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Performance and simulation of thermoplastic micro injection molding

V. Piotter, K. Mueller, K. Plewa, R. Ruprecht, J. Hausselt

Abstract Originally developed for the replication of high aspect ratio LIGA structures, micro injection molding is presently on its way to become an established manufacturing process. Enhanced technological products like micro optical devices are entering the market. New developments like the different kinds of injection molding with several components open up opportunities for increasing economic efficiency as well as for new fields of applications. Software tools for the simulation of the thermal household of the molding tool and/or the moldfilling process itself can provide useful but not wholly sufficient assistance for the optimization of micro injection molding.

1 Introduction

It will not be long before miniaturized products will surround us in our everyday life as well as in industrial manufacturing and services. Such tiny devices are not only limited to microelectronics, of course. There are also a lot of applications in automotive industries, telecommunication systems or medical engineering, just to mention a few fields. It can be easily imagined that manufacturing such micro components which often carry functional units in the micrometer size (or even smaller) requires new or basically modified manufacturing processes. One of these technologies with a special qualification for large-scale series production is micro injection molding. Development started about a decade ago and nowadays, first products have already entered the market or are on their way to do so. In the following chapters, the technology of micro injection molding including special variants as well as the current development trends will be described.

2 State of the art

When the development of micro injection molding started in the late eighties, no appropriate machine technology was available. Therefore, only modified commercial units, hydraulically driven and with a clamping force of usually 25–50 t, could be applied for the subtle way of replicating microstructured mold inserts with high aspect ratios by injection molding (Fig. 1).

The situation changed in the middle of the nineties when first efforts were made by mechanical engineering companies in cooperation with research institutes to develop special micro injection units or even completely new machines for real micro parts. The task was to reduce the minimal amount of injected resin, which is necessary to guarantee a stable process, down to minimum shot weights of only 0.025 g (Fig. 2).

The critical minimal dimensions which can be replicated in good shape by injection molding are mainly determined by the aspect ratio. For aspect ratios smaller than one, these minimal structural details reach values in the submicrometer scale (e.g. CD and DVD fabrication).

By using the special features of “classic” micro injection molding like evacuation and the variotherm process, polymeric microstructures with minimum wall thicknesses of 10 μm, structural details in the range of 0.2 μm, and surface roughnesses of about $R_Z < 0.05$ μm have been manufactured. Especially the sharpness of replication still offers potential for further improvements. Today, the greatest advantage of applying a variotherm process lies in the manufacturing of walls of some ten microns with maximum aspect ratios up to 20 [Rup00, Shk00].

These plastic microstructures are used as components for micro systems in various fields of application like micro optics or medical/biological technology. Figures 3–6 only provide a short overview of typical examples of micro injection molding.

Table 1 shows a summary of the polymers being commonly employed and points out some examples of practical use. Due to the small volumes of micro components, materials costs are less important so that technical and high-performance polymers are often applied [Rog98].

A good example of the actual performance of micro injection molding is the manufacturing of RibCon®

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V. Piotter (✉), K. Mueller, K. Plewa, R. Ruprecht, J. Hausselt
Forschungszentrum Karlsruhe GmbH,
Institut fuer Materialforschung III,
P.O. Box 3640, 76021 Karlsruhe, Germany
e-mail: volker.piotter@imf.fzk.de

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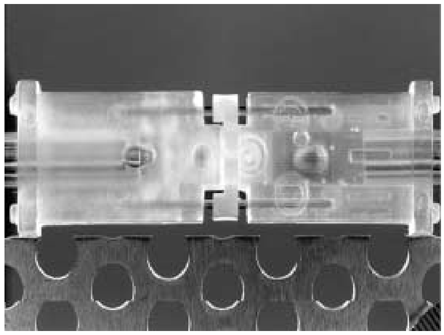
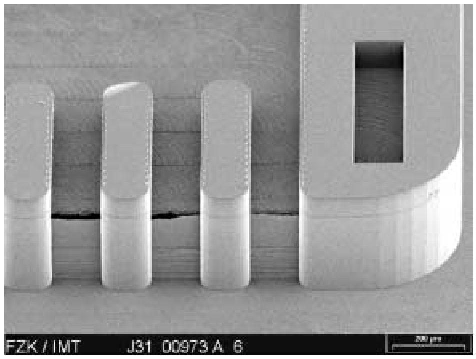
Figs. 1, 2. 50 t injection molding machine with special equipment for micro molding (Ferromatik K 50, top); 5 t micro injection molding machine for minimal shot weights (Battenfeld Microsystem 50, bottom)





