Hot Embossing and Injection Molding for Microoptical Components

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ABSTRACT

After the successful development of microoptical components today the first commercial applications are arising. This induces the necessity of adapted production technologies. Hot embossing and injection molding are two techniques to fabricate microoptical components characterized by lateral structure details below 1 μm, structure heights up to one millimeter and aspect ratios between 20 and 100. Injection molding is famous for its short cycle times which makes this method well suited for mass production. Very delicate microstructures and multilayer components can be fabricated e.g. within the framework of the LIGA-process by hot embossing. Examples for microoptical components fabricated by molding as well as process equipment will be discussed.

Keywords: Plastic molding, microoptics, hot embossing, injection molding, microspectrometer.

INTRODUCTION

The market for microoptical components is growing steadily and fast, caused by more and more applications in telecommunication. It is not so much the high-performance parts that are responsible for this growth, but the cheap parts which can be fabricated easily and which are suitable for a broad range of applications. They are ideal to be molded in polymers: low material costs, a lot of different materials that can be chosen from and high numbers of pieces offer many possibilities in this field.

The main topic of this article will be the molding of polymers using mold inserts made by the LIGA-technology. High structures in combination with a high aspect ratio and a low roughness of the surfaces are the characteristics of LIGA and make it specially interesting for optical applications. The polymers can be processed by injection molding as well as by hot embossing. The advantages of both techniques will be demonstrated by the presentation of some optical components.

LIGA

Only a few manufacturing techniques are as well adapted to a wide field of applications especially in microoptics as the LIGA-process (deep-etch X-ray lithography, electrodeposition, molding)[1,2]. This technique, which has been developed at the Karlsruhe Research Center (Forschungszentrum Karlsruhe, FZK), offers possibilities of free lateral patterning in the submicrometer range.

In the first step of the LIGA process, a polymer layer of several hundred micrometers thickness which is applied onto a substrate, is patterned by means of highly parallel, high intensity synchrotron radiation. After development a primary microstructure is obtained. This primary structure is the basis for a complementary secondary structure manufactured from metal by electroplating. This in turn is used as a tool (mold insert)[3] for molding of ternary structures (which are exact copies of the primary structure), thus opening the door for the mass fabrication of high quality microstructures.

Typical structures as narrow land widths and deep trenches with aspect ratios of up to 100 allow very high components to be made, whose lateral dimensions are still in the micrometer range. Very smooth walls with a surface roughness below $\lambda/10$ even for the visible spectral range are also typical for the LIGA process [4]. Because there is only little loss on every inversion step all this properties are also true for the mold inserts and molded parts.

MOLDING

In contrast to standard molding processes micromolding requires modifications of the molding machinery, the molding tool's construction as well as of the adaptation of the molding parameters to the small geometrical dimensions and the large flow length to wall thickness ratio (≡ aspect ratio) of the plastic mold.

This results in two main features of molding machines: The possibility to evacuate the mold to obtain complete filling of the microstructures and the heating of the mold[5]. The reason for this is, that the high aspect ratio of LIGA microstructures implies a high ratio of flow length to wall thickness as well as a large surface to volume ratio of the plastic melt. Hence a rapid heat exchange between the plastic melt and the mold insert occurs with a final mold temperature approximately equivalent to the temperature of the mold insert. In any case solidifying of the plastic has to be avoided due to an increase of the material's viscosity upon cooling by several orders of magnitudes. Hence the micromold inserts must be heated to a temperature in the range of the melting point of the plastic material for a complete filling. Thermal shrinkage during the cooling process has to be compensated by a corresponding holding pressure. The cooling step is followed by the demolding process which is carried out at temperatures below the glass transition or melting point for a sufficient mechanical tensile and shear strength. A reliable demolding without any cracks or flaws is supported by the plane parallel structural walls without any inclination and the excellent surface quality of LIGA microstructures with an average roughness of 40 nm.

Two molding techniques are used currently: thermoplastic injection molding with relatively short cycle times and the rather convenient and flexible vacuum hot embossing. Additionally, for special applications, reaction injection molding of curable reactive resins is used.

