MICROFABRICATION OF A MOLD INSERT MADE OF HARDENED STEEL AND FIRST MOLDING RESULTS

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Introduction

For the production of plastic, metallic and ceramic microparts, microstructured mold inserts are used in replication techniques, such as injection molding and hot embossing. Replication was developed as part of the LIGA process, and considerable experience has been gained by the Karlsruhe Research Center in the fabrication of molded microstructures /1/. The factor limiting the number of replications is the mold insert material, currently electroplated nickel and nickel alloys (made by LIGA), and brass, copper, aluminum and other non-ferrous materials (made by mechanical micromachining using diamond tools). As known from the conventional mass production of macroscopic structures, masters made of steel are desired for microstructures as well, in order to ensure a long mold insert lifetime.

Steel can be cut by using micro end-mills made of hard metal (tungsten carbide) with a minimum cutter diameter of less than 50 µm available /2/. The burrs occurring during the cutting process have to be removed to ensure a secure molding process, namely, an easy mold release. It was shown that the burr removal can be done by electrochemical polishing /3/.

So far, electrochemical polishing has been performed on a structured area of some 100 mm^2, due to the limited currents of the power supplies available /4/. The structured area of the mold inserts usually used at the Karlsruhe Research Center, and as required for many technical applications, has a maximum size of 26 x 66 mm^2. In this work, we present a microstructured mold insert of that size, the burr removal by electrochemical polishing, and the replication of the hardened mold insert.

Results

Micromachining

The microstructuring work of mold insert fabrication is done by mechanical micromachining, using hard metal tools for cutting of trenches with approx. 100 µm minimum width. The martensite steel 1.2709 (X 3 NiCoMo18 9 5) is chosen as the workpiece material. The material is structured in the unhardened state and hardened after structuring by maraging at 490°C for 3 to 5 hours, with an overall shrinkage of 0.09%. One of the main advantages of the steel 1.2709 besides easy structuring is the low warp after hardening.

For the burr removal tests and the molding experiments, mold inserts were prepared with a trench structure in a 300 µm and 500 µm pitch. The actual trench widths were approx. 220 µm and 420 µm, respectively, and the depth ranged from 200 µm to 330 µm. Burrs occurred at the upper edges of the freestanding wall structures between the trenches, with a height of approx. 15 µm (Figures 1 and 2).

Electrochemical Polishing

In the experimental setup a 1.5 liter thermostated etching vessel, an electrically insulating housing for the mold insert with a window for the structured 26 x 66 mm^2 area and a metallic cathode plate with 78 x 70 x 3 mm^3 in outer dimension were used. The distance between the anode and the cathode was 40 mm. For etching, a stirred standard solution /5/ of 70%(vol.) concentrated phosphoric acid, 10%(vol.) of concentrated sulfuric acid and 20%(vol.) water was used at an etching temperature of 40°C.

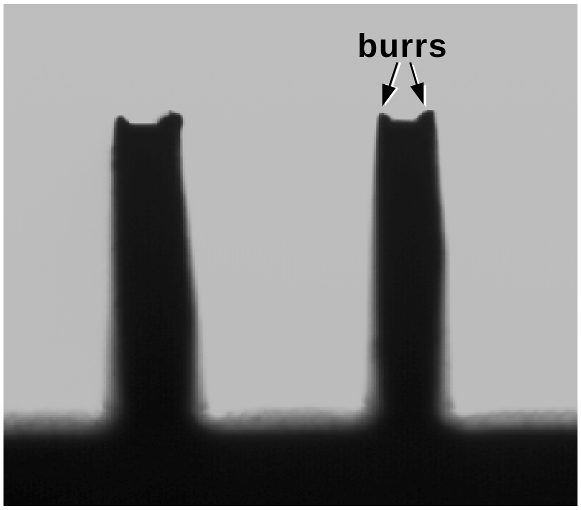

Figure 1: **100 µm**
Light-microscopic side view of trenches (light) and walls (dark) with burrs on top of the walls.

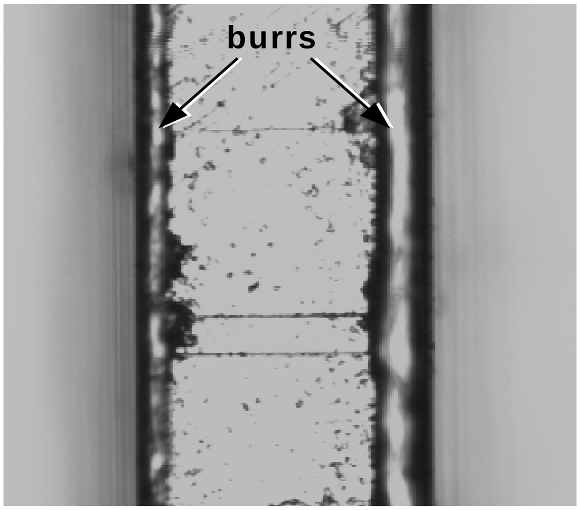

Figure 2: **25 µm**
Light-microscopic top view of burrs at the upper edges of a wall structure.