Figs. 3, 4. Multimode fiber connector made of PMMA (top), SEM figure of leading structures for optical fibers (bottom)

optical fiber connectors with up to 16 multi-mode fiber channels. As mold halves, both LIGA as well as micro milled inserts are used [Wal01]. The acceptable tolerances of the PMMA parts are no more than a few micrometers; they could be kept within a process reliability of more than 90% (up to 99% depending on measurement accuracy) for the injection molding step during pre-series fabrication campaigns.

3
Micro injection molding with several components

Due to the very small dimensions and weights of micro components, assembly of the entire micro systems is a difficult and time-consuming procedure.

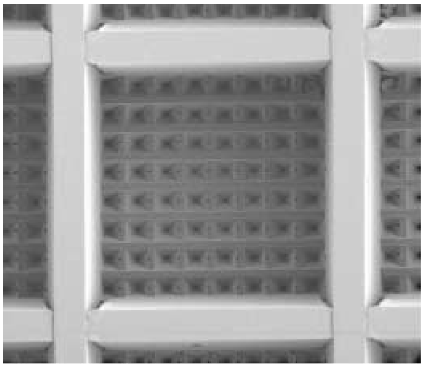
Developed with the aim of reducing the mounting costs and shortening manufacturing time, micro assembly injection molding [Mic99] or micro insert injection molding (MIIM) has been investigated at IKV, Aachen or at Forschungszentrum Karlsruhe respectively using alloyed steel inserts which had been placed in the cavity of a microstructured mold with a minimum distance of only 15 μm to the mold surface. Injection molding experiments using polyethylene showed that the defiles were filled completely so that the insert parts could almost be embedded by the polymer. The related flow length to wall thickness ratios were calculated to be more than 230 [Shw98].

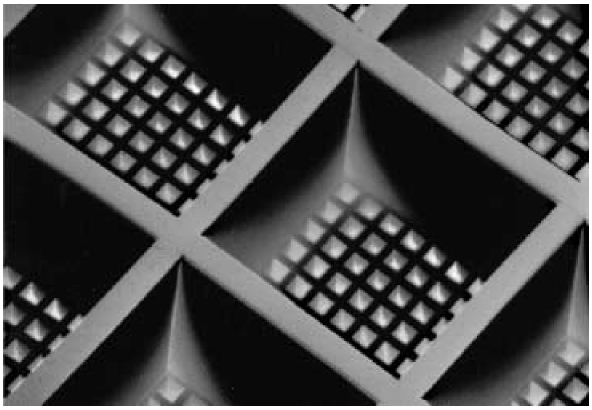
Two- or multi-component injection molding on the micrometer scale would reveal advantages similar to using insert parts. The main technical challenges are the process parameters which have to be suitable for both materials and adhesion. Micro multi-component injection molding technology is widely expected to attract further attention in the future.

4
Simulation of micro injection molding

The reasons for applying simulation programs in micro systems technology are nearly the same as in conventional fabrication. To avoid the risks of costly re-engineering or simply mis-investments, the functions of the final products as well as the manufacturing steps are simulated extensively before starting real work.

In micro manufacturing technology, software tools adapted from conventional injection molding can provide useful assistance for the optimization of molding tools, mold inserts, micro component designs, and process parameters. At Forschungszentrum Karlsruhe, the software package ABAQUS is used for simulating the temperature distribution in the tools during the different steps of a complete molding cycle. For the filling process itself, the well-known MOLDFLOW software is applied [Nor96].





