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Micro structuring of borosilicate glass by high-temperature micro-forming

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Abstract A new process technology is presented which allows the direct micro structuring of various glasses, especially bondable borosilicate glass (e.g. Pyrex®7740), by means of forming at high temperatures with a micro-structured tool. The technology and fabrication equipment are described on the basis of a molded demonstration structure, and possibilities for application and transfer to industrial manufacturing are shown.

1 Introduction

Glass is a material used commonly in micro system technology. Applications range from usage in the optical data transmission, MOEMS, applications in micro-fluid analysis and bioengineering, packaging for housing and as insulating substrate for bonding. In many cases functional structures are applied in array arrangements on the glass wafer thereby following other wafer level processes of micro system technology.

For the manufacturing of microstructures in glass materials various serial (laser, water jet) and parallel (etching, photo structuring) erosive as well as cutting processes (micro grinding, -milling, -drilling) were examined and structure sizes between a few millimetres down to 10 μm were achieved. However, surface quality and geometry variety, particularly with the smaller structures, were not always acceptable and cracks often arose through mechanical and thermal processing. Besides this the variety of glasses that can be processed with erosive processes is limited (Westkämper et al. 1996; Gessenharter et al. 2004; Sinhoff 1996; Hülsenberg 1997; Ostendorf et al. 1999). But particularly with regard to subsequent processes it is of largest importance to structure standard glasses for micro system technology (Pyrex, Borofloat). For this reason the attempt appears promising to shape the glass in a ductile condition.

Beneath the numerous possibilities to structure glass at the surface, hot embossing is one of the economically most favourable processes, in particular for the manufacturing of higher quantities with high surface quality (Burkhardt et al. 2002; Manns 2004). Against this background for several years research and development at the Fraunhofer IWU have been accomplished for the application of forming micro-structured components. An emphasis of this work is the development of embossing technologies along with suitable machinery and equipment. With high-temperature micro-forming a technology was developed, which makes the molding of metals and glasses feasible, far beyond the possibilities of hot embossing.

2 State of the art in embossing

For molding microstructures into thermoplastics apart from injection molding, particularly hot embossing was established. For this process machinery and equipment of different manufacturers is available currently for industrial application. During hot embossing a thermoplastic is warmed up to temperatures above the softening point and formed afterwards between a micro-structured tool under high forces. Subsequently the tool system must be cooled down below the softening temperature, so that a demolding of the microstructure from the forming tool becomes possible. In comparison to injection molding fewer tensions are brought into the plastic thereby, since it must flow only from the unstructured substrate into the cavities of the tool. For this reason also the forming temperature of the thermoplastic can be kept lower, which again positively affects shrinking as well as the friction during demolding (Heckele and Schomburg 2004).

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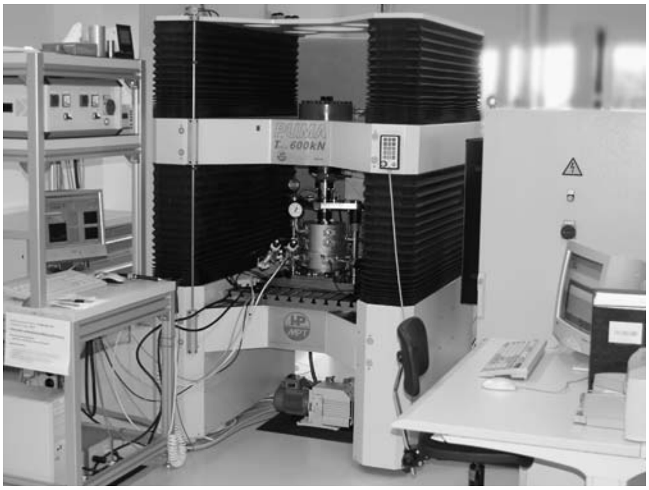


Fig. 1 Picture of the process chamber integrated in the precision press equipment

For the mass production of optical lenses from inorganic glasses precision glass pressing is used. A heated glass body is placed in a press with tools kept at a moderate temperature and formed. The tool temperature is lower thereby than the glass temperature, so that the glass is cooled down during the shaping (Weck et al. 2002). For this reason, the process is only conditionally suitable for forming and micro-structuring of relatively thick glass parts and cannot be used for the structuring of thin wafer-like flat glass. If structure widths within the lower micron-range are aimed at, embossing must take place isothermally or approximately isothermally. For this the temperature plays a crucial role, because the viscosity of the particular glass is determined by it. At the same time, sticking of the glass to the forming tool must be prevented, in order to ensure a safe demolding.

