Injection Moulding of Parts with Microstructured Surfaces for Medical Applications

Christian Gornik

Battenfeld Kunststoffmaschinen GmbH, Wr. Neustaedter Strasse 81, 2542 Kottingbrunn, Austria
E-mail: gornik.c@bku.battenfeld.com

Summary: m2M-systems (micro-to-Macro) are parts with lateral dimensions of macroscopic scale and structures on the surface in the dimension of microns. The microstructure on the surface has a specific function depending on the intended purpose of the parts. With the use of m2M-systems new methods of medical diagnostics are possible. Nowadays for the realisation of such parts mainly planar methods known from microelectronics and their standard materials silicon and glass are used. An alternative is to make m2M-systems by injection moulding of plastics which lowers the manufacturing costs. In order to get an acceptable replication of the microstructure the use of special moulding techniques is necessary. The results of investigations in the variotherm moulding process and the requirements for the injection moulding machine are described in this paper.

Keywords: biotechnology; injection moulding; micro-to-Macro (m2M); polycarbonate; variotherm process

Introduction

The use of surfaces as functional elements, and not only the increasing degree of miniaturisation, is contributing to the growing importance of micromoulding. Beside the electronic and telecommunication industry microstructures become more and more common in applications for biotechnology and medical applications. One of the main reasons for the use of miniaturized apparatuses is the tremendous increase of analysis, e.g. the genom-project. On the other hand some analysis can only be done with small amounts of reagents in order to avoid contamination with other substances. So called lab-on-a-chip applications will replace conventional laboratory equipment and will lead to reduced times for analysis. These devices must be mass produced at low costs. The replication by injection moulding of plastics is one way to get a high production volume at low costs. Hot embossing of plastics is another way to produce microstructured surfaces. Hot embossing is essentially the stamping of a pattern into a polymer softened by raising

 DOI: 10.1002/masy.200451332

the temperature of the polymer just above its glass transition temperature. The stamp used to define the pattern in the polymer may be made in a variety of ways including micromachining from silicon, and machining using a CNC (computer numerical controlled) tool. A wide variety of polymers have been successfully hot embossed with micron-scale size features, including polycarbonate and PMMA (Poly(methyl methacrylate)). This technique is used primarily for defining micro-channels and wells for fluidic devices. Because the cycle times are about 10 to 30 minutes for one part and the costs of the mould are lower than that of a mould for injection moulding this technique is usually used for the production of prototypes. Another competitor of the injection moulding process for m2M-systems is the silicon technology which is well established in the microelectronic industry. For some applications silicon is the preferred choice, e.g. when electronic is combined with other functions on one chip. One application is the Flow-Thru Chip.[1]

Another application is the LILLIPUT microtiterplate (fig. 1) which has been developed for clinical microbiological applications. Microchannels link the wells to sample reservoirs and are automatically filled utilizing the capillary effect. Therefore sharp edges on the microstructure are necessary.[2]

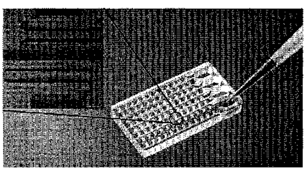

Figure 1. The LILIPUT microtiterplate.

Mould Making Methods for Microstructures

Conventional tooling methods as for example milling or EDM (electrical discharge machining) do usually not meet the requirements for micro-applications. Micro machining of brass or aluminium alloys with diamond tools is possible on suitable machine tools. Micro-EDM is a further development of conventional EDM with the aim to reach finer structures. Photo-imaging (called the LiGA technique in German from the word Lithographie, Galvanoformung, Abformung) is an expensive method that yields to high-quality surface.[3,4] In this method, a resist (a film of PMMA, Poly(methyl methacrylate)) is applied to a metal substrate. This film is then exposed to X-ray radiation through a mask. The molecular chains in the irradiated regions become shortened and can be removed by a solvent. The UV- (ultraviolett) LiGA, which is also called poor man's LiGA, is a similar process but instead of a synchrotron radiation source a UV-source is used for lithographic structuring. Both optical and X-ray lithography have common drawback, which limits their field of application: the possible shapes of the Microsystems are strongly limited. Although high aspect ratios can be achieved more complex shapes, such as rounded edges or specific curvatures cannot be fabricated with these techniques. Other mould making methods are e-beam (electron-beam) lithography and excimer laser machining. Some investigations have been done with silicon mould inserts. But these inserts are very brittle so they have to be handled with care and the injection moulding process conditions have to be smooth in order to avoid destruction.