INJECTION MOLDING

Injection molding of LIGA microstructures has been developed at FZK since 1986. Basic differences to conventional injection molding machines are the higher precision in the micrometer range in displacement travel and speeds, the control of the molding cycle specific to microtechnology, and the integration of peripheral equipment[5]. The machine periphery comprises a vacuum unit for evacuating the mold's cavity, and temperature control units for each half of the molding tool (see Figure 1). At FZK a fully automatically driven two component Ferromatik Milacron K50S2F injection molding machine allows small and medium scale plastic microstructure fabrication[6,7]. In cooperation with a machine vendor an all-electric injection molding machine has been adapted for the requirements of micromolding. Besides the enhanced precision and optimized control possibilities this new generation of molding machines will be more economic in operation and is suitable for working under cleanroom conditions which is necessary for the fabrication of optical components. Micro injection molding profits from the long experience in conventional injection molding. High technical standard and advanced automatization are the result of some ten years of development of this technique.

HOT EMBOSSING

Hot embossing means that a molding tool, the so called mold insert, is pressed under vacuum into a semi-finished polymer at a temperature above its glass temperature. Characteristic for this technology are comparably simple machines, low mechanical influences on the mold insert, the possibility to mold extremely small structures, the exact replication over large distances and the possibility to produce optical components[8]. Another advantage of the hot embossing technique is the use of thin polymer foils. By this way the required material quantity is very small and enables also the use of expansive polymers

In macrotechnology, hot embossing often is the preferred technique for the production of optical components, so it is evident to use this technique also for microoptical components. Important are not only very smooth surfaces but also high purity of the bulk material.

To replicate the excellent surface roughness of LIGA mold inserts it has to be ensured, that polymer and mold insert keep in contact as long as the temperature is above the polymer's glass transition temperature. Pressure and cooling have therefore to be controlled precisely. To achieve a homogenous material distribution without any anisotropic components, the molten material has to flow as little as possible. The use of polymer foils between the mold insert and the closing unit ensures a flow length only of the order of the structure height. The small lateral dimensions of the microstructures might lead to extremely high flow velocities, even with the risk to cause the polymer chains to break. Such effects, which also lower the optical quality of the structures can be avoided by low molding velocities. Finally, slow cooling has the same effect as a hot plate (tempering) process and helps eliminate internal stress which would induce scattering centers unfavorable for optical devices. For many applications it is advantageous when the polymer layer that remains between substrate and mold insert is as thin as possible. In optical applications like waveguides a residual layer would cause an intensity loss by outcoupling light from the core layer. The production of the UV/VIS-LIGA-microspectrometer[16] has been developed to a state where no more residual layers occur. This is only possible if the vertical position of the mold insert can be controlled very precisely.

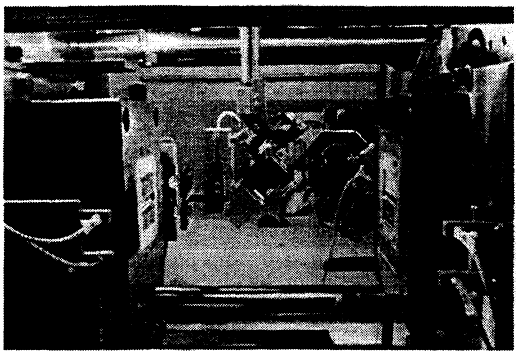

Figure 1: View inside the tool of an injection molding machine adapted to micromolding purposes. Additional handling systems increase production rate.

Figure 2: Microspectrometer production under clean room conditions. Modular machine idea is demonstrated by use of a tandem machine for molding and welding processes.

To meet all these requirements we developed a modular hot embossing system on the base of a material testing system (supplier Zwick, Germany) (see Figure 2), adding a standard heating system (made by LAUDA, Regloplas or Single) and a vacuum chamber [9]. The entire embossing cycle can be controlled easily by means of the standard testing system software. The only component which is not a standard product is the vacuum embossing chamber with the tool support. This is the center piece of the unit, where the molding step takes place, and this is where the real know-how of the FZK is to be found. Standardization was attempted by using as many commercially available components as possible.

