Integrating functions in polymer optical components

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ABSTRACT

One of the big advantages of polymer optics is the possibility of integrating several functions into one component. These functions can range from mechanical reference datums all the way to micro channels in "lab-on-chip" type of applications. In this paper an overview on several design- and manufacturing principles of such integrated components will be given. Furthermore the next steps in the Design – Build – Test cycle will be discussed as well: mold manufacturing, molding and finally metrology.

Keywords: precision molding, function integration, mold manufacturing, molding, cycle time, metrology, polymers

1. INTRODUCTION

In today's applications more and more functionality is integrated on an ever decreasing volume. Mobile phones are equipped with cameras, MP3 players, GPS systems. All this functionality fits in the same volume or even smaller than of the phone 10 years ago. Head-mounted displays become available for personalized video and gaming. Medical and health tests become more sophisticated, deliver more information in a shorter time. At the same time these tests are leaving the hospital and are being brought closer to the consumer or patient. In order to do so, these tests need to be made reliable and cheap, most of the times including consumables. Glucose measurements for diabetes is one of these examples, many others will follow. One of the key components in bringing all this functionality to the consumer is high volume manufacturing of sophisticated devices and consumables. In this area injection molding is the technology of choice. In injection molding once effort has to be put in making the correct master form and after that many parts can be replicated with repeatable quality and relatively low costs. However before getting the replicated parts in repeatable quality, some process investigation and optimization has to be done as well. This is a crucial step in getting to the desired results.

In this paper, the chain from product and then mold design through process optimization and not to forget metrology is described. The emphasis will be on integrating several functions such as optics, microfluidics, and electrical interconnection into one part.

2. DESIGN

2.1 Design for functionality

Once the product functionalities and requirements are known, designing to realize these functionalities can start. One common optical functionality that can be added onto injection molded surfaces is a diffractive optical element. This is usually done to do color correction – achromatization – or performance enhancement over a temperature range – athermalization.[1] While the theoretical design of these structures is more or less straight forward, the success of the actual product depends a lot upon the realization of the diffractive structures in the mold and then later in the molded product. Figure 1 shows the ideally calculated profile of a diffractive structure superimposed upon an aspheric surface of a lens. The important feature is the vertical transition between the different zones of the diffractive element. Since perfectly vertical is hardly possible in a mold, the draft angle should be as small as possible. Also the radius in the tip of the transition zone has to be minimized. In figure 2 the results of a simulation of the theoretical performance of a color corrected lens and also two cases with different transition zones are displayed. Since every transition in such a design will cause some light loss in the form of straylight, these transitions should be realized as good as possible, or from a design point of view, one should investigate if a design with viewer diffractive transitions is feasible as well. That might mean to slightly under correct the chromatic aberrations, but in the end because of reduced straylight effects the overall result might be better.

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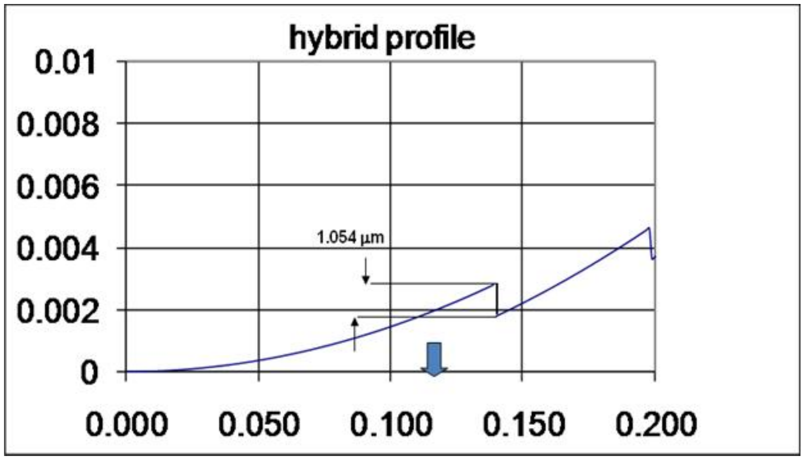