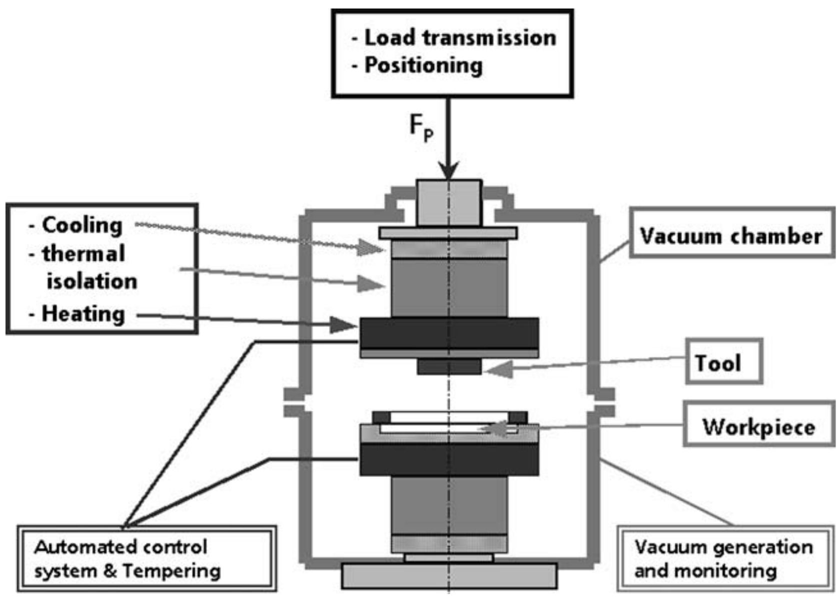
In contrast to glass pressing, it is necessary during micro-structuring of small or thin components to heat the tool system up to the material temperature necessary for molding and to utilize a precise time–temperature–force-cycle during heating, molding and demolding. The technology is characterized by an extremely precise regime of the process parameters temperature and embossing force, whereby depending upon type of glass typically temperatures between 400 and 1,000°C are necessary. For process-safe molding and following demolding from the form it must be worked in a very close viscosity window between softening temperature and upper cooling temperature. It could not finally be clarified yet whether and to what extent further parameters apart from the viscosity have influence on the occurrence of sticking effects between the forming tool and the glass.

3 Experimental equipment

A process chamber, which was integrated into a precision press equipment, forms the core of the test rig for high-temperature micro-forming at the Fraunhofer IWU. It forms the mount for the tool system, medium supply, as well as the sensors for process control. Positioning and load transmission are realized by the precision press equipment. For accurate molding of the microstructure on a flat substrate, exact controlling of the path of the tool is necessary. To satisfy these requirements, the press is equipped with four spindles and four synchronized servo-drives (Fig. 1).

With this system, precise, isothermal tempering can be ensured at forming temperatures up to 1,000°C by suitable control loops in a tight process window. The temperature is separately adjustable for upper and lower die with a deviation of 1 K. The present structure of the tool system allows heating and cooling rates of 25 K/min. Significantly faster temperature changes do not seem meaningful due to the absolutely necessary