Process Technique

The injection moulding process consists of the injection, the holding, the cooling and the ejection stage. During the injection the velocity of the reciprocating screw is controlled and the melt is injected into the cavity of the mould. A peak in the pressure, the so called switch-over pressure, indicates that the cavity is volumetrically filled. The following holding pressure compensates the shrinkage of the polymer during the cooling of the part. As soon as the temperature of the material is lower than the maximum ejection temperature, which depends on the relationship temperature-mechanical properties of the polymer, the frozen part can be ejected. The temperature of the mould is usually controlled by a temperature control unit. When the melt contacts the cavity wall there is a slight increase in the mould temperature in the conventional injection moulding process.[5] For the replication of microstructures a modified process is necessary which is explained in detail later on.

Well known applications of microstructures in plastic parts are the CD (compact disc) and DVD (digital versatile disc). The aspect ratio, which is the ratio of the depth and the lateral dimension of the microstructure, of optical data carriers is less than 1. Typical m2M-applications have an aspect ratio of more than 1. In order to produce high aspect ratios with sharp corners, a variotherm process sequence is required.[6]

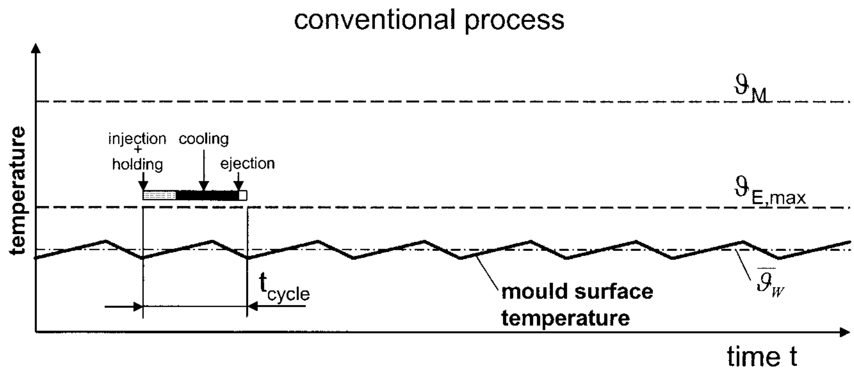

Figure 2. Conventional injection moulding process with an almost constant mould surface temperature. ϑ_M (melt temperature) and $\vartheta_{E,max}$ (maximum ejection temperature) are shown in comparison to the mould surface temperature. Typical cycle times, t_{cycle}, are between 5s and 30s.

In the conventional injection moulding process the mould surface has a temperature far below the melt temperature. The mould surface temperature is slightly increased by the hot melt during the injection and holding stage. The mould is cooled continuously and therefore the temperature goes down again as shown in figure 2. During the injection a frozen layer is formed close to the cavity walls. Therefore microstructures can not be replicated even when a high holding pressure is used (fig. 3). During injection the cavity wall has to have a higher temperature close to the melt temperature of the polymer during injection. So the mould is heated before the injection of the melt starts as shown in figure 4. Therefore the viscosity of the plastic material is kept to a low level until the microstructures in the cavity are filled. After the injection phase the mould has to be cooled down to the ejection temperature which is below the maximum ejection temperature.

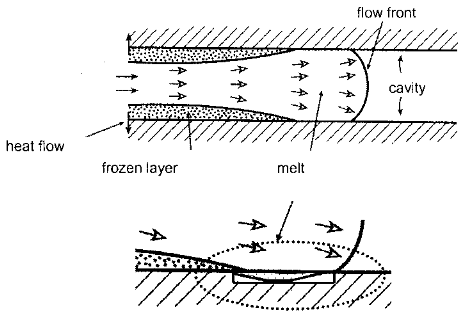

Figure 3. Forming of a frozen layer in the conventional process which prevents the replication of microstructures with an aspect ration of more than 1.

