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Fabrication of microstructures with high aspect ratios and great structural heights by synchrotron radiation lithography, galvanoforming, and plastic moulding (LIGA process)

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Abstract. Under the LIGA process for fabricating microstructures having high aspect ratios and great structural heights, synchrotron radiation lithography produces a primary template which is filled with a metal by electrodeposition. The metallic structure so produced is used as a mould insert for fabricating secondary plastic templates which, in mass production, replace the primary template. This is a report about the status of work performed by the Karlsruhe Nuclear Research Center with the cooperation of Siemens AG and the Fraunhofer Institute for Solid State Technology: By irradiation and development of polymethyl methacrylate (PMMA) plates, primary templates were produced which, for structural heights of several hundred μm, exhibit deviations in critical dimensions of less then some 0.1 μm. The best results were obtained with an X-ray mask consisting of a 25 μm thick beryllium foil and 18 μm thick absorber structures consisting of copper and gold. Practically perfect metallic replicas were obtained by electrodeposition of nickel in the PMMA microstructures and even details in structure of less than 0.1 μm size were reproduced. Moulding was done with a methacrylate-based casting resin with an internal mould release agent. By electrodeposition of nickel in the secondary templates, secondary metal structures were produced which practically do not differ from the primary structures. The LIGA process can be expected to be superior to other methods for fabricating microstructures with high aspect ratios if, in series production of microstructures with complex shapes, stringent requirements are imposed on the resolution, the aspect ratio, the structural height, and the parallelism of the structural walls.

Keywords. Synchrotron radiation lithography, galvanoforming, plastic moulding, X-ray masks, aspect ratio, equipment, applications, microstructures, complex shapes, microconnectors.

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Erwin Willy Becker was born in Magdeburg, Germany, in 1920. He received a diploma and a Doctor's degree in physical chemistry from the University of Munich. He is full professor at the University of Karlsruhe and head of the Institut für Kernverfahrenstechnik at the Kernforschungszentrum Karlsruhe, where the LIGA process is being developed. He holds the DECHEMA Prize and the Heinrich Hertz Prize for the development of the separation nozzle process for uranium enrichment.

Wolfgang Ehrfeld was born in Karlsruhe, Germany, in 1938. He received a diploma in physics and a Doctor's degree in engineering from the University of Karlsruhe and is habilitated as a university lecturer. He worked in the fields of rarefied gas dynamics and uranium isotope separation and, since 1978, he is engaged in microfabrication. He is responsible for the development of the LIGA process at the Kernforschungszentrum Karlsruhe. He holds the Technology Transfer Prize of the Bundesminister für Forschung und Technologie.

Peter Hagmann was born in Mengen, Germany, in 1951. He studied physics at the University of Karlsruhe and received a diploma in physics about measurements of the flux-flow resistance of type II superconductors with strong coupling in 1976. In 1982 he received a Doctor's degree and is now engaged in the development of the LIGA process. He is responsible for the development of the micromoulding process.

Asim Maner studied mechanical engineering and received a diploma and a Dr.-Ing. degree from the University of Karlsruhe in 1977 and 1983, respectively. He joined the Kernforschungszentrum Karlsruhe in 1977. He is responsible for the application and R&D on galvanoforming techniques for the fabrication of metallic microstructures.

Dietrich Münchmeyer was born in Karlsruhe, Germany, in 1954. He has a diploma in physics from the University of Karlsruhe. He worked on nuclear physics and the medical application of negative pions. Since 1979 he is engaged in microfabrication. In 1983 he received the Dr.-Ing. degree from Karlsruhe University, the subject of his thesis being the accuracy potential of synchrotron radiation lithography. He is responsible for synchrotron radiation lithography and X-ray mask technology in the LIGA process at the Kernforschungszentrum Karlsruhe.

1. Introduction

In recent years, in the Nuclear Research Center of Karlsruhe, a process has been developed for the mass production of microstructures with high aspect ratio and great structural height. It is based on combining synchrotron radiation lithography, galvanoforming, and plastic moulding (LIGA process) (Fig. 1). The purpose of synchrotron radiation lithography is to generate a primary plastic template which is filled with a metal by electrodeposition. The metal structure so produced is used as a mould insert for the fabrication of secondary plastic templates which, in large-scale production, take the place of the primary plastic templates.