Fig. 2 Schematics showing the test equipment in principle



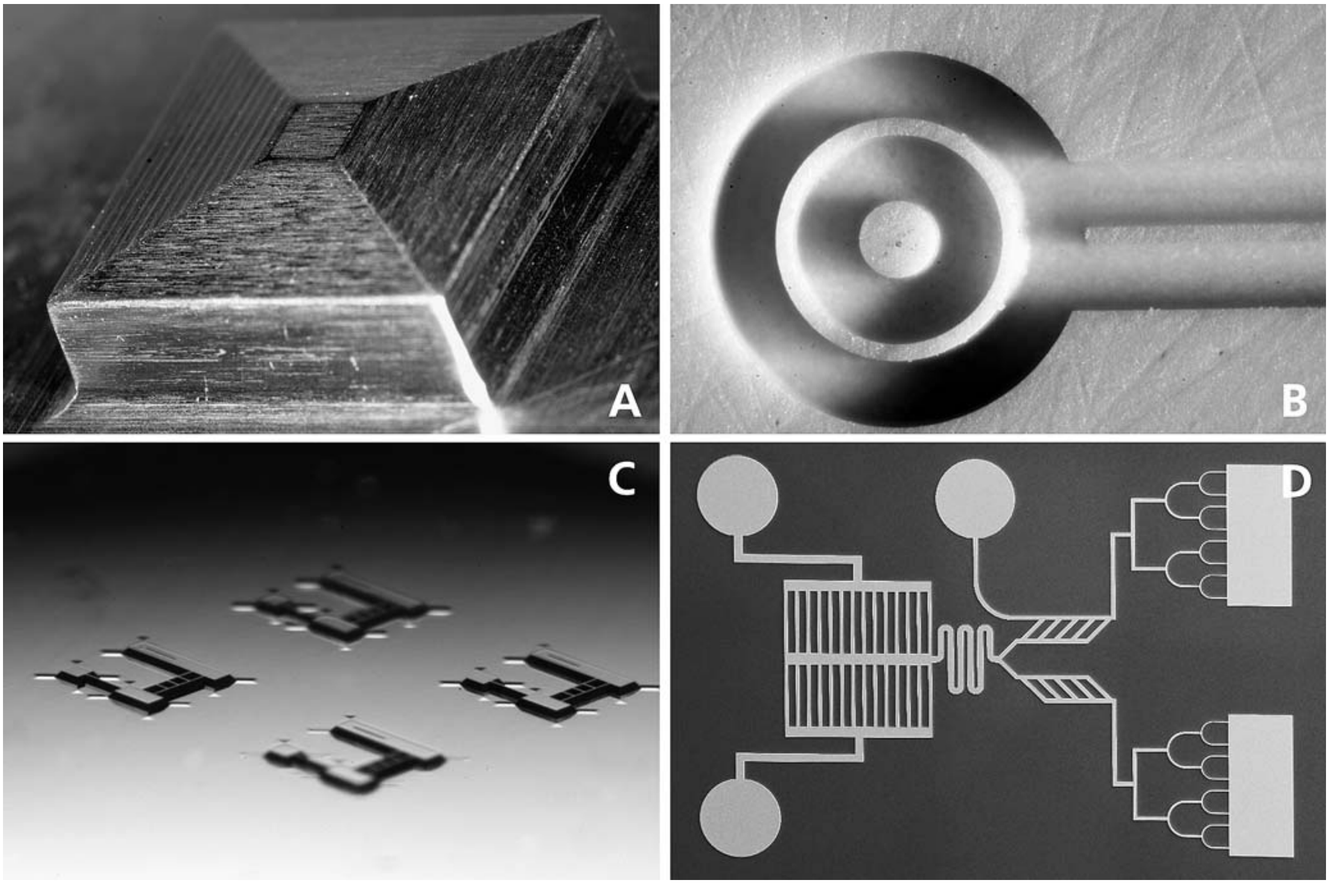


Fig. 3 Different tools for high-temperature micro-forming. **a** Grinded pyramid shaped molybdenum tool, **b** test structure in the ceramic 'Shapal-M soft', **c** wet-etched silicon tool, **d** SEM-picture of dry-etched silicon tool

isothermal tempering. However in combination with a preheating station process times of a few minutes could be realized.

At the same time, embossing forces up to 50 kN on a pressing area of 50 mm in diameter can be applied with the test equipment. The control system permits force- or path-regulated positioning of the tool with a resolution of force of 17-Bit where the accuracy is dependent on the load cell used. To avoid oxidation as well as to assure a complete form filling of the microstructures, it is possible to work either within the fine vacuum range or under an inert gas atmosphere (Fig. 2).

4 Forming dies

The manufacturing of micro-structured components by means of forming processes makes high demands on the forming tools. The tools used for the high-temperature micro-forming have to fulfil special requirements under several criteria. On the one hand the tools must be heated up to forming temperature for micro-structuring, contrary to conventional warm forming processes, due to the small thermal capacity of the components to be molded. This justifies high requirements to the heat resistance as well as the thermo-chemical stability of the deployed materials. The suitable methods for micro-structuring of the tool material must be present. The tool structure is to be distinguished by small surface roughness and high structure accuracies at the same time. At present few suitable materials and process technologies exist, which fully meet all these requirements. In particular the production of precise microstructures with very high surface quality in high-strength, high-temperature robust materials causes large problems at present.