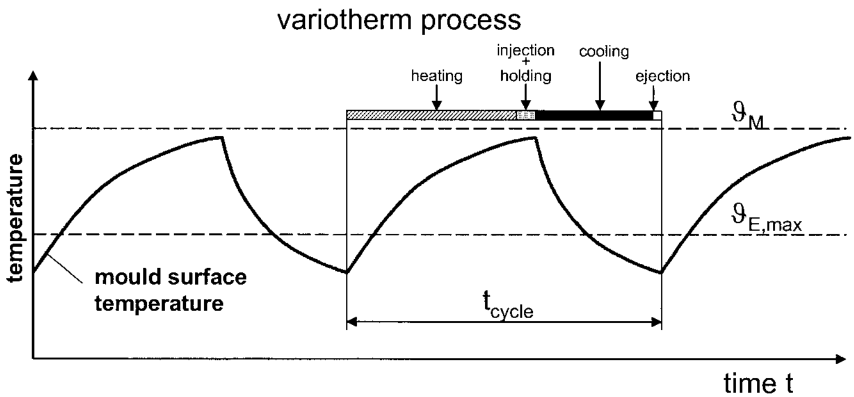

Figure 4. Variotherm process with a varying mould surface temperature. ϑ_M (melt temperature) and $\vartheta_{E,max}$ (maximum ejection temperature) are shown in comparison to the mould surface temperature. Typical cycle times, t_{cycle}, with the variotherm process are between 100s and 300s.

Trapped air can cause a bad replication of the microstructure. Therefore the cavity should be evacuated before injection. For that a vacuum pump in combination with small holes within a sealing element in the mould is used. The whole process steps are shown in fig. 5.

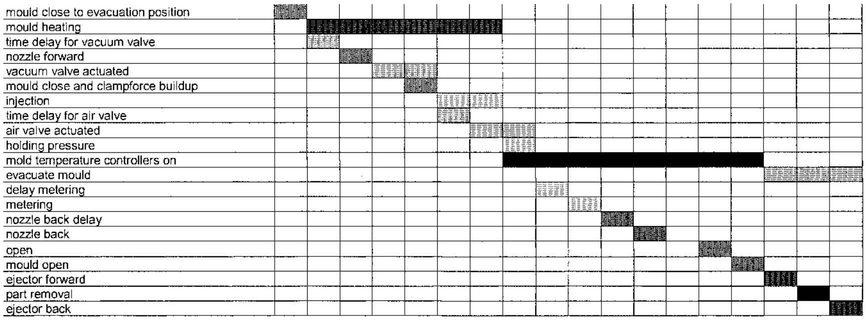

Figure 5. Process steps for the injection moulding of m2M-structures.

The quality of the replication depends on the rheological and thermal melt behaviour of the plastic material. Polycarbonate which has a high viscosity and a low thermal conductivity tends to form a frozen layer much faster than Polystyrene. So the level of the cavity temperature and the switch-over pressure have different effects on the replication for these materials which is shown in figures 6 and 7. In these figures H is the height of the replicated microstructure on the surface of the part. For polycarbonate even a switch-over pressure of 1000 bar and a mould temperature of 160°C are not sufficient to replicate the microstructure in the cavity which has a depth of 210 µm. With polystyrene a switch-over pressure of 600 bar and a mould temperature of 80°C are sufficient to fill the microstructure almost completely.