The power supply used was a “Knuerr Heinzinger Type PTN 65 - 60 2P” with 65 Volts maximum voltage and 60 Amps maximum current. The voltage and current were varied from 5 Volts / 6 Amps to 16.7 Volts / 35 Amps. Good etching results were achieved with duty cycles of 10 seconds etching time and 10 seconds current-free time. For the given structures, the burrs could be removed completely after 4 to 6 high current cycles. After electropolishing of the surface, grain boundaries were clearly visible.

As to be expected, the material removal was not uniform for all height levels of the microstructures. In particular we observed that for high currents most material was removed from the burrs and the upper surface of the wall structures, whereas at the bottom of the trenches almost no etching was observed. For low currents, a planarization of the complete surface (both wall top and trench bottom) took place. By combination of low and high current cycles (e.g. 4 x 10 seconds 35 Amps and 6 x 10 seconds 6 Amps) we achieved burr removal and overall planarization of the surface with a structure height loss of 5 to 9 µm (Figures 3 and 4).

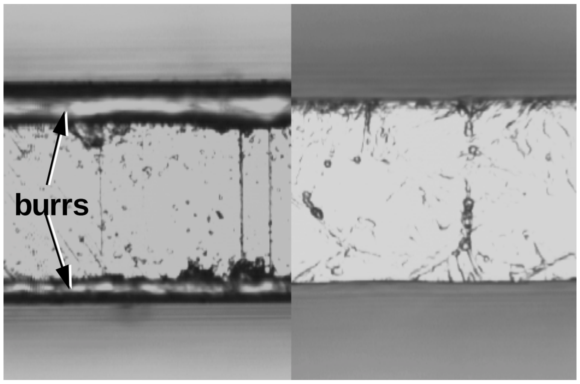

Figure 3: **25 µm**
Light-microscopic top view of a wall structure before (left) and after (right) electrochemical polishing. The burrs were completely removed. The width of the wall is reduced from 92 µm to 76 µm. The lateral material removal of 8 µm is of the same order as the reduction of the structure height.

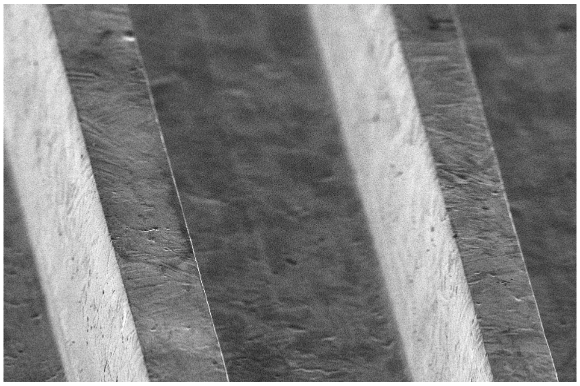

Figure 4: **100 µm**
SEM detail view of an electrochemically polished mold insert. Please note that there is no burr visible and that all surfaces (dark bottom, light sidewalls, gray top) show a similar smoothness. The radius of curvature of the upper wall edges is estimated to be less than 2 µm.

Hardening

The deburred mold insert was hardened to a Rockwell hardness of 55 to 57 HRC by maraging at 490°C for 4 hours. Vacuum was applied to prevent any oxidation.

Molding Tests by Using Hot Embossing

Hot embossing is starting to be a production technology for sophisticated plastic components with delicate microstructures, such as microspectrometers or microvalve housings. Due to the versatility of the hot embossing machines, this technique allows a quick exchange of the microstructured mold insert. The experimental setup and molding parameters can be varied easily, which is important for the valuation of the molding tool quality during the experimental phase as well as for an inexpensive small-scale production of microparts.

The molding experiments were run on a hot embossing machine type WUM 1, a prototype built by the Karlsruhe Research Center, which is the base for the commercially available HEX02 machine from Jenoptik Mikrotechnik (Jena, Germany).