Experiences at the Fraunhofer IWU have shown the suitability of different high temperature-firm metals (nickel-base alloys, molybdenum alloys), ceramic tool materials (silicon carbide, aluminium nitride) as well as silicon for the micro-structuring of inorganic glasses.

The metallic high-temperature alloys are characterized by a good thermal diffusivity and toughness. They can be structured by means of high precision chipping, which is also a field of research at Fraunhofer IWU, or by eroding. However there still is a need for optimization in order to realize very small structures below 50 μm. So far, surface qualities for optical applications were not reached. Nevertheless, for applications in electronic packaging and micro fluidics these processes offer an optimal solution.

Due to its very good micro-structuring possibility and high hardness the use of structured silicon for micro molding tools appears promising. A further advantage of micro-structured silicon tools is their excellent surface quality and small surface roughness. In order to avoid adhering of the tool to the substrate during demolding, however, coating of the tool is inevitable.

On the basis of these different characteristics of the tool materials, a molybdenum tool (TZM), grinded in a pyramid form, was used for first forming attempts into glass wafers of Pyrex® 7740. Subsequent micro-structuring experiments were done with a wet-etched silicon tool with a titanium nitride coating. Thereby the smallest structure size of the silicon tool was laterally 10 µm at a structure height of 50 µm (Fig. 3).

5 Results

Earlier research results by this research group on structuring of fluoride glasses had shown the possibility of micro-structuring the material glass by molding. Through molding experiments with a steel tool it became clear that the surface roughness at the flanks of the tool as well as finest burr can lead to substantial problems during demolding (Burkhardt et al. 2002). However, using dry etched silicon tools with sufficient surface quality and a suitable coating, complex structures with the quality determined by the tool can also be molded (Schubert and Burkhardt 2003) (Fig. 4).

One of the goals of this study was to prove the structuring possibility of bondable borosilicate glass. This became technologically attainable by the modification of the test equipment and the thereby higher forming temperatures and better control of the process.

For the determination of a suitable process window for high-temperature micro-forming of Pyrex® 7740 first experiments with the pyramid-shaped molybdenum tool were accomplished. The deformation dependent on the viscosity of the glass could be examined by a systematic rise in temperature from 700 to 760°C with otherwise constant process parameters. The viscosity of the glass is thereby between 10E9.5 and 10E8.5 dPa·s, which is be-

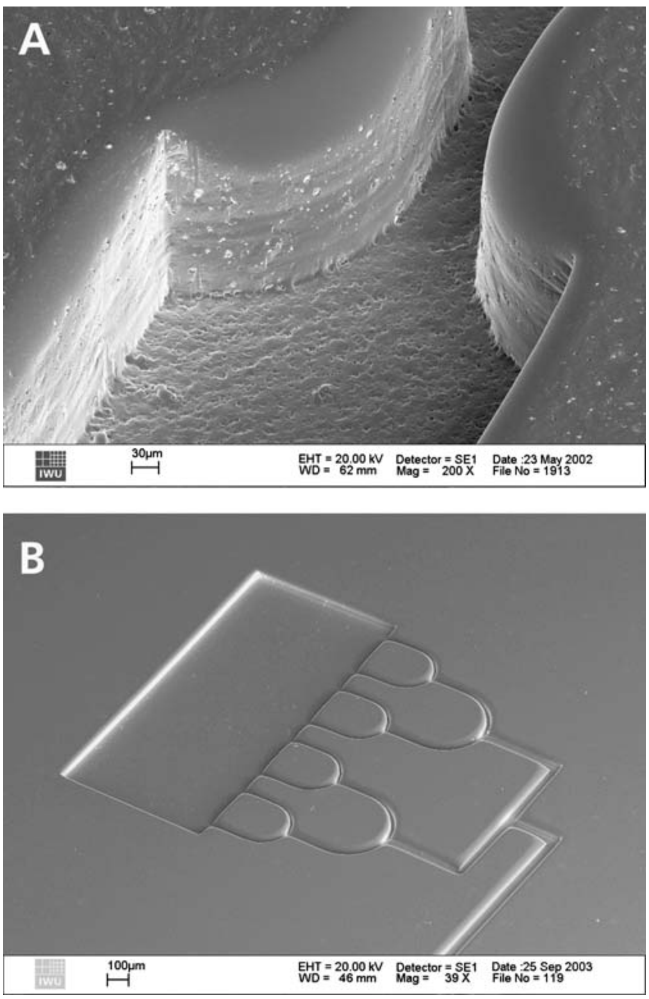


Fig. 4 Micro structures in fluoride glass, molded with a steel tool (**a**) and a dry-etched silicon tool (**b**)