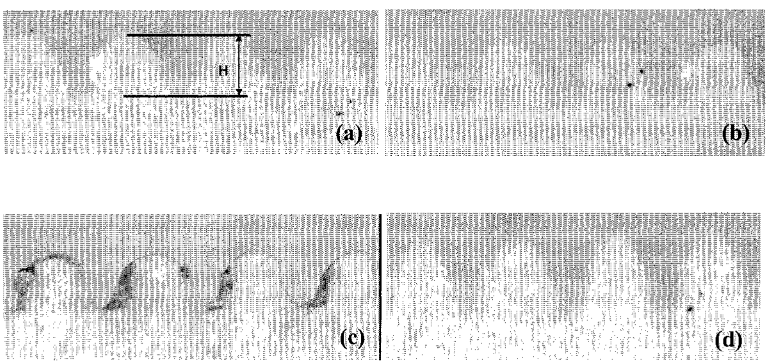

Figure 6. Replicated microstructure in Polycarbonate with a switch-over pressure of (a) 400 bar and a mould temperature of 80°C (H=139 µm), (b) 1000 bar and 80°C (H=146 µm), (c) 400 bar and 160°C (H=143 µm) and (d) 1000 bar and 160°C (H=158 µm).

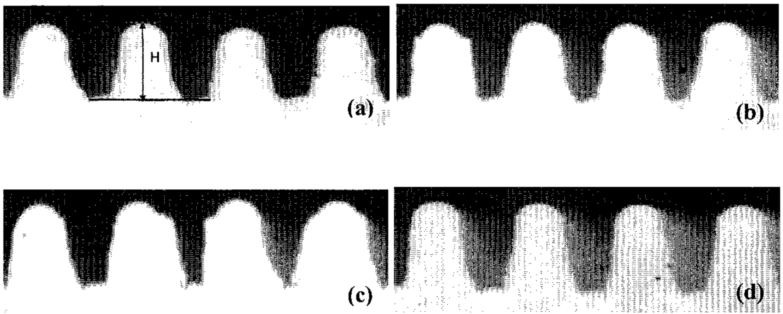

Figure 7. Replicated microstructure in Polystyrene with a swith-over pressure of (a) 300 bar and a mould temperature of 80°C (H=189 µm), (b) 300 bar and 80°C (H=201 µm), (c) 450 bar and 80°C (H=201 µm) and (d) 600 bar and 80°C (H=207 µm).

The higher the mould temperature the better the replication of the microstructure but the longer the time needed to heat up and cool down the mould.

The measuring of the microstructures can be done with a light-microscope, AFM (atomic force microscope), SEM (scanning electron microscope) or with so called profilometers. Figure 8 shows the results of a 3D-topographic measuring and of the surface roughness which can be extracted from the 3D-measuring.

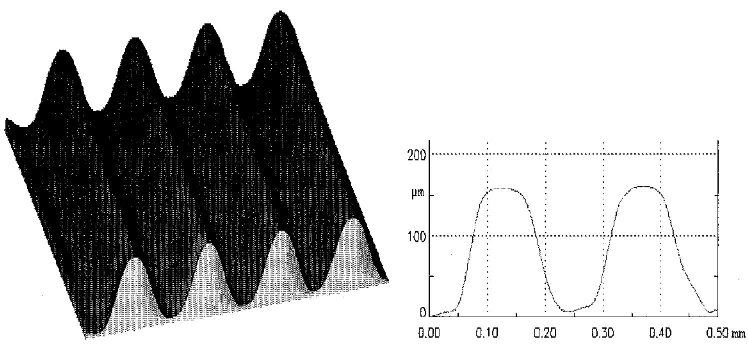

Figure 8. Measuring results with a profilometer of a microstructured surface.

The generally known equation 1 for the calculation of the cooling time can not be used because the mean mould temperature $\overline{\vartheta}_W$ is higher than the ejection temperature $\overline{\vartheta}_E$.

$$t_K = \frac{x^2}{\pi^2 \cdot a_{eff}} \cdot \ln\left(\frac{4}{\pi} \cdot \frac{\vartheta_M - \overline{\vartheta}_W}{\overline{\vartheta}_E - \overline{\vartheta}_W}\right) \quad (1)$$

t_K cooling time

x wall thickness

a_{eff} effective temperature conductivity

ϑ_M melt temperature

$\overline{\vartheta}_W$ mean mould temperature

$\overline{\vartheta}_E$ ejection temperature

Instead of equation 1 an iterative method which takes the changing surface temperature into consideration has to be used. Therefore the energy balance between the coolant, the affected mould areas and the plastic is needed.