Investigations carried out in collaboration with Siemens AG and the Fraunhofer Institute for Solid State Technology were originally aimed at producing extremely small separation nozzle systems for uranium enrichment making use of the first two process steps [1]. Microstructures have been obtained showing high spatial resolution, high aspect ratios, great structural heights, and perfectly parallel edges. To date, the combination of these outstanding features has not been described elsewhere. Given these results and in view of the recently developed third process step which allows plastic moulding in mass production being independent of a synchrotron radiation source, there is a growing interest in the LIGA process focusing on the production of other kinds of microstructures as well. New fields of applications

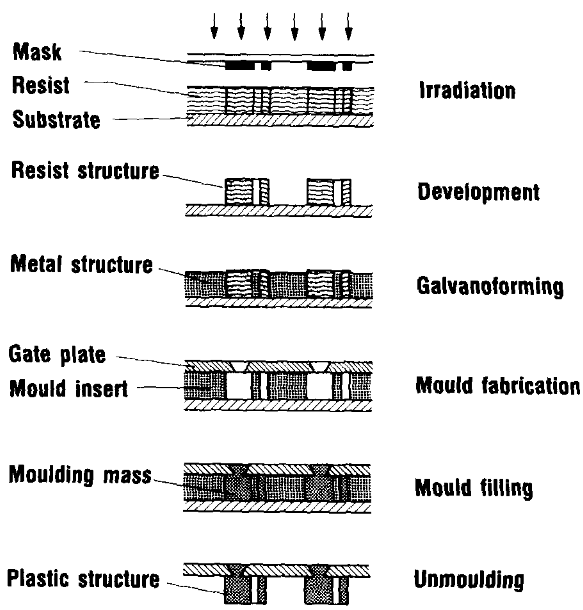


Fig. 1. Process steps of the LIGA process: A primary plastic template is produced by synchrotron radiation lithography which is then filled with a metal by electrodeposition. The metal structure so produced is used as a mould insert for the fabrication of secondary plastic templates which, in mass production, take the place of the primary plastic template.

are opened in microelectronics, integrated optics, process technology, and medical technology.

This is a report on the state of the art achieved for the individual steps of the LIGA process which, as a matter of fact, are also applicable separately or in other combinations.

2. Production of primary microstructures using synchrotron radiation lithography

2.1. *Special requirements imposed on the lithographic process and theoretically obtainable accuracy*

At present, synchrotron radiation lithography is being developed primarily for the large-scale production of microelectronic circuits with characteristic dimensions in the submicron range [2]. For this application, resist layers of a few micrometers thickness are sufficient. They are produced in an adequate quality by spinning a liquid resist on the substrate and subsequent baking for solvent removal. As the thickness of the resist is small, relatively soft synchrotron radiation is required (characteristic wavelength $\lambda_c \approx 2$ nm), as is for example provided by the electron storage ring BESSY in Berlin. The prospective application of X-ray lithography within the scope of the LIGA process is concerned with the production of plastic templates, which, on the basis of characteristic dimensions in the micrometer range, have a structural height of several hundred micrometers. The corresponding process step is therefore sometimes called X-ray depth lithography [3, 4]. When using synchrotron radiation for the LIGA process, advantage can be taken of its high intensity and in particular of its excellent parallelism.

In earlier experiments on the LIGA process [1] which were performed at the electron synchrotron of the Bonn University using a characteristic wavelength of $\lambda_c = 0.7$ nm, a structural height of 400 μm was obtained by four times irradiating and developing of a polymethyl methacrylate (PMMA) sheet. The resolving power of synchrotron radiation lithography was investigated on the basis of computer calculations [3, 4]. The results demonstrate that the effect of diffraction, which is growing as the wavelength increases, and the effect of the secondary electrons in PMMA, which is growing as the wavelength decreases, lead to a minimum of structural deviations due to these effects, when the characteristic wavelength ranges between 0.2 and 0.3 nm. At this wavelength, using PMMA, the proposed structural heights on the order of 500 μm are obtained by a single irradiation and development step. The variations in critical dimensions which are likely to occur between the ends of a 500 μm high structure due to diffraction and secondary electrons are estimated at approximately 0.2 μm.