Figure 1: theoretical profile of a diffractive element superimposed upon an aspheric surface

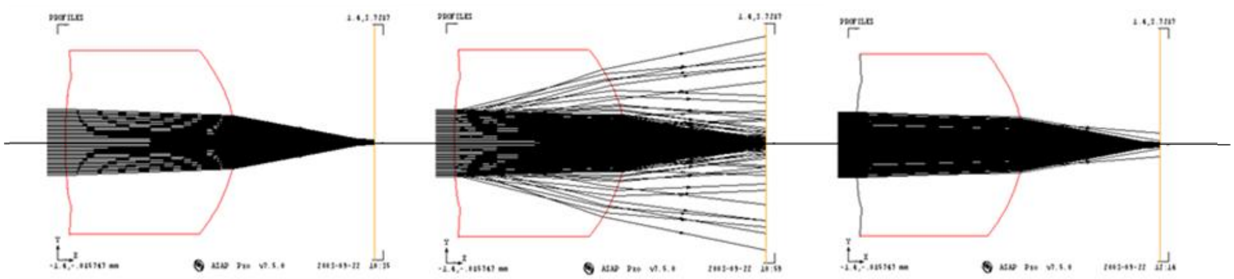

Figure 2: simulation of lens performance with ideal profile, large draft angle, optimized draft angle

Another optical functionality in plastic parts might for instance demand low birefringence. To realize this, an optimum has to be found in material choice, mold design, and injection molding process settings. Since birefringence results from net frozen-in orientation of polymer molecules, materials should display easy flow behavior at chosen process setting. Generally, plastics containing relatively short polymer chains will display low viscosity and relatively fast relaxation of stresses. The mold design and gate location should be chosen such to reduce flow lengths, especially in sections having reduced wall thickness, and to avoid too early cooling off of the plastic during flow. Process parameters such as mold temperature, melt temperature, and injection speed can finally be used to optimize the overall process.

In microfluidic applications, a common microfluidic transport method is the one induced by capillary forces. To properly control liquid transport, sharp corners in the fluidic channels should be avoided since these can induce un-controlled capillary flow in these corner sections of the channels. Also smooth channel surfaces are desired to assure a smooth fluid transport without risk of flow stopping. Both before mentioned aspects are significantly affected by the technique chosen to realize a mold. For instance, electrodischarge machining (EDM) produces relatively rough surfaces and rounded edges while focuses ion beam (FIB) produces very smooth and sharp features. Furthermore, a proper choice for a plastic material should be made to enable any after treatment of plastic parts. For instance surface modifications to realize hydrophilic/hydrophobic surface properties or a treatment to enable immobilization of biomolecules.

2.2 Design for assembly

In lab-on-chip or biomedical devices, microfluidic and electrical interconnections might be required from the device functionality. Microfluidic structures can easily be created in a thermoplastic part while electrical interconnects are traditionally made in thermosetting or highly thermostable thermoplastics, e.g. Polyimide. Joining of these different materials can be realized for instance by gluing techniques that might require auxiliary features in one of both parts.

Figure 3 shows a lab-on-chip device, integrating microfluidic functionality realized in a thermoplastic part (COP, Zeonex E48R) and electrical interconnection with GMR based biosensor in a flex foil from Polyimide.[2] The thermoplastic part contains an auxiliary microfeature to enable assembly via UV curing glue, i.e. a so called knife-edge. Figure 4 shows a visualization and dimensional measurement of this knife-edge performed using interferometry. The knife-edge completely surrounds the microfluidic channel and ensures a fluid tight joining of both parts. However, a high flatness of the thermoplastic part including the knife-edge to realize a fluid tight connection is demanded from the microfluidic functionality, i.e. in the order of 10 μm peak-to-valley over the entire device area. Additionally, the joining technique demands a tight tolerance in the order of some microns with respect to the height of the knife-edge for rapid glue curing. This means that dimensional control and quality of replication are critical in realizing the knife-edge feature. Specific mold design and process optimization are in order to realize this.