UV-REACTION INJECTION MOLDING

Beside of these two techniques in with thermoplastics are used, for some special applications also reaction injection molding can be used, especially when instead of heat UV-radiation is used to initiate the polymerization[10]. The advantage is that no heating is needed. Concerning the dimensional stability of the product the lack of any thermal shrinkage is a great advantage, however, demolding can be rendered difficult. For optical applications, UV-Reaction Injection Molding can be used for the production of waveguides when high dimensional stability is demanded or trenches have to be filled up with materials of different diffraction numbers.

EXAMPLES FOR MICROOPTICAL COMPONENTS

A vast part of the optical structures made by molding of polymers are diffractive structures with lateral dimensions in the range of some hundreds of nanometers and low heights. The lowest structures molded at the FZK are monomode waveguides[11]. Trenches with some microns depth and an aspect ratio of one can be molded easily. The reason why we use LIGA-mold insert in this case is the required precision and the handling of materials with different diffraction numbers. There are more activities at FZK in the field of multimode applications. A typical example are coupling elements (see Figure 3). The critical area is the edge that chops the light. Its quality determines the distribution of light at the exit. With the LIGA-process, curves with radii of <1μm at structural heights of up to 1000μm can be fabricated. Such parts are needed in great numbers of pieces for optical networks; they are therefore preferably made by injection molding.

When different microoptical components are to be combined, for instance spherical lenses with waveguides, microoptical benches (see Figure 4) are indispensable. They demand an extreme dimensional precision [12,13]. This is a challenge for polymer technology with its materials of comparably high thermal expansion. By optimization of design and molding parameters modern high performance polymers, such as e.g. PEEK, yield good results.

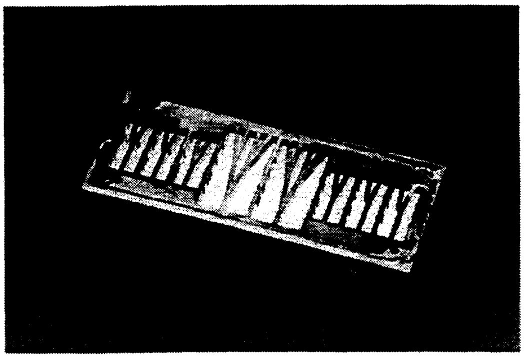

Figure 3: Mold insert for coupling elements (structure height 1050µm). In the center of the mold insert two elements for splitting the intensity to four equal parts.

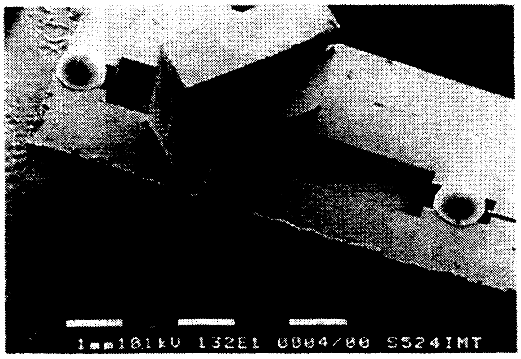

Figure 4: SEM-picture of the microoptical bench completely assembled with a beam splitter and two microlenses.

Lenses are other important optical components. Their dimensions are large compared to those of diffractive elements. Again, the requirements to be met in surface quality demand the highest precision. Various approaches exist to achieve the curved lens surface for producing mold inserts. One way is by remelting cylindrical LIGA microcolumns and further processing them into mold inserts[14]. Molding by hot embossing in different thermoplastics produces microlenses of excellent quality (see Figure 5), which are used in microobjectives because of their imaging accuracy. Similar results can be obtained by molding with a silicon mold insert in which lens shaped impressions were made by isotropic etching (see Figure 6). The surface quality of silicon in this case determines the quality of the polymer lens[15].

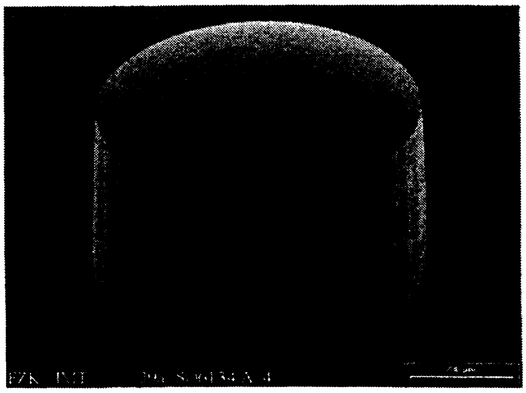

Figure 5: Microlense (diameter: 600µm) by molding from a LIGA-mold insert.

