Microsyst Technol (2008) 14:1599–1605
DOI 10.1007/s00542-008-0572-9

TECHNICAL PAPER

Replication technologies for HARM devices: status and perspectives

V. Piotter · W. Bauer · T. Hanemann · M. Heckele · C. Müller

Received: 15 July 2007 / Accepted: 18 January 2008 / Published online: 5 February 2008

Abstract Replication processes offer a number of considerable advantages for the production of micro components. This is not limited to the high economic efficiency achieved by numerous multiplications of master structures. Furthermore, micro devices can be produced of nearly every kind of material by one or a sequence of replication steps. In this contribution, five important processes of micro replication will be described, reflecting the wide variety from rapid prototyping over small and medium series to mass production. For future development, three main trends can be observed: the steady further miniaturization of shaping capability, the efforts to increase economic efficiency mainly by reducing cycle times and enlarging work areas, and the different approaches to combine shaping and joining procedures thus obtaining a minimum of process steps.

1 Introduction

Miniaturization of single devices as well as of whole systems clearly represents a global trend of our time. For the economic success of MST, however, the availability of appropriate manufacturing processes is still a prerequisite. Fortunately, a wide range of such processes is under development or is already in industrial use, like silicon micro machining by different etching methods or down-scaled cutting processes like milling, drilling, EDM, ECM, etc. The number of micro fabrication processes increases and opens different opportunities of shaping liquid materials or re-forming of primarily structured devices, usually summarized as micro replication (Heckele and Schomburg 2004).

These methods are of remarkable importance as they combine various technological properties with high economic standard. Regarding the latter, the outstanding possibility of reproducing high-quality singular master structures thousands or even millions of times, thus building the bridge from single to mass production, must be emphasized. Comprehensive cost studies revealed the tremendous fall of costs per part with increasing number of pieces as shown in Fig. 1. Although these exemplary calculations were based on injection moulded devices the main result, i.e. the cost reduction by multiplication, applies for every replication process.

As further advantage, many replication processes can be derived to process widely different materials ranging from polymers and ceramics to metals, special functional materials, etc. (Piotter et al. 2007). Last but not least, micro replication can also be used for rapid prototyping with the special possibility to produce parts from ceramic or metal materials. An overview on the most important currently applied replication processes is provided by Table 1.

Replication processes are usually classified as continuous or discontinuous. Although the first ones exhibit a large economic potential, in large-scale production their suitability for manufacturing high aspect ratio parts is very

V. Piotter (✉) · W. Bauer · T. Hanemann
Karlsruhe Research Centre, Institute for Materials Research III,
P.O. Box 3640, 76021 Karlsruhe, Germany
e-mail: volker.piotter@imf.fzk.de

M. Heckele
Institute for Micro Structure Technology, P.O. Box 3640,
76021 Karlsruhe, Germany

T. Hanemann · C. Müller
Freiburg University, IMTEK, Georges-Köhler-Allee,
79085 Freiburg, Germany

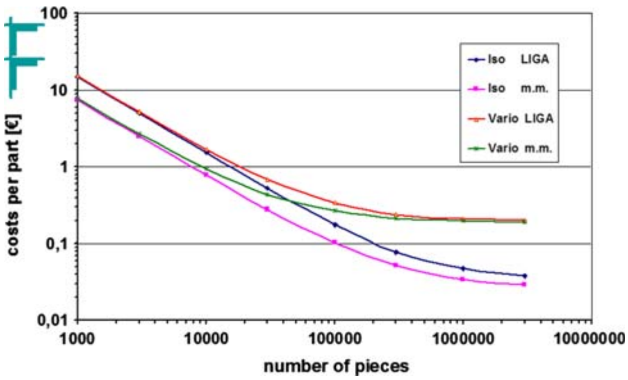

Fig. 1 Costs per part versus number of pieces for a fictive injection moulded micro part. Although the absolute values depend strongly on the particular product, the considerable cost reduction achieved by multiplication is obvious. Further parameters are the kind of process conduct (*iso* isothermal, *vario* variothermal) and the type of mould insert used (*m.m.* micro machined). In principle, such cost versus piece number interdependencies are the same for every replication technology