With respect to fully utilizing the accuracy potential, the local divergency of the synchrotron radiation at the sample must not exceed some 0.1 mrad. At

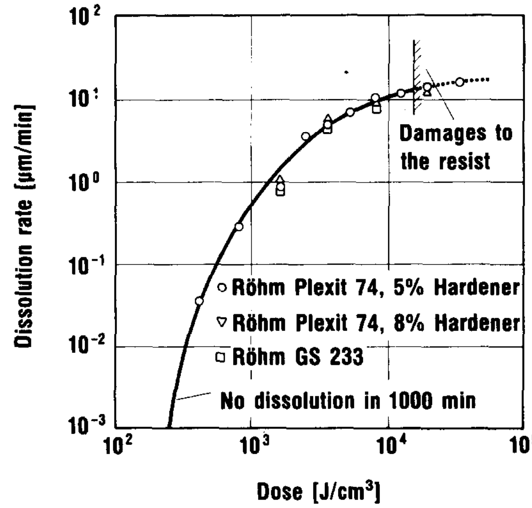


Fig. 2. Dose dependency of the dissolution rate of extremely high molecular weight or cross-linked PMMA in a multicomponent developer [3, 4].

the electron synchrotron of the Bonn University, operated at 2.0 GeV electron energy, the radiation divergency at the point of origin lies between some 0.1 and slightly below 1 mrad in both directions. An appropriate irradiation distance always results in a small local divergency in horizontal direction. In vertical direction, however, the sample is usually scanned periodically through the irradiated plane so that the full impact of the divergency of the source is effective. If, however, the electron beam is scanned through the bending magnet in a way that the sample is fully illuminated by the synchrotron radiation, the actual divergency in this direction also decreases in inverse ratio to the distance. At a high power density it is necessary to scan the electron beam quite rapidly to allow a sufficient dissipation of the generated heat.

For fully utilizing the accuracy potential of synchrotron radiation lithography it is furthermore essential to use a resist and developer system with a ratio of the dissolution rates in the exposed and unexposed areas of approximately 1000. An adequate developer is for example a mixture of a glycolic ether, an azine, a primary amine, and water [5]. This mixture causes an infinitely small dissolution of high molecular weight and, in particular, cross-linked PMMA types and achieves a sufficient dissolution rate in the exposed area (Fig. 2). The resist is commercially available as prefabricated plate (GS 233) or is used in the form of a casting resin (PLEXIT 74).[1]

2.2. *Fabrication of X-ray masks with high contrast*

The comparatively short wavelength used in synchrotron radiation lithography within the LIGA process and the high power densities required for a

[1] GS 233 and PLEXIT 74 are manufactured by Röhm GmbH, Darmstadt, F.R.G.

short irradiation time make far greater demands on the masks in terms of transparency of the membrane, its resistance against high irradiation doses, and its contrast than are usually known in the field of synchrotron radiation lithography. This is why along with the development of the LIGA process new kinds of masks, i.e., new mask blanks and related structuring technologies for the absorbers, have been developed.

Within the relevant wavelength range only beryllium has sufficient transparency for being used as a mask membrane at a thickness permitting an easy processing and handling. The necessary absorption of the absorber structures is obtained by application of a 10 to 15 μm thick gold layer on the membrane. Compared to common X-ray masks this is an increase by a factor of ten.