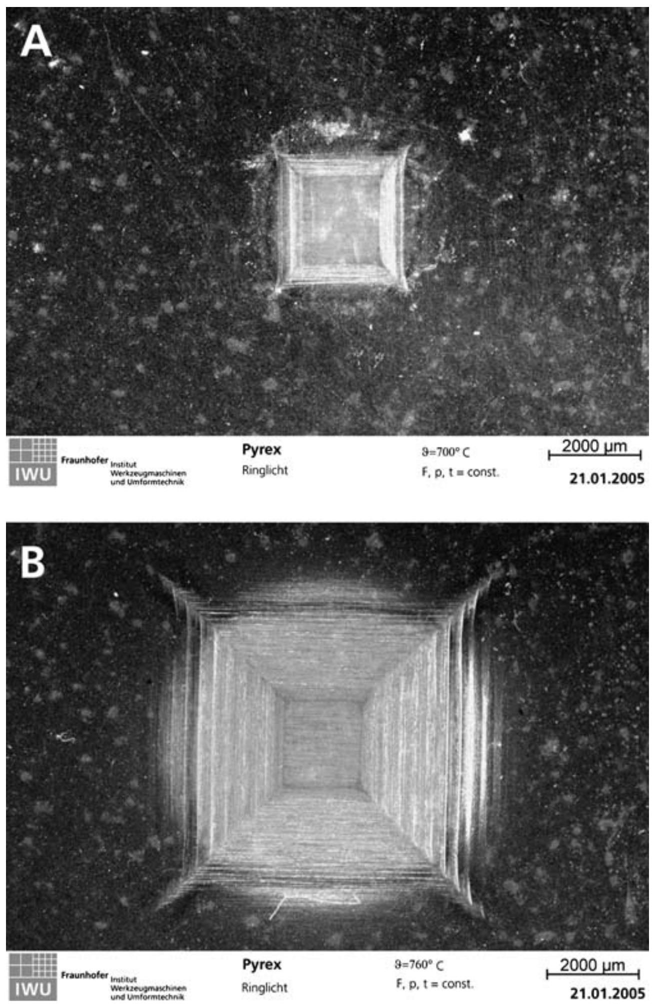


Fig. 5 Comparison of molding results at different viscosities. **a** 10E9.5 dPas, **b** 10E8.5 dPas