Table 1 The most important replication processes in micro fabrication

Materials	Replication processes	
	Continuous	Discontinuous
Polymers	Extrusion melt spinning, rolling/calendering	Micro injection moulding (MicroTIM), reaction injection moulding, hot embossing/nanoimprint, thermoforming
Metals	(Stamping)	MicroPIM galvanoforming, micro casting reaction, injection moulding
Ceramics	Extrusion (of green bodies), gravure printing (of green bodies)	MicroPIM, slurry casting, sol–gel casting, electrophoresis, reaction injection moulding

limited. Therefore, this publication will focus on the discontinuous processes.

In the following chapters, the probably most important micro replication processes, i.e. microinjection moulding and micro hot embossing, will be described. To cover the areas of small-scale series production as well as rapid prototyping further sophisticated micro replication processes like reaction injection moulding and low-pressure powder injection moulding will be covered as well.

2 Micro injection moulding

2.1 General description of the process

Injection moulding represents a well-proven technology for manufacturing macroscopic devices in our present industrial world. On the other hand, if such tiny parts like micro components with details in the micrometer range have to be produced, some additional features have to be taken into account:

In certain cases, for example, an evacuation of the core area of the moulding tool is necessary as the cavities in many micro moulding tools represent “bag-type holes” which are not permeable to gases at the bottom. If hot melt was pressed into such a cavity without prior evacuation, the compressed and heated air would cause the organic material to be burnt. A second specialty of micro moulding is the so-called variotherm temperature control which is often applied in the case of micro components with high aspect ratios. The moulding tool is heated to approx. the melting point of the polymer prior to the injection step. As a result, flowability of the resin is sufficient to fill even smallest structural details down to the submicrometer range. After the mould has been filled completely, the tool with the resin contained therein has to be cooled down until the strength of the moulded part is sufficient to ensure defect-free demoulding.

Due to the high sensitivity of the microstructures, very precise tool movements have to be guaranteed. For an automatic process conduct, the control software of the injection moulding machines available has been backfitted accordingly.

2.2 Multi-component micro injection moulding

Micro components are, of course, much smaller and lighter than macroscopic parts. Therefore, assembly of the entire micro systems is a more difficult and time consuming procedure. An interesting development to reduce these mounting costs and shorten manufacturing times is Micro Assembly Injection Moulding (Michaeli and Opfermann 2006) or micro insert injection moulding.

Two- or multi-component injection moulding in the micrometer scale displays advantages similar to using insert parts. In principal, it can be employed in micro dimensions by using either polymer or metal/ceramic materials. The latter represents a combination of multi-component technology with MicroPIM. The main technical challenges are the special tool design with additional feeders, the process parameters which have to be suitable for both materials, and the question of adhesion in micro areas. It can be expected that this technology will win further attention in the future.

2.3 Micro powder injection moulding (MicroPIM)

Due the specific demands of their application, many MST products consist of metallic or ceramic materials. If large

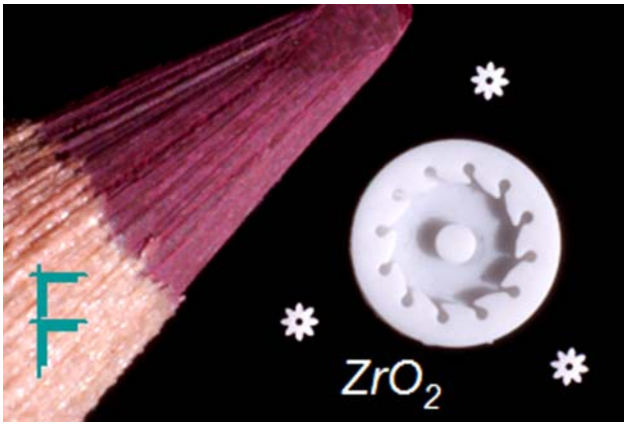

Fig. 2 Turbine housing and micro gear wheels made of zirconia by powder injection moulding: outer diameter of the gear wheels approx. 600 µm