In collaboration with Siemens AG, a process for the fabrication of masks was developed. First, an optical mask is contact-printed onto a glass substrate which, previously, was coated with an adhesion promoting layer, a plating

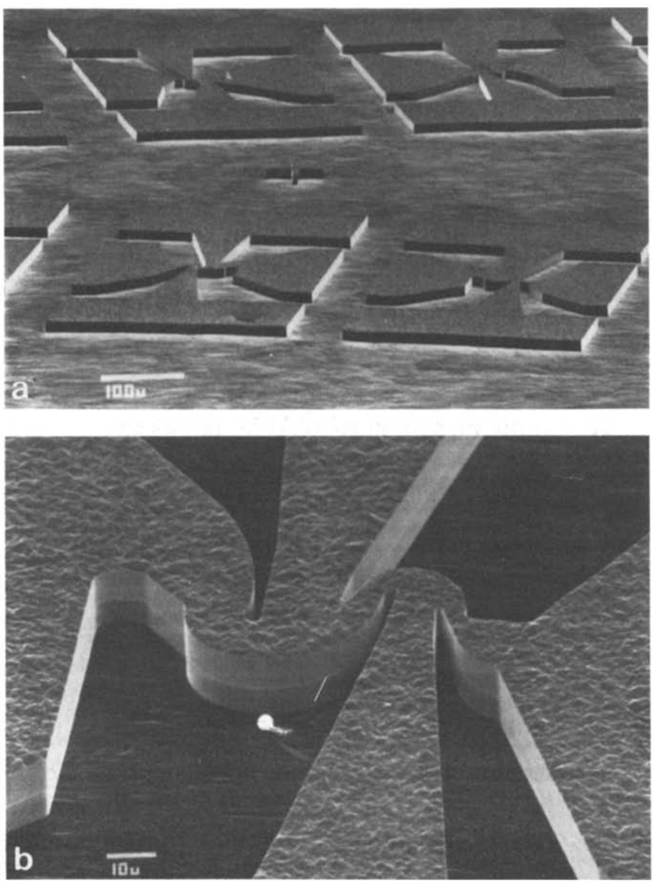


Fig. 3. Scanning electron micrographs of a mask used for synchrotron radiation lithography. The membrane is a 25 μm thick beryllium foil. The absorber structure consists of an approximately 8 μm thick copper layer onto which a 10 μm thick gold layer is deposited (Siemens AG).

base, and a 1.5 μm thick diazo-type resist. After development, the gaps in the resist structure are filled with gold by electrodeposition, the resist is stripped, polyimide is spun on, and subsequently polymerized in an oven. Finally, a window is etched into the glass substrate from the rear. The so produced interstage mask is then printed by synchrotron radiation into a PMMA resist whose thickness corresponds to the desired absorber thickness. The gaps in the resist are filled by electrodeposition starting with copper followed by gold. The plating base is a 30 nm thick gold layer sputtered on an approximately 25 μm thick, rolled beryllium foil.[2] This membrane is suspended in a rigid metal frame. Figure 3 illustrates scanning electron micrographs of such kind of mask.

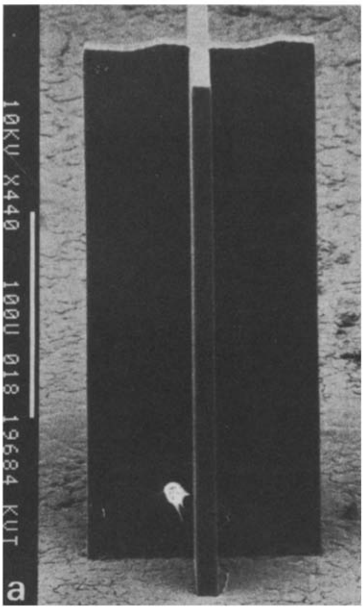
In order to facilitate the fabrication process, a number of successful experiments dealing with the direct fabrication of interstage masks using an electron beam writer and a trilevel resist were performed at the Fraunhofer Institute for Solid State Technology, Department of Microstructure Technology, Berlin. In addition, the process provides significantly higher accuracies of the produced absorber structures than the optical process. It is even more favourable to produce the thick absorber structure on the same substrate that is used for the interstage mask [6]. This has the advantage that deviations in dimensions being caused for example by temperature variations during the printing process are, to a great extent, reduced.