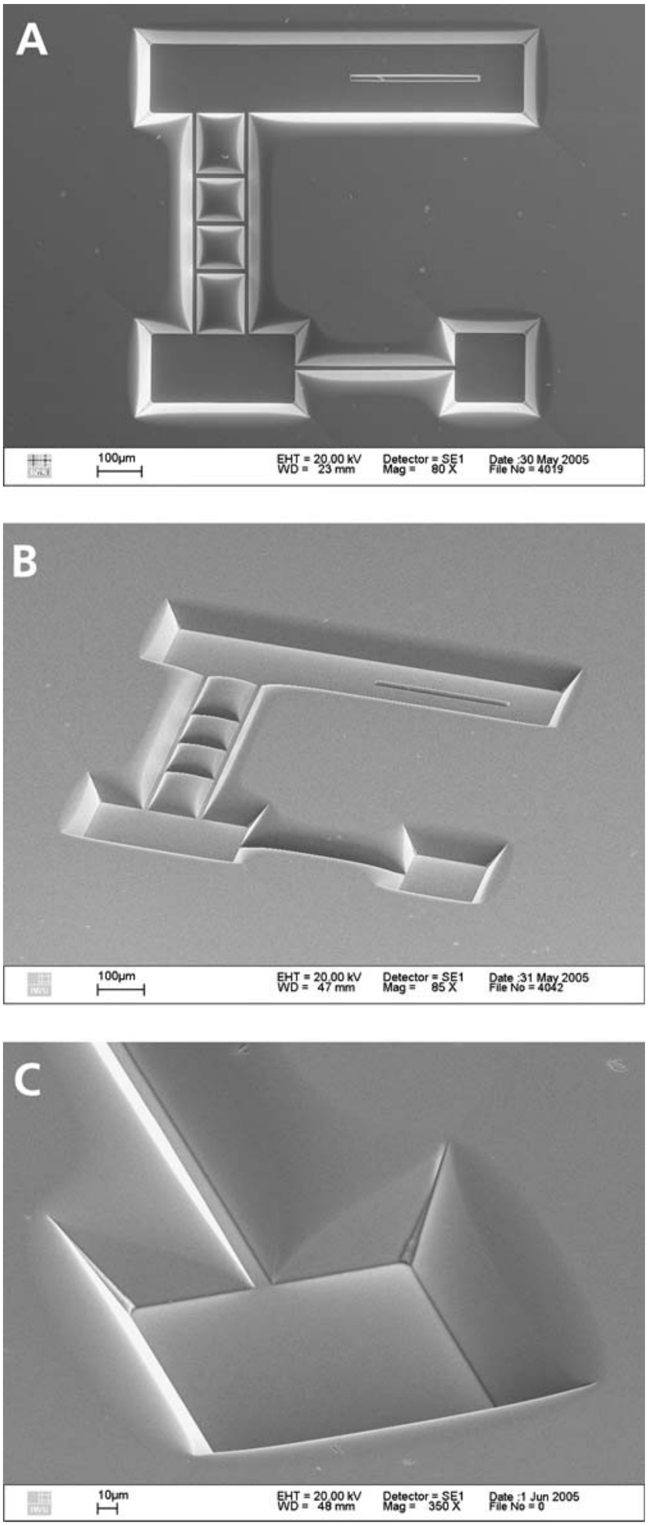


Fig. 6 SEM photographs of the molded micro structure in borosilicate glass. The details demonstrate the high potential of the technology

low the softening point of the glass. Only in this way, the molded structure can be prevented from being destroyed during or after demolding.

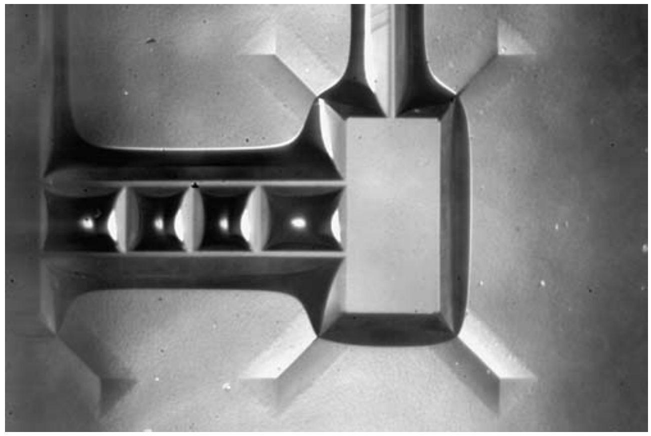


Fig. 7 Replicated residues of the compensation structures from wet-etching

At the margin of the structure almost no bulge arose. The sinking viscosity with increasing molding temperature leads to a subsidence of the necessary surface pressure during forming, which expresses itself in the molding result by a rising displaced volume, because the parameters embossing force, molding time and process gas pressure were kept constant during the test series. The formation of the surface microstructure in the bottom, which reproduces the roughness of the grinded tool detail faithfully, shows the structuring possibilities of the process (Fig. 5).

Following these preliminary tests, experiments using a wet-etched silicon tool for structuring were accomplished. The molding results show an accurate replication of the microstructure in the bottom of the embossed structure and thus demonstrate the high potential of the technology for production of precisely structured micro components with high surface quality. Both, formation of the mold and quality of the surface, as well as the workpiece edges correspond to the requirements of functional structures of the micro system technology in principle. The blurred passage from the structure to the ground level of the wafer still requires further process optimization. With optimal molding parameters, isogonal replication should be possible (Fig. 6).

No impediment to molding of significantly smaller structures could be determined in principle. This is revealed by the exact replication of residues of the compensation structures which were used on the mask of the wet-etched silicon tool (Fig. 7).