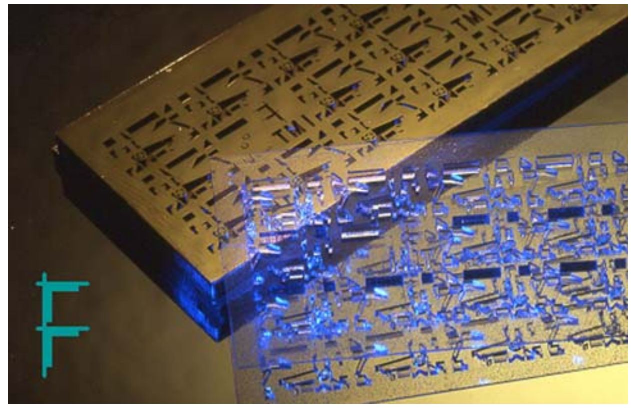

Fig. 3 FEMOS mould insert and hot embossed micro optical bench, height 800 µm. Material polycarbonate

numbers are called for powder injection moulding (PIM) is often the right choice for fabrication.

Investigations started with commercially available powders and binders, e.g. metal (Fe, 316L, 17–4PH, W, etc.) or ceramic (alumina/zirconia oxide, etc.) materials (see Fig. 2). Powder metallurgical manufacturing in micro dimensions soon proved to require specially developed feedstocks mainly because powders of finer grades than usually applied have to be operated to achieve a high dimensional accuracy as well as enhanced surfaces. For example, best surface qualities obtained were $R_{max} = 2$–3 µm with ultrafine ceramic powders whereas in case of rough metal powders surface qualities became worse. Maximum AR reached so far are approx. 10 or even higher.

Despite the influence of particle size, the MicroPIM process enables more than sufficient shaping qualities and a lot of prototypes for micro products like different designs of gear wheels or micro test specimens have already been realised. Nominal dimensions could be replicated within tolerances of 0.5% usually, whereas the process accuracy can be enhanced in certain cases.

3 Micro hot embossing

In hot embossing, a micro structured tool (mould insert) in an evacuated chamber is pressed with high force into a thermoplastic foil that has been heated above its softening temperature. The mould insert is filled by the plastic material that replicates the microstructures in detail. Then, the setup is cooled down and the mould insert is withdrawn from the plastic.

As the embossing die and countertool cannot be closed completely, a characteristic carrier layer remains during hot embossing. On this layer, the microstructures are arranged. Due to the vertical structuring direction and the setting of very small moulding rates, microstructures with very high aspect ratios (ratio between the height and width of the structure) can be produced.

Vacuum hot embossing, which was developed for the replication of LIGA structures more than 10 years ago, has meanwhile proved suitable for the production of microstructures or even nanostructures of highest quality, e.g. micro-optics or holographic safety features. Hot embossing is particularly suitable for the structuring of plane plates or foils, as only a small amount of plastic has to be moulded. Other examples are fluidic components, such as CE chips, micro titre plates, or micro optical benches (see Fig. 3).

Hot embossing technology allows for a very simple setup of the plant, which is particularly advantageous in case of tool or plant reconstructions or modifications. This results in very short set-up times. When using standardized mould inserts, a few minutes are sufficient to change a tool. On the other hand, the simple plant technology is connected with relatively long cycle times. They are mainly caused by the fact of the embossing die and countertool also being employed for heating the semi-finished products and of the heated polymer not being supplied continuously by an injection unit. Still, non-continuous material supply may be advantageous, if several materials are to be compared. In this case, various semi-finished products can be put into the machine successively without further modifications being required.

Originally designed for the LIGA standard format of 26×66 mm^2, the embossing area was extended considerably in the past years. By combining individual mould inserts and using techniques such as mechanical micromachining, UV lithography, or etching in silicon, areas of up to 6″ can be structured at the moment. Moulding of such large areas adds to the economic attractiveness of the technology. Micro titre plates accommodating 96 complete capillary electrophoresis chips on an area of 86×126 mm^2 can be produced. However, with increasing area, shrinkage of the plastic component gains significance. A sophisticated process conduct is required to prevent deformations, such as overdrawn edges of the components or even damage of the mould insert (Mehne et al. 2006). Another method of minimizing shrinkage is the reduction of the residual or carrier layer. Further process improvement is reached by the development of appropriate software routines (Worgull et al. 2006).