2.3. *Results of synchrotron radiation lithography*

For the fabrication of primary microstructures using synchrotron radiation lithography the PMMA resist is applied to a 3 mm thick substrate in the form of a casting resin and is then hardened by heating. The substrate is either austenite steel or copper plated with gold, titanium, or nickel. Prior to applying the PMMA layer, the surface of the substrate is treated by microgrit blasting with corundum or by a chemical wet process in oxidizing media. This improves the adhesion of the polymer structures on the surface.

Irradiation experiments were done at the electron synchrotron of the Bonn University. Its characteristic wavelength, under standard operating conditions, is approximately 0.5 nm which is significantly above the optimum value of 0.2–0.3 nm calculated for the proposed application (see Section 2.1), i.e., the mean depth of penetration is too small. Hence, the soft portion of the radiation spectrum was suppressed by filtering with a 100 μm thick polyimide foil thereby avoiding excessive differences in dose deposition along the beam. As a consequence, irradiation and development times amounting to several hours for each process must be accepted. Development requires twice the time necessary for complete uncovering of the structures. This "overprocessing" insures that the structure edges closely represent surfaces of equal dose deposition and that the accuracy potential of synchrotron radiation lithography is utilized to a high degree.

[2] The beryllium foil is manufactured by DEGUSSA AG, Frankfurt/Main, F.R.G.



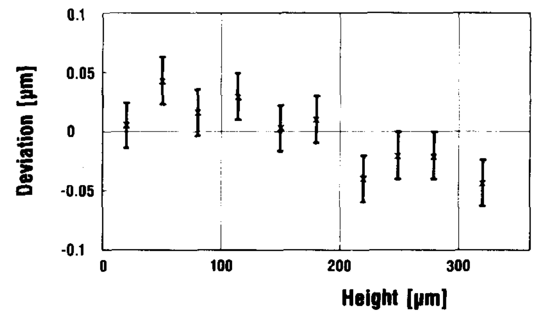


Fig. 4. (a) Scanning electron micrograph of a 330 µm high PMMA test structure produced by synchrotron radiation lithography. The bar width is 8 µm. (b) Deviation of the bar width from the mean value as was determined by a critical dimension measuring system. The figure demonstrates that the difference between the bar widths at the two structure ends only amounts to 0.1 µm.

Figure 4(a) shows a 330 µm high PMMA structure in the shape of a cross having 8 µm wide bars. Figure 4(b) demonstrates that the difference between the bar widths at the two structure ends only amounts to 0.1 µm as is to be expected by the theoretical analysis of the accuracy limiting effects [3, 4].

The honeycomb structure of Fig. 5 proves that PMMA structures having an aspect ratio on the order of 100 and structural heights of several 100 µm preserve their shape even in larger arrays. At a size of 80 µm, the honeycomb has a wall thickness of 4 µm and a structural height of 350 µm. The open space in the centre of the top micrograph which is surrounded by the sectioned honeycomb structure allows an assessment of the structure accuracy in deeper regions.

Figure 6 shows details of a 300 µm high primary plastic template made of PMMA for the fabrication of separation nozzles. The minimum width of the extremely complex plastic structures is 3 µm. The smallest radii in the wedge-shaped slits of the template are below 0.5 µm.

2.4. *Developments in synchrotron radiation lithography equipment*

The primary plastic templates shown in Figs. 5 and 6 were produced on comparatively simple irradiation equipment. For the purpose of repeatably