During repeatability experiments, problems with adhesion of the tool to the glass arose at corners and edges of the microstructure. Due to this phenomena breakouts of the tool structure could be determined. This is attributed to an insufficient covering of the structure with coating material in the region of atomically sharp edges. Process-related, the coating is about eight times thinner at such edges in comparison to the even surface. An improved coating of the tool should eliminate these problems (Fig. 8).

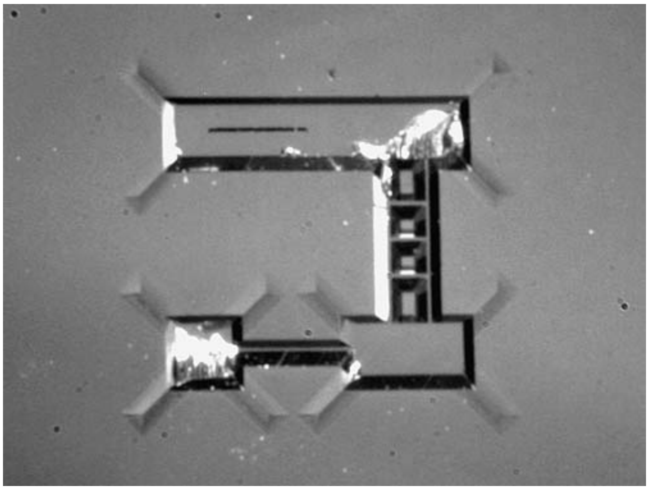


Fig. 8 Micro structure on the forming tool with breakouts after several experiments

6 Conclusions and perspectives

With the technology of high-temperature micro-forming it is possible to mold functional structures of micro system technology directly into bondable borosilicate glass. After improving the equipment technology of hot embossing with respect to achievable forming temperatures, isothermal tempering and accurate controlling of the load transmission, the possibility to micro-structure glass wafers of Pyrex®7740 could be proven within a suitable process window.

Accompanying the process development at the Fraunhofer IWU, a device for high-temperature micro-forming in a production environment was developed together with partner companies. This hot embossing equipment distributed under the label "MicroShape" comprises a complete handling system and is therefore suitable for automated production (Roth and Rau 2005).

Concerning form filling of the structures further optimization of the process parameters is necessary. The sharpness of the edges of the molded structures permits the conclusion that highest accuracies can be achieved, comparable to optical quality. For this purpose, however, the molding tools also must achieve optical quality regarding surface roughness. Moreover, improvement of the coating is necessary, in order to minimize wear of the tools. The experiments nevertheless show the high potential of the technology.

References

Burkhardt T, Ebeling P, Schubert A, Semar W (2002) Micro structuring of glass with hot embossing. In: Proceedings of the euspen 3rd. ISBN 3-926832-30-4 2:363–366

Gessenharter A, Autschbach L, Grimme D, Riemer O, Brinksmeier E (2004) Ultraprecision machining and polishing of structured molds. Ann WGP Prod Eng 11(1):11–14

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

Hülsenberg D (1997) Mikrostrukturierung von Glas. Spektrum der Wissenschaft 12:112–118

Manns P (2004) Blankpressen von innovativen optischen Komponenten aus anorganischen Gläsern. Fraunhofer IWM Jahresbericht 2003

Ostendorf A, Rinke M, Hesener H (1999) Produktionsverfahren für die flexible Mikrostrukturierung passiver optischer Bauteile. FZKA PFT 198

Roth , Rau AG (2005) MicroShape Hot Embossing Equipment. http://www.roth-rau.de/php/process_systems.php?mod = detail&&nummer = PR7

Schubert A, Burkhardt T (2003) Abformtechnologien zur Mikrostrukturierung von Glas. Chemnitzer Fachtagung Mikromechanik Mikroelektronik 6:45–50

Sinhoff VR (1996) Feinbearbeitung optischer Gläser in der Kleinserie. Diss.: Rheinisch-Westfälische Technische Hochschule, Aachen

Weck M, Wenzel C, Winterschladen M (2002) Process chains for replication technologies of complex optic components. In: Proceedings of the euspen 2nd international conference, pp 349–352

Westkämper E, Hoffmeister H-W, Gäbler J (1996) Spanende Mikrofertigung. Flexibilität durch Schleifen, Bohren und Fräsen. F + M 104/7-8: 525-526,528,530