The application scope is extended by moulding on both sides. This particularly holds for fluidic structures. It must be noted that the structures have to be adjusted towards each other. Hence, orientation of both tool halves must be possible. The methods are based on positioned moulding on pre-structured substrates. In extreme, a microstructure even protrudes into the plane of the opposite plate.

Another special process derived from simple hot embossing technology is hot embossing of composite layers. Interesting effects may be achieved by replacing the simple semi-finished product by a composite of several foils. A classic example is the micro spectrometer for the UV–VIS range. By combining PMMA foils of variable refraction coefficients, a waveguide for light transmission is obtained. If polymers are chosen which are not welded during embossing but still adhere strongly to each other so that they can be demoulded together and separated afterwards, through-holes or separate 3D microstructures can be generated (Mehne et al. 2006).

Last but not least, the second material may be a metal conduction path on the surface of the plastic semi-finished product. During hot embossing, this conduction path follows the topology and thus provides for an electric connection from the surface to the structure base. This is an excellent way of providing fluidic structures with additional properties.

4 Nanoimprint

Since being listed as one of ten *emerging technologies that will change the world* in MITs Technology Review (Fairley 2003) Nanoimprint lithography (NIL) is gaining more and more popularity. This technology was proposed by Chou et al. in 1995 and is meant to be a low-cost and high-throughput manufacturing technology to produce nano-features (Chou et al. 1995). Nanoimprint technology is based on deforming a very low viscous (normally spin coated) polymer by mechanical embossing. Because of this mechanical forming the resolution of NIL is not limited by diffraction, scattering or interference effects, which are crucial in optical lithography. Except for high aspect ratio applications NIL does not need evacuated tools. A huge benefit of NIL is the cheap equipment compared to other technologies used for the generation of features in the nanoscale. Solely a (hot-) embossing tool and (if needed) a UV light source is required.

The mould materials used for NIL contain rigid materials (quartz, silicon, nickel, SiC, silicon nitride) or flexible materials [PDMS, Teflon layers (Bender et al. 2006)]. Rigid stamp materials are used for state-of-the-art high-resolution applications with linewidths of several 10 nms. For these stamp materials a very high surface quality of the substrate in terms of waviness is required. When using a flexible stamp there are fewer demands concerning this surface-quality, but a reduced resolution. Furthermore, the surface of the mould can be modified to minimize adhesion to the imprinted polymer. To achieve this, either a low-surface-energy coating can be applied to the mould or its surface properties can be modified by a plasma treatment (Guo 2007).

The resist has to be low viscous to guarantee fast filling of cavities and thus small cycle times. There are the different approaches of Thermo-NIL, Photo-NIL and the combination of both of them. In Thermo-NIL thermoplastics like PMMA, PS or PC are typically used as resist materials. There are also commercially available resists like mr-I 7000, mr-I 8000 and mr-I T85 (Microresist Technology), BASF́s Laromer and NXR-1000 (Nanonex). Prior to the imprint process in Thermo-NIL, the resist is heated up slightly above its flow temperature (T_f) and is cooled down while pressure is still applied.

In Photo-NIL acrylate- and epoxide-based materials combined with photo-initiators are used. Commercially available materials are mr-UVCur06 (Microresist Technology), NXR-2000 and NXR-3000 (Nanonex), BASFs Laromer and ordinary negative tone resists (SU8, ma-N, AZ nLOF 20XX). The resist material is polymerised during imprinting by UV-curing through the mould. Obviously, the mould material for Photo-NIL has to be transparent.

In both types of NIL it is unavoidable to obtain a residual layer. This residual layer can be removed by an oxygen plasma treatment. After removing this layer, the substrate can be structured by Reactive Ion Etching. This offers the possibility to create high aspect ratios (AR > 10).