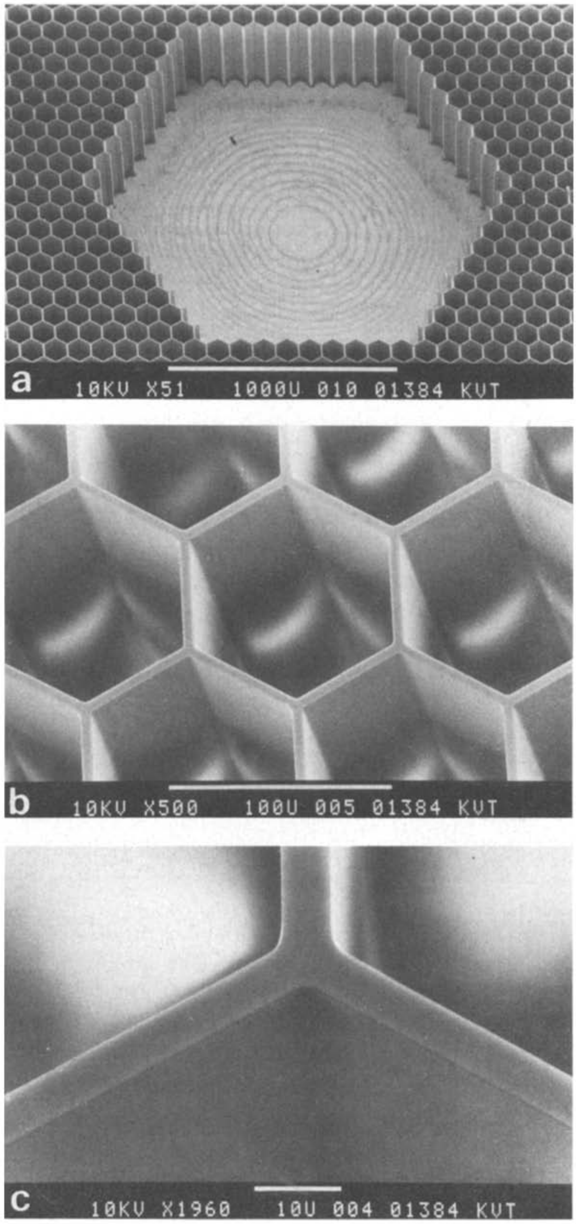


Fig. 5. Scanning electron micrographs in different magnifications of a PMMA honeycomb structure produced by synchrotron radiation lithography. The honeycomb has a size of 80 μm, a structural height of 350 μm, and a wall thickness of 4 μm. The length of the bars at the bottom micrograph edges corresponds to (a) 1000, (b) 100, and (c) 10 μm.

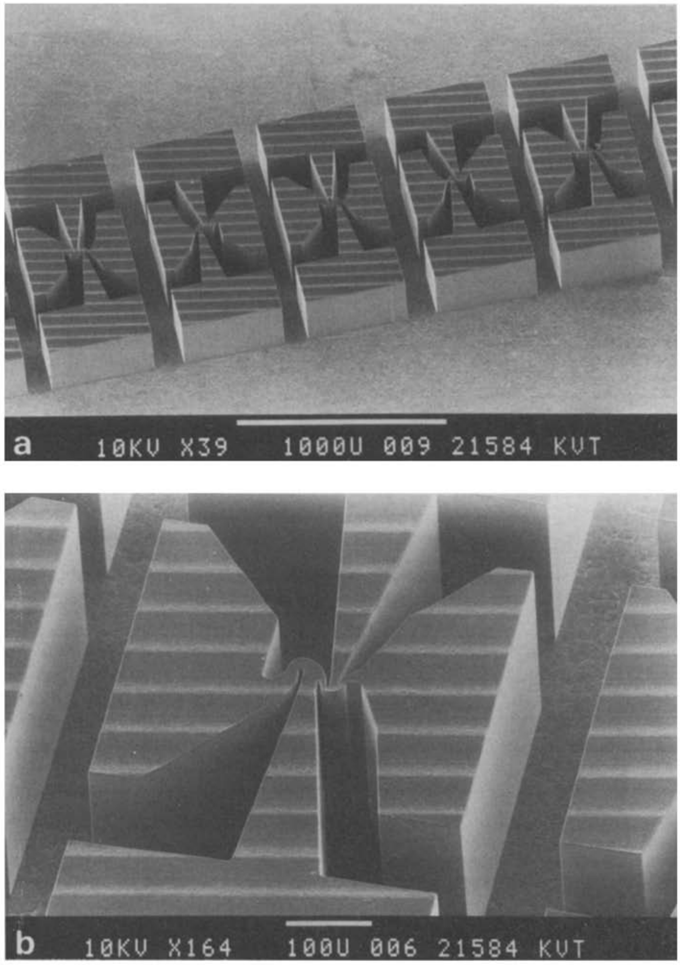


Fig. 6. Scanning electron micrographs of a PMMA template produced by synchrotron radiation lithography for the fabrication of separation nozzles. The length of the bars at the bottom micrograph edges corresponds to (a) 1000, and (b) 100 μm.