The following processes can be used:

1. Dive-in of heating elements, e.g. induction to heat the cavity walls,
2. Oil variotherm operation,
3. Electrical heating of the mould and cooling with water or oil,
4. Heating by electrical induction and cooling with water or oil.[7]

Another possibility is the use of special surface coatings as heating elements. There are a couple of layers. One that provides electrical isolation to the basic mould material and the other provides electrical conductivity in order to make electrical resistance heating possible. The advantage of that technology is that mainly the cavity wall is heated and less energy goes into the other mould elements.[8]

With the usually used technique, this is electrical heating and cooling with oil, the up and down in temperature during one cycle takes a couple of minutes. In order to reduce cycle time the use of water would be helpful. But the temperatures which are usually used are higher than the boiling point of water. Water has a better heat transfer coefficient than heat transfer oil. So the cooling times in comparison to oil can be reduced. In order to avoid boiling of the water during heating of the mould the water is sucked out of the mould cooling channels after the ejection of the part. To reduce heating time the mould elements which are heated should be as close to the cavity as possible. The basic mould should be isolated from the heating elements. But care should be taken that the stiffness of the mould stays high. The more material has to be heated the longer the heating time. The mould opening and ejection has to be done carefully in order to avoid damaging of the microstructures (fig. 9).

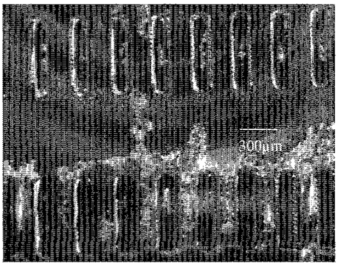

Figure 9. Damaged microstructure because of rough ejection.

A toggle clamping unit provides constant low speeds during the first millimetres and a speedy opening because of the varying transmission ratio of the toggle system (Fig 10). An abrupt opening which damages the microstructured surface can be avoided.

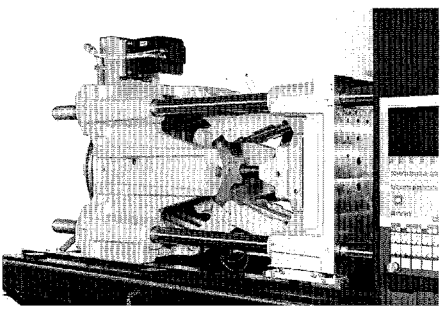

Figure 10. Servo electric driven toggle clamping unit.

It is known that, compared to an hydraulic machine, a fully electric injection moulding machine provides noticeable better precision and reproducibility during injection in addition to higher acceleration and deceleration. It is recommended to produce m2M-parts under clean room conditions. Standardized solutions based on a laminar-flow-box can be used to reach clean-room classes from 100 to 10.000.

Conclusion

For the development of components and systems for molecular biotechnology microtechnical manufacturing methods play a key role today. One economical manufacturing technique for disposables is injection moulding of plastics. In order to get a good replication of the microstructured surface a variotherm process is required.

[1] B.J. Cheek, A.B. Steel, M.P. Torres, Y.-Y. Yu, H. Yang, *Analytical Chemistry*. **2001**, 73, 5777-5783.
[2] F. Nökker, in: „*Spritzgießen 2001*", VDI-Verlag GmbH, Düsseldorf **2001**.
[3] W. Ehrfeld, H. Lehr, *Radiation Physics and Chemistry*. **1995**, Volume 45, Issue 3, 349-365.
[4] W. Menz, J. Mohr, *Mikrosystemtechnik für Ingenieure*. VCH-Verlag **1996**.
[5] F. Johannaber, *Injection molding machines*. Carl-Hanser-Verlag **1994**.
[6] H. Eberle, *Kunststoffe – plast europe*. **1998**, 9, 1344-1346.
[7] A. Rogalla, PhD thesis. **2001**.
[8] H. Bleier, C. Gornik, patent registration no. DE-102 46 942.3.