Several groups around the world demonstrated the imprint of structures with features in the size of sub 20 nm up to several μms (Chou et al. 1997). Cycle times of this process are varying in a wide range from a few seconds to 200 s, depending on the complexity of the structures, the resist type, the resist thickness, and the way of curing the resist. The roughness of the imprinted structures is equivalent to the surface quality of the tool.

Applications which are in the focus of research for the use of NIL can be found in the disciplines of electronics (nanoelectronic devices in Si, hybrid plastic electronics, organic electronics), photonics (organic lasers, diffractive optical elements, broadband polarizers, photonic crystals) and biology (nanofluidic channels, the effect of imprinted nanostructures on cell culture) (Hershey et al. 2006).

5 Micro replication processes for small series and rapid prototyping

5.1 Reaction moulding of polymer, metal, and ceramic micro components

Micro reaction moulding allows a rapid prototyping of micro structured components made of polymers, metals, and ceramics. The setup was originally designed for the realization of micro structured plastic parts via photocuring of polymer based reactive resins (Pfleging et al. 2003). Structural details down to the micrometer range and aspect ratios up to 20 have been realized. The micro reaction moulding technique uses polymer resins, i.e. low viscous monomer–polymer-mixtures which can be cured either thermally or by light. The moulding equipment setup shows some similarities to injection moulding (moulding tool geometry, die plate, demoulding support, et al.), but contains one transparent mould half facing the light source. The whole moulding cycle (under ambient conditions) can be divided into four basic process steps

1. Closing and evacuation of the tool
2. Low pressure resin injection
3. Photocuring under applied dwell pressure
4. Demoulding

Solid plastic parts can be replicated within 2 min independent from the microstructures' aspect ratio. The addition of at least 40 vol% ceramic or metal fillers to the reactive resin enables the realization of dense ceramic or metal parts according to the process sequence feedstock formation, replication, debinding, and sintering. In contrast to the pure resins the polymerization reaction has to be thermally activated using peroxide as initiator and exploiting the heat evolved by the broadband light source. A solidification time around 20–30 min results in a 2 mm thin plate carrying microstructures on top. Depending on the ceramic (SiO_2, Al_2O_3, ZrO_2) or metal (Fe, 17–4PH stainless steel) used, suitable debinding and sintering programs have to be developed (Hanemann et al. 2007). The current state of the art of micro reaction moulding is summarized in Table 2.

Table 2 Rapid prototyping of polymer, composite, ceramic and metal parts using reaction molding

	Polymers	Ceramics	Metals
Reactive resins	Unsaturated polyester, acrylates, methacrylates		
Fillers	–	SiO_2, Al_2O_3, ZrO_2	Fe, 17–4PH
Moulding temp. (°C)	25	25–60	25–60
Curing time (min)	2–5	20–30	20–30
Sinter density (% thD)	–	99.2	Fe 98.8; 17–4PH: 96.3

5.2 Low-pressure powder injection moulding

Low-pressure injection moulding (LPIM) is similar to the conventional high-pressure injection moulding process (HPIM). However, there is one essential difference between the two processes: the pressures employed to LPIM range from 0.1 to 1 MPa whereas HPIM is run at a pressure of more than 50 MPa. This difference results from the use of a low-viscous paraffin or wax instead of a high-viscous polymer binder. Due to the different binder system, HPIM and LPIM show differences in feedstock preparation, injection moulding machinery, and debinding process. Nevertheless, the methods are closely related, as the basic principles of plastic shaping are common for both processes.

LPIM is strongly propagated as a method for prototyping and small series fabrication. In contrast to HPIM with its high costs of tooling requiring mass-production for a return of investment, LPIM can work with simple and inexpensive moulds and is economical even for a small number of parts. The good flowability of the low-viscous feedstocks and the ability to employ fine scaled powders also recommend LPIM for the injection molding of micro dimensional parts (Knitter et al. 2001).