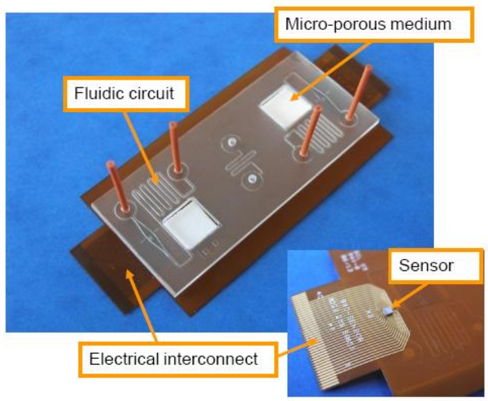

Figure 3: Microfluidic and electrical interconnect functions integrated into a lab-on-chip device.

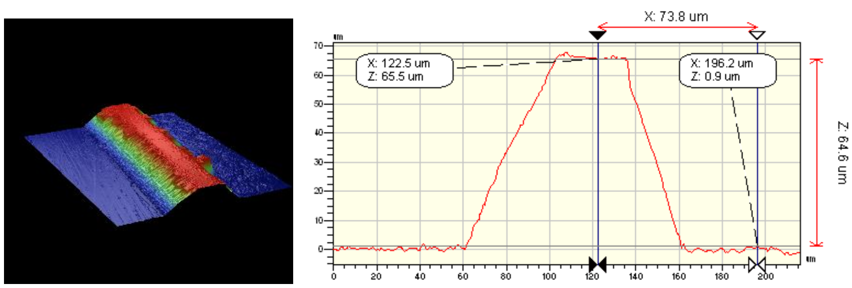

Figure 4: Visualization and dimensional measurement of the knife-edge used for gluing.

2.3 Design for cycle time

After generating the concept the first step is the design of the appropriate part. To do so, the true functionality of the part should be well understood. Only when the final function is clear, one is able to divide the plastic part in functional blocks that are then implemented. This first step is important, since it will determine a lot of the tolerance settings, which in the end will play a major role in price and throughput time. Another important parameter is the optimization of the part in terms of injection molding parameters.

One of the first rules in injection molding is to try to avoid vastly changing wall thicknesses. If a product is designed such that there is significant non-uniformity in part thickness, parts with narrow diameter will cool off, while other parts are still being filled. That will lead to intrinsic stresses, and sometimes even non repeatable mechanical dimensions and dimensional instability over time. Also the molding cycle time can be influenced negatively by such designs. Increased cycle time is directly linked to increased cost. Therefore a design for cycle time is important as well.

Another parameter that has to be taken into account during the design for cycle time is the location of the gate. Choosing the right gate location and parting lines in a mold design will enhance the product quality. When the gate location and its geometry are chosen properly, the plastic part can fill evenly and quickly. While for many parts the experience of the molder is sufficient to choose the correct gate location, for some of the more complex parts a numerical flow analysis can help[3]. Figure 5 shows an example of such an analysis for a more complex part.

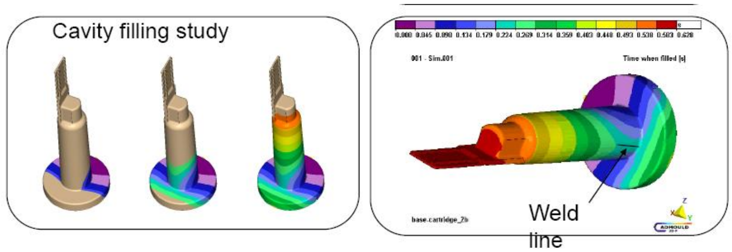

Figure 5: Numerical flow analysis of an injection molded part using Cadmould[2]
showing location of the flow front in time

It is shown, how the part fills and where potential risks such as air inclusions and weld lines can be expected. Air inclusions result in incomplete filling of the part while weld lines are potential weak spots from a mechanical point of view. Furthermore, even and symmetric filling of a product will result in a part with less frozen-in stresses and high dimensional accuracy.