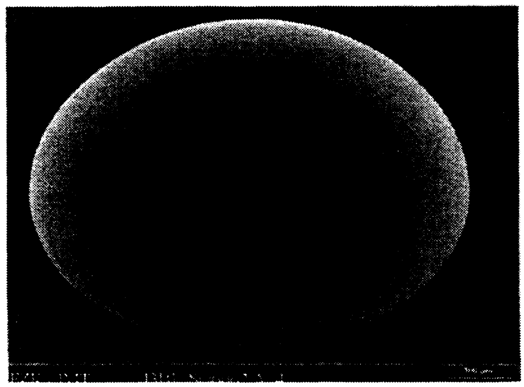

Figure 6: Microlense (diameter: 340µm) by molding from isotropicly etched silicon.

The LIGA UV-VIS-microspectrometer (see Figure 7) is already commercially available and sold over 4000 times. In principle, this is a waveguide structure, but as far as function is concerned, a microspectrometer is already a complete microsystem [16]. In addition to the beam guide system in the waveguide, a self-focusing diffraction grating as well as a launching shaft and a sloped edge for coupling out the diffracted light onto a diode array are integrated components. A system of this type never needs to be adjusted; this feature, in addition to production by plastics molding, is the reason for the low price. From the point of view of production technology, two types of spectrometers are distinguished. The UV/VIS-spectrometer consists of three layers, with light being conducted in an embossed core layer. A major problem in this design is the sharp transition from the structured core layer to the unstructured cladding layer, where loss of light into the cladding layer must be avoided. Hot embossing is the technique of choice in such problem cases. The infrared spectrometer (see Figure 8) is a hollow waveguide component where light is conducted in the air. Microstructures are integrated into the support structure and the light conduction structure. The advantage of this technique lies in only one material being employed, which allows large numbers of spectrometer components to be produced by injection molding[17].

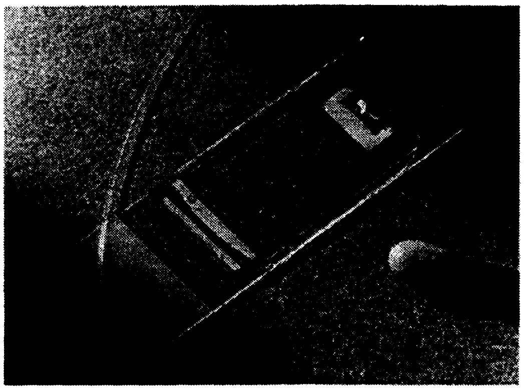

Figure 7: UV-VIS-Microspectrometer complete with fiber (spectral range: 380nm-780nm).

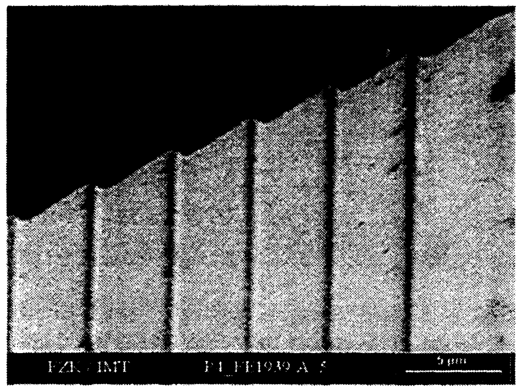

Figure 8: NIR-spectrometer. Detail of the nickel mold insert (structure height 145µm). The optical grating has a step height of 1µm.

CONCLUSION

In this article it is shown, that production of microparts of optical quality at low cost condition is possible. There are various microoptical components for different purposes. Some of them are in an early research state. Other elements like the UV-VIS-LIGA microspectrometer are already commercialized. Different molding techniques are suitable for the replication of microoptical components in a polymer. Depending on the microstructure injection molding or hot embossing technique can be applied.

Actual research activities are orientated towards shorter cycle times in the injection molding process. To establish an economic process for mass production this is very important. For the hot embossing process a new machine generation allows to work under industrial conditions. With the modular machine idea, hot embossing is applicable for the manufacturing of prototypes as well as for the production of first small series.

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