The major drawback of LPIM is the low mechanical strength of the used binders. This can lead to rupture of patterns during the demoulding of the green compact, especially when fine particulars with high aspect ratio must be withdrawn from the cavity. For that reason, LPIM is normally limited to parts with lower complexity. However, this problem can be overcome by customized tooling concepts, like soft tooling with silicone rubber moulds (Bauer and Knitter 2002) or lost moulds (Elsebrock et al. 2004). Silicone rubber is the material preferred for prototyping tasks with LPIM. A silicone mould can be prepared from a model of the final part within a few hours. Due to the compliancy of the material, no further accessories are required for the demoulding of undercuts or details with high aspect ratios. Even structures with high surface roughness, which cannot be demoulded from rigid molds, can be shaped in silicone moulds (see Fig. 4). On the other hand, the compliancy of the material requires an adapted injection process to guarantee dimensional accuracy of the moulded part. This sometimes gives rise to restrictions for

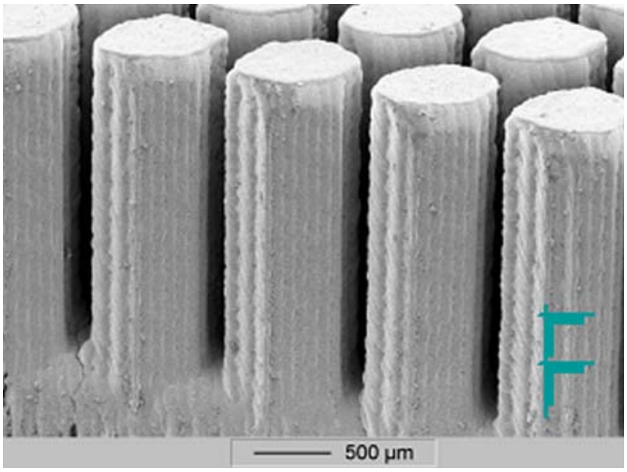

Fig. 4 SEM micrograph of lead zirconate titanate (PZT) columns made by LPIM using silicone rubber moulds. A wax ink printer has prepared primary model

the shaping of complex parts with high accuracy. In addition, silicone has a very high thermal expansion. Thus, temperature control is of vital importance for the work with silicone.

Despite these limitations, LPIM using silicone rubber moulds has proven an efficient method for the fast and cost effective manufacturing of micro parts in small numbers for a large variety of ceramic materials (Bauer et al. 2006).

6 Summary and outlook

Nearly all replication processes and subvariants have proved their suitability for the production of high-quality micro components with different geometries. As mentioned above, these processes complement each other providing a portfolio of replication technologies that ranges from individual prototyping to mass procurement of micro components. For the potential user, it is possible to select the best solution for various problems. This variability of processes is supported by the availability of various mould insert technologies.

The present capabilities of the micro replication processes are summarized in Table 3.

All replication processes presented here have been already proven to be suitable for the production of high-quality plastic micro components of various geometries.

At present, three main trends for the further improvement of micro replication can be detected.

First, there is the demand for ongoing miniaturization of structural details with a clear direction towards the submicron or even nanometer scale. Such dimensions have up to now been realized at aspect ratios of approx. 1 or less only.

Second, as micro replication has already reached an industrially relevant status all possibilities for increasing throughput and reduce costs are of outstanding importance. The main attempts head for the reduction of cycle times, increasing the number of cavities in one moulding tool for injection moulding, or the enlargement of the working area for hot embossing.

Last, with the aim of cutting costs and exploring new perspectives at the same time, the approaches for multi-component micro replication do not only reduce the assembly expenditure for micro systems, but also provide for enhanced joining procedures and entirely new functional units.