3. MANUFACTURING

3.1 Tool making

Several applications can require microstructures to be present in a product. These microstructures can range from diffractive optical structures for achromatizing, athermalizing lenses to channels for microfluidics in a lab-on-chip device. To generate microstructures in an injection molded part, its negative image has to be realized in the mastering tool, i.e. the mold or mold insert. Several so called mastering techniques are available to create microstructures dependent on the material used for the mold. Mastering techniques can roughly be divided into direct and indirect techniques. Direct mastering techniques create microstructures into a material that is directly used for the mold. Indirect mastering techniques are based on an initial lithographic structuring step, often by structuring SU8 on a silicon or glass wafer, that is then transferred into another material which is finally used as mold insert. Various routes are known to transfer this initial SU8 structure into a material that can be used as mold insert.

Figure 6 gives an overview of some direct mastering techniques. For instance, diamond tip milling can be used for non-ferro metals such as brass, aluminum or nickel but is not suited for carbon containing metals. Electro discharge machining (EDM), conventional milling, and laser ablation are more suited for the latter materials. The choice for a specific mastering technique is not only determined by the material that can be used for the mold or mold insert. Two other parameters that determine the mastering technique of choice are the feature size and aspect ratio of the microstructures. Different mastering techniques offer different properties for generating feature sizes and aspect ratios. In figure 4, an indication of dimensions and aspect ratios is given. Furthermore, the mastering technique also determines inherently the minimum reachable surface roughness, possible resulting surface patterning, and sharpness of features.

Focussed Ion Beam	Laser Ablation	Diamond-tip milling	Micro-EDM	Polishing for optics
- Material: non-ferro - Features: ~ nm - 10 µm - Aspect ratio: < 1	- Material: steel - Features: ~ 1 - 10 µm - Aspect ratio: ≤ 1	- Material: non-ferro - Features: ~ nm - 10 µm - Aspect ratio: 1 - 10	- Material: steel - Features: ~ 100 µm - Aspect ratio: 1 - 5	- Material: steel - Features: ~ 5 nm Ra - Aspect ratio: << 1

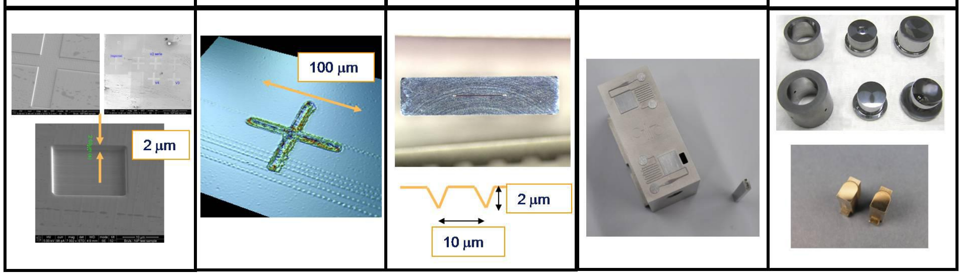

Figure 6: Overview on several direct mastering techniques with respect to material, feature size, and aspect ratio

Of the indirect mastering techniques, electroplating of nickel onto lithographically structured SU8 on a glass wafer is well known from making CD/DVD mold masters. Several companies offer the fabrication of such mold masters on a commercial basis. Over the years, specific nickel grades are developed that enable the growth of relatively thick layers of some hundreds of microns to be plated with little internal stresses. Another less known route is the use of epoxy mold inserts. Here, the microstructure created in SU8 is first replicated into a rubber [4]. This rubber cast is then used as master for casting an epoxy material which is used as mold insert. Dependent on the epoxy material grade and on additional thermal post-treatments, a thermo-stable mold insert can be created suitable for use in the hot-embossing or injection molding process. Figure 7 shows a microfluidic structure realized in SU8 on a silicon wafer (a). This structure was replicated into a rubber (PDMS, Sylgard 184, Dow Corning) which was subsequently used for casting an epoxy mold insert (b). After exposing the epoxy to a carefully chosen thermal post-treatment, a glass transition temperature of the epoxy of 220 °C could be reached. Finally, this epoxy mold insert was used to replicate the microfluidic structure with high accuracy into a plastic (COP, Zeonex E48R) via the process of hot-embossing (c).