utilizing the accuracy potential to the aforementioned theoretical limits yet performing as time-effective as possible, an advanced irradiation equipment has been built. Its benefits are an almost vibration-free bedding of critical components, an exact thermostatic control, a precision scanner for the periodic movement of the sample through the irradiation plane, as well as a computer control and monitoring system (Fig. 7).

With 100 mm scanning length and 10 mm/s speed, the deviations of the scanner movement from a straight line are below 0.1 minute of arc. An automatic window changing device is provided for the polymide window which isolates the vacuum of the accelerator from the helium atmosphere serving as coolant for substrate and mask in the irradiation chamber. The window is fed

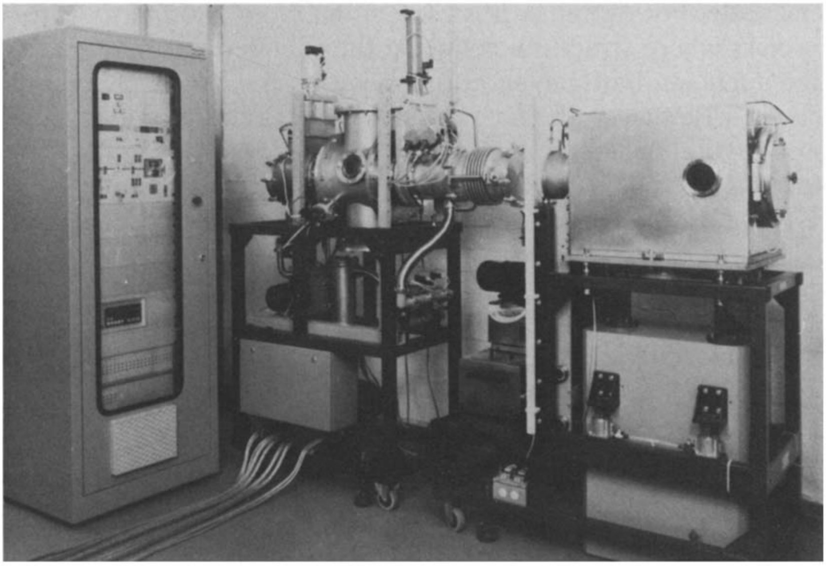


Fig. 7. Irradiation equipment to be connected to a synchrotron radiation source (manufactured by Arthur Pfeiffer Vakuumtechnik GmbH, Aßlar, F.R.G.).

into the beam from a magazine containing 6 windows. With an evacuated irradiation chamber, window changing takes a few seconds only.

A dedicated machine based on experience has been designed not only for the irradiation process but also for the development step. It is fitted to the special demands of synchrotron radiation lithography with extreme aspect ratios. The specific problems are a continuous and homogeneous transport of developing and rinsing agents into the deep structure elements and the removal of the dissolved resist from these structures. As a consequence, in this equipment, several substrates are arranged vertically on a rotor with each structure surface facing to the outside. Three independent medium circuits are available for immersion and spraying processes. Drying of the substrates is done by spinning and blasting with dry nitrogen. A programmable control system ensures a flexible sequence of process steps.

3. Fabrication of metallic microstructures by electrodeposition of metals into plastic templates

3.1. *Specific requirements imposed on the galvanoforming process*

The fabrication of metallic relief structures by electrodeposition of metals on patterned polymer surfaces is a process long since experienced on a commercial scale. For example, it is used in the fabrication of tools for records and video disks where structural details in the submicron range are transferred [7]. For the application of galvanoforming within the LIGA process, however, new problems arise due to the fact that the aspect ratio of the microstructures increases by several orders of magnitude.

Considering the high aspect ratio, it is impossible to generate the electrode necessary for galvanoforming by applying