compression molding. Injection-compression molding is preferred for molding parts with micro structures, e.g. lenses with diffractive structures.

Common to both processes is the injection of a "hot" polymer melt into a (compared to the melt temperature) cold mold cavity. This will introduce additional internal stress during the cool down and may spoil lenses for applications in polarized light [3]. To overcome this potential show stopper one may temper lenses, which is practically not feasible because they will lose their shape, or to use compression-injection molding processes which have some big advantages here.

Molding processes are very complex with a lot of different (often counteracting) parameters and influence factors (see figure 8).

Summarizing injection molding process parameter ranges, some important are:

- Mold temperature: 90 °C up to 170 °C
- Compound temperature: 180 °C up to 330 °C
- Cycle time: 30 sec to several minutes
- Packing pressure: part/material specific (up to >1000 bar)
- Injection velocity: mold/part/material specific

The mold process in PIM is a part-specific process and has to be developed for each part separately. Process developments are based on the experience of the process engineers, on smart process evaluation strategies and statistic process evaluation methods. Common process strategies can be found in [3] and might serve well as a starting point.

Some important parameters, such as shrinkage, are not only material specific but process and part specific too. In our experience they cannot be determined accurately enough for part tolerances in the low micron range without molding trials. Hence VIAOPTIC is relying on another strategy for high precision optical parts (see figure 2).

First we start designing and building a mold tool without taking shrinkage into account. In a second step we develop an injection molding process with the smallest part to part deviations and the widest process window. Then we are checking the molded parts and "pre" correct the shape of the mold. This procedure enables high process stability and high precision as well, but requires the right equipment in the metrology and tool shop department and some mathematical skills in the design department.

Future Outlook

Precision injection molding paves the way for polymer optical components into high demanding high volume precision applications. Back in the early seventies when VIAOPTIC started to produce the first polymer

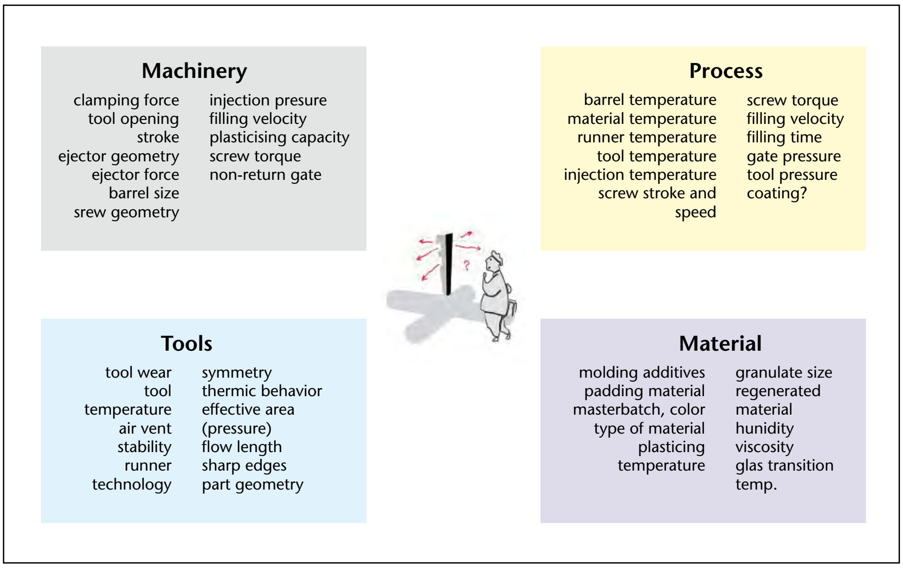

FIGURE 8: **Parameters for Injection Molding.**

optical part for a LEICA camera (a viewfinder screen) nobody could imagine what is possible today. But there is still room for some improvements which I would like to summarize here:

Process and Parts Metrology:

- easy to use, reliable and accurate (<0.1µm) non-tactile metrology for aspheric and freeform surfaces (reflective and transparent)
- improvement of in-mold sensor systems

Mold Design:

- improvements in mold flow analysis for high precision parts
- easy to use software for mold design/ mold flow analysis
- high precision diamond cutting of ferrous materials

Polymers:

- temperature stable optical polymers with a larger n and n range
- more accurate and temperature stable refractive index
- less prone to ”micro cracking“

Mold Machine Design:

- high rigidity
- high thermal stability
- high mechanical accuracy
- accuracy and repeatability of process parameters
- sensor technology: melt-flow, viscosity, pressure …
- cleanliness, e. g. oil spillage, dust through wear …
- easy to clean

Literature

[1] *Greener, Jehuda*; Precision Injection Molding, Hanser 2006

[2] *Holden, Frank C.*; A Review of Dimensional Instability in Metals, Memorandum 189, Defense Metals Information Center, 1964

[3] *Bäumer, Stefan (ed.)*; Handbook of Plastic Optics, Wiley-VCH 2005