(a) (b) (c)

Figure 7: Microfluidic structure embossed into plastic using an epoxy mold insert

It should also be mentioned that besides the practical technological limits and possibilities, availability and the economic factor play an important role as well in deciding which mastering technology to use. Some of the listed techniques are more cost- and labor intensive than others. This argument is especially important when looking at expected volumes and anticipated lifetime of the mold or mold insert. Also not everyone has got access to every technique. And since a close cooperation between mastering and molding is desirable the availability of the technique might be important as well.

3.2 Process optimization

The combination of mastering tool, plastic material properties, and process settings will determine the final product dimensions and quality of replicating microstructures. For the above mentioned lab-on-chip application, a study is performed to optimize the replication of microfluidic features via hot-embossing. The material used is a COP (grade Zeonex E48R) with a Tg of about 140 °C. As the sequence of pictures in figure 8 clearly shows, the temperature of the mold has a significant influence on the quality of replicating microfluidic features. With decreasing size and increasing aspect ratio of the microstructure, the influence of the mold temperature on the quality of replication increases. This is shown in figure 9, where the combined influence of temperature and pressure on the replication of wall-like microstructures is shown. The width of these walls varies from 20 to 100 μm while the height is kept constant to 100 μm. As a result, the aspect ratio of the walls varies from 1 to 5. The significant influence of mold temperature is most clearly shown for replicating a wall width of 20 μm (aspect ratio 5). Summarizing, both for hot-embossing as for injection molding, the mold temperature is the most critical process parameter with respect to replication of microstructures into plastics. In case of injection molding, the melt temperature, injection speed and holding pressure are less critical.

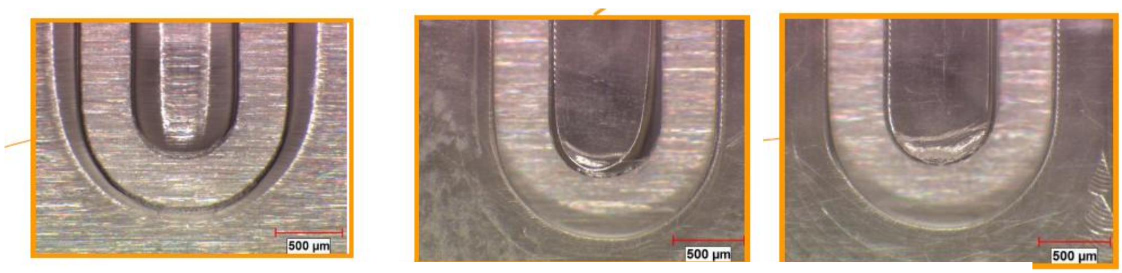

Figure 8: replication of a section of a serpentine-like microfluidic channel via hot-embossing at different mold temperatures: a) 140 °C, b) 190 °C, c) 220 °C