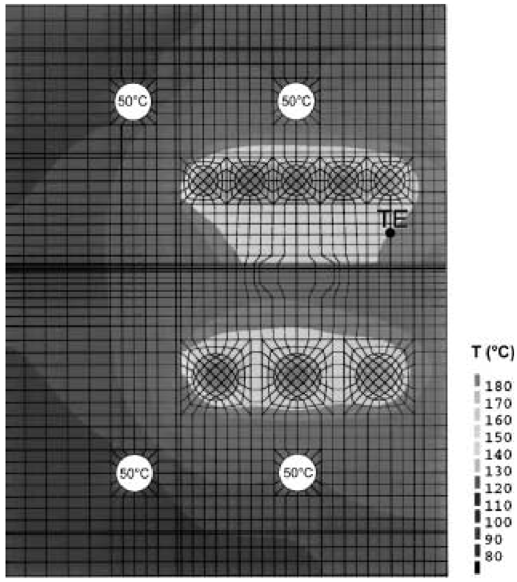
Figs. 5, 6. Micro containers for cell cultivation injection molded with PC (top), PMMA (bottom)

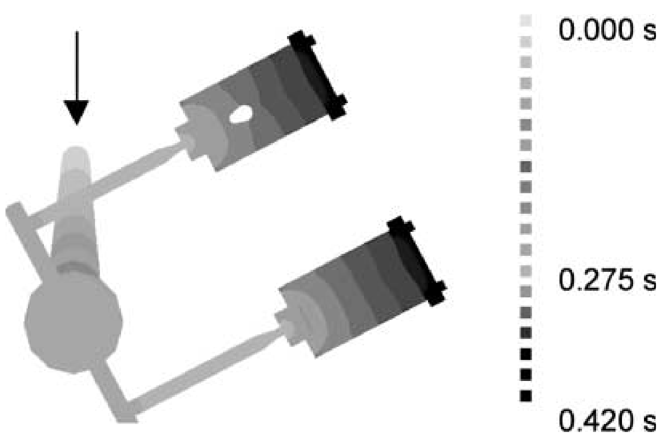
Table 1. Polymer materials often used in micro injection molding, maximum aspect ratios (AR), minimum structural thicknesses (s_{min}), and typical applications

Polymer	Abbr.	AR	s_{min} [μm]	Example of application
Polymethyl methacrylate	PMMA	20	20	Optical fiber connector
Polycarbonate	PC	7	350	Cell container
Polyamide	PA	10	50	Micro gear wheels
Polyoxymethylene	POM	5	50	Filter with defined pore diameters
Polysulfone	PSU	5	270	Housings for microfluidic devices
Polyetheretherketone	PEEK	5	270	Housings for micro pumps
Liquid crystal polymers	LCP	5	270	Microelectronic devices
Polyethylene	PE	230*	20	Components for micro actuators
Conductively filled polyamide	PA 12-C	10	50	Housings for electrostatic micro valves

* flow length to wall thickness ratio

It has to be mentioned that the simulation tools only work adequately from a qualitative point of view. This enables the prediction of, for example, welding lines, but numerical values cannot be calculated as precisely as necessary. The reason might be that the commercial software developed for macroscopic applications does not consider microscopic aspects properly. Especially the simulation of injection molding with highly filled polymers leads to quantitative discrepancies between real and calculated values. Therefore, the development of software tools specifically tailored to micro applications is one of the main future tasks.





Figs. 7, 8. Heat dissipation in a molding tool during the heating period (top); simulation of filling time for an injection molded multimode fiber connector (bottom)

5
Outlook

The future potential is revealed not only by the estimated market development, but also by the increasing research efforts in public institutions as well as in industrial companies.

Originally developed for the replication of high-aspect-ratio LIGA structures, micro injection molding is presently on its way to becoming an established sub-species of the macroscopic technology. This is demonstrated by the recent attempt of improving this technology from the economic point of view as well as by renowned machine manufacturers having started to apply very low shot weights.

New developments like the different kinds of injection molding with several components open up opportunities for increasing economic efficiency as well as new fields of applications.

On the other hand, there is still some work to be done. This does not only concern the economic optimization of the process itself, but also supplementary functions like materials development, simulation techniques, process control, testing of micro components, etc.

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