Previously used mold inserts cut into brass very often showed a significant burring. The burrs are forming undercuts which increase the demolding force when separating the microstructured polymer part from the mold insert. Because of the low mechanical stability of the burrs, a repeated replication process leads to a progressive deformation of the burrs or even to a complete tear-off of these burrs and a reduction of the undercuts. Thus, a multiple repetition of this hot embossing step can be used as a cleaning procedure. Unfortunately, this is no exactly defined procedure and damaging of the structures is also possible. In contrast to this, working with deburred mold inserts from steel is free from this inconvenience. From the first replication on, the demolding forces which are measured to be inferior to those known for brass-made mold inserts indicate that the microstructure surface of the steel mold inserts is smooth and that there is no need of a cleaning procedure due to the lack of burrs. The polymer used for the first tests was PMMA. The quality of the molded microstructures is good and reproduces the surface quality of the mold insert (Figures 5 and 6), so other thermoplastic polymers used in hot embossing will also be applicable. The advantage of using steel is the greater temperature range which can be covered in the hot embossing technology, resulting in an extended material choice from the high-temperature polymers, such as polyetheretherketone (PEEK).

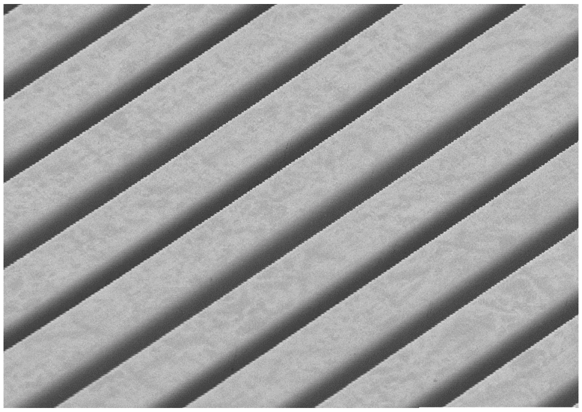

Figure 5: **200 µm**

SEM of a PMMA structure, replicated from an electrochemically polished mold insert made of hardened steel. The trenches of the mold insert were transformed into broad walls (light), whereas the walls of the mold insert appear as narrow trenches (dark).

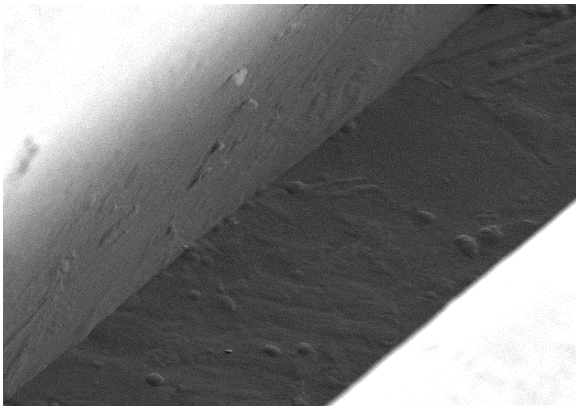

Figure 6: **20 µm**

SEM detail view of a trench wall showing the surface smoothness of a replicated PMMA structure. The trench bottom appears dark (middle), the sidewall gray (left). The light areas at the upper left and lower right are the top of the walls (out of focus).

Discussion and Outlook

Steel mold inserts have been tested successfully for the replication of microstructures by hot embossing. For the first time, burr-free mechanically microstructured mold inserts made of hardenable steel are now available for microparts production. The material properties will ensure a long lifetime of the mold insert compared to the brass and nickel mold inserts available so far. Even abrasive filled polymers will be accessible for molding.

Further molding experiments will be performed using injection molding. Injection molding of plastic microparts using microstructured mold inserts has been performed at the Karlsruhe Research Center for more than ten years. The mold inserts were made mechanically by cutting into brass and aluminum alloys or by replication of nickel structures from a master structure by means of electroforming. All these mold materials restricted the economic use of the mold inserts to unfilled plastics. For PMMA (polymethylmethacrylate), PSU (polysulfone), PA (polyamide), PE (polyethylene), POM (polyoxymethylene) and PEEK (polyetheretherketone) small-scale production processes are available. Without any chemical corrosion a mold insert lifetime of more than 10,000 cycles can be achieved /6/. The lifetime is reduced to less than 5,000 cycles when using filled plastics because of tool wear. The newly available microstructured mold inserts made of hardenable steel are the key to a higher wear resistance, resulting in cost reduction for molding of particle-filled plastics (POM, PA, liquid crystal polymers). Due to their hardness and better wear resistance, the steel mold inserts are expected to be well fit to the metal and ceramic injection molding processes and will be tested in the replication using metal or ceramic powders mixed with polymer.

Acknowledgments

Although the structures being “micro”, the contributions to this paper have been “macro”. We would like to thank the staff of the Mechanical Microengineering Labs, namely, D. Scherhaufer for the microtool fabrication, F. Messerschmidt for the mold insert preparation, L. Eichhorn for the steel hardening experiments. Special thanks go to H. Jackisch for building the electrochemical polishing facility and P. Abaffy for the SEM investigations.

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