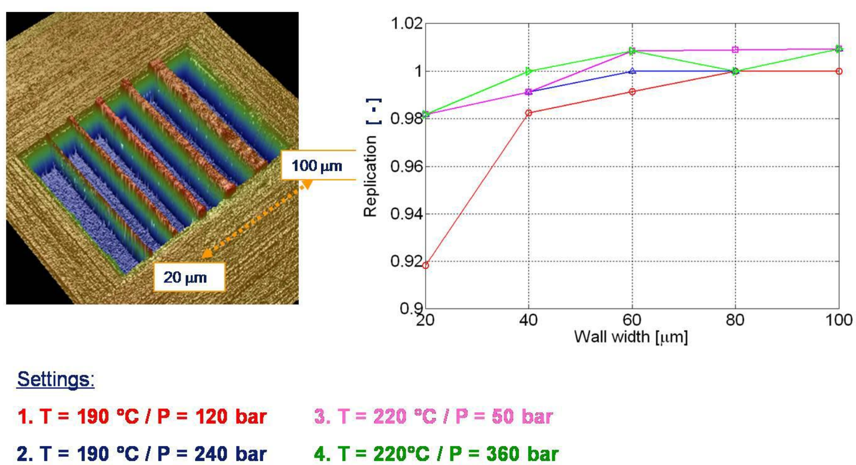

Figure 9: Combined influence of mold temperature and pressure on the replication of microstructures via hot-embossing

4. METROLOGY

As important for injection molding and adding all functions to the product is metrology. Parallel to the product- and mold design a metrology plan should be thought of. This is something that many times is neglected, with the consequence that an unnecessary amount of time is wasted once the product comes out of the mold. The product is there, but it cannot be measured.

4.1 Generic metrology equipment

The first evaluation that has to be made is the one whether there is standard equipment available that can solve the metrology task for the specific problem. If that is the case, the metrology plan might reduce to the task of determining which are the critical features to be measured, and designing / building appropriate fixtures for the product. Here the basic considerations are: feature size, measurement range and –area, 2D or 3D information. Depending on what is needed, the equipment can be chosen. Figure 10 gives a limited overview on some state of the art equipment that can be used in assessing injection molded parts.

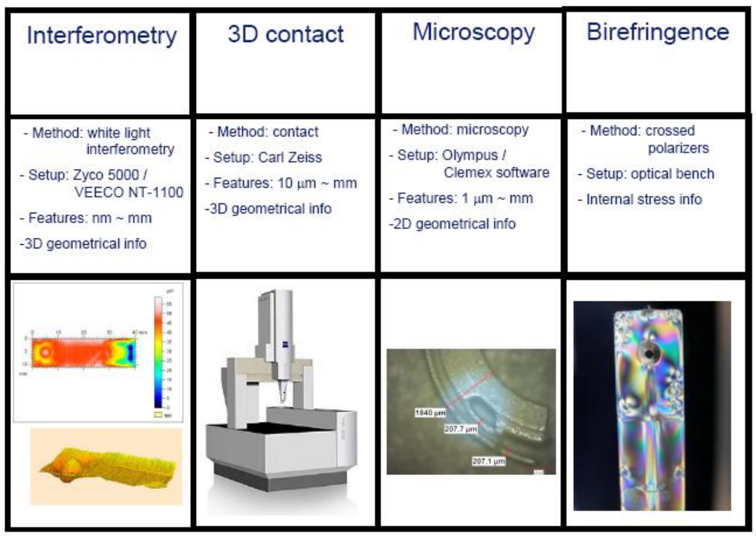

Figure 10: overview on several metrology methods for analyzing injection molded parts

4.2 Specific metrology equipment

While integration of function is one of the big advantages of injection molded optics, sometimes the price for the integration has to be paid in metrology. If 3 or 4 functions are integrated in one product, the question might be asked: are all of these functions critical for the performance? Can all the functions be measured on 3 to 4 standard metrology set ups? Even if that is the case, the time it takes to move the product from interferometer to 3D CMM to vision system might not be adequate in production.

If using standard equipment for measuring integrated functions is not an option, one will have to design and build product specific metrology. In many cases this specific metrology will be a more or less functional test. So a fixture has to be designed in which the product is places and then the circumstances of use are limited. While this is very direct pass / fail check, there are 2 major problems with this approach.

One of them is lead time to build the equipment. Sometimes designing and building that metrology equipment takes as long as mold manufacturing. The second challenge is to link the result of the measurements back to process parameters or important product features.