Table 3 Key data of the selected replication processes

	LP-PIM	Reaction moulding	Hot embossing	Nanoimprint	Injection moulding
Mode of production	RP and small series	RP and small series	Small and medium series	Small and medium series	medium and large series
Max. aspect ratios	16 (free structure) 15 (channel)	Polymers 20	50	>10 (free and sunken structures)	TIM: 25 PIM: >10
Surface quality	≤0.1 µm		10 – 40 nm		50 nm
Smallest details	25 µm (hole Ø)	Polymers 200 nm metals, ceramics <100 µm	Polymers 200 nm	<20 nm (10 nm hole in PMMA)	polymers: 200 nm metals, ceramics < 60 µm
Typical materials	Ceramics (metals)	Polymers ceramic and metal powders	All thermoplastics	Thermoplastics, reactive polymers	all thermoplastics PIM: metals, ceramics
Temperature conduct	Vario	Iso	Vario	Vario or iso (curing polymers)e	iso or vario
Tool evacuation	Yes	Yes	Yes	High AR only	often
Typical cycle times	2–3 min	Polymers 2–5 min metals, ceramics 20–30 min	≥5 min	up to 200 s	4 s–8 min
Mould insert materials	Si, Al, brass, Ni	Ni, Ni-all., brass, steel, polymers, ceramic, silicon	Ni, Ni-all., brass, steel, Si, polymers	Ni, Ni-all., ceramics, Si, quartz, PDMS	Ni, Ni-alloys, brass, steel

Acknowledgments The authors would like to thank their colleagues for their friendly and always helpful cooperation. Additionally, the authors thank for the financial support by the European Commission within the 4 M-Network of Excellence, the BMBF and the Deutsche Forschungsgemeinschaft DFG (SFB 499).

References

Bauer W, Knitter R (2002) J Mater Sci 37:3127–3140

Bauer W, Knitter R, Müller M, Ritzhaupt-Kleissl H-J (2006) Cfi/Ber. DKG 83 13:65–69

Bender M, Fuchs A, Plachetka U, Kurz H (2006) Status and prospects of UV-nanoimprint technology. J Microelectron Eng 83:827–830

Chou SY, Krauss P, Renstrom P (1995) Imprint of sub-25 nm vias and trenches in polymers. Appl Phys Lett67 (21)

Chou S, Krauss P, Zhang W, Guo L, Zhuang L (1997) Sub-10 nm imprint lithography and applications. J Vacuum Sci Technol 15, November/December, Nr. 6

Guo LJ (2007) Nanoimprint lithography: methods and material requirements. Adv Mater Nr 19:495–513

Elsebrock R, Makovica C, Meuffels P, Waser R (2004) Mater Lett 58:3348–3349

Fairley P (2003) 10 Emerging technologies that will change the World. Technology review, February

Hanemann T, Honnef K, Haußelt J (2007) Process chain development for the rapid prototyping of microstructured polymer, ceramic and metal parts: composite flow behaviour optimization, replication via reaction molding and thermal postprocessing. Intern J of Adv Manuf Techn 33:167–175

Heckele M, Schomburg WK (2004) Review on micro molding of thermoplastic polymers. J Mircomech Microeng 14:R1–R14

Hershey R, Miller M, Jones C, Ganapathi M, Lu X, Doyle G, Lentz D, LaBrake D (2006) PhotonicCrystal patterning for high volume LED manufacturing. proceedings of SPIE, sixth international conference on solid state lighting 6337, September

Knitter R, Bauer W, Göhring D, Haußelt J (2001) J Adv Eng Mater 3:49–54

Mehne C, Heckele M, Steger R, Warkentin D (2006) Hot embossing of large area microfluidic devices with through holes. In: 6th International Conference of the European Society for Precision Engineering and Nanotechnology (EUSPEN), Baden, A, May 28–June 1

Michaeli W, Opfermann D (2006) Micro assembly injection moulding. J Microsyst Technol 12:616–619

Pfleging W, Hanemann T, Torge M, Bernauer W (2003) Rapid fabrication and replication of metal, ceramic, and plastic mould inserts for application in microsystem technologies. J Mech Eng Sci Proc Instn Mech Engrs 217(Part C):53–63

Piotter V, Finnah G, Zeep B, Ruprecht R, Hausselt J (2007) Metal and ceramic micro components made by powder injection molding; materials science forum. Trans Tech Pub 534–536:373–376

Worgull M, Hetu J-F, Kabanemi KK, Heckele M (2006) Modeling and optimization of the hot embossing process for micro- and nanocomponent fabrication. Microsyst Technol 12(10–11):947–952