The Philips Twin – Eye Laser Sensor is an example of such an integrated system where several functions are integrated in one small package.[5] The optics comprise two light paths combined into one single molded piece of plastic. Also since the system by itself is rather small (a few millimeters in geometric size), it has been proven quite difficult to check its performance on standard equipment. There for dedicated test equipment was build to check and control its optical performance. Figure 11 shows the Twin – Eye Laser Sensor as a light engine and the test equipment that was build for it. Many times, when the dedicated metrology set up approach is taken, the measurements are more or less so called functional. The tester resembles (part of) the important functions. In the example of the Twin Eye Laser Sensor, the test equipment is designed to test the optical function, by also the mechanical references. The tester is designed in such a way, that the piece under test is referenced to its mechanical reference surfaces in the tester. Only when both, geometry and optical function work properly, the sample will pass. Together with the design of the tester some optical simulations have been done in order to be able to differentiate various causes of failure from the compound signal. This kind of supporting simulation is essential in building functional, dedicated test equipment.

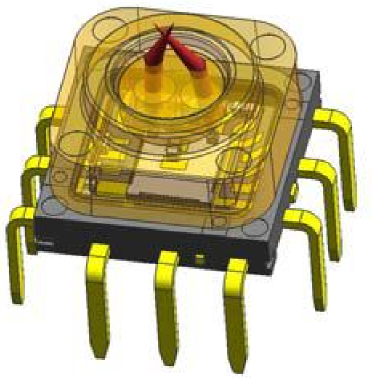
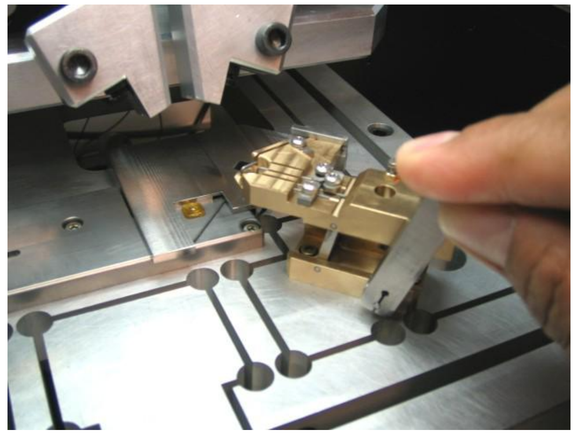

Figure 11: Philips Twin – Eye Laser Sensor – product and tester

5. CONCLUSION

Optical components made from polymers are extremely suited for integration of other functionalities ranging from optical functionality to fluidic to electrical interconnection. However, realization of the functionalities in plastics is determined by the combination of materials used, mold manufacturing, and molding process. Thorough knowledge of functional design (optical, fluidic, etc.), plastic material properties, mold design, mold making techniques, polymer processing, and metrology are therefore crucial. In designing such integrated components, none of the steps should be omitted, and communication between the different disciplines is key. While the replication technology in injection molding is at a very high level, it is many times the mold manufacturing and insert making, which determines the quality of the end product. Especially in the step, a good look at different available technologies is essential. This knowledge together with the availability of the necessary equipment can ensure the mass manufacturing of integrated polymer optical parts with high quality.

REFERENCES

[1] Stefan M. B. Bäumer, Wim A. G. Timmers, Mark Krichever, Vladimir Gurevich, “Temperature-compensated plastic lens for visible light”, PROC SPIE 3737, 354 – 362 (1999).

[2] M. Megens, M.W.J. Prins, “Magnetic biochips: a new option for sensitive diagnostics”, J. Magn. Mag. Mat, 293, 702, (2005)

[3] www.simcon-worldwide.com

[4] J. Steigert, T. Brenner, M. Grumann, L. Riegger, R. Zengerle, and J. Ducree, MEMS 2006, Istanbul, Turkey, 22-26 January (2006).

[5] http://www.business-sites.philips.com/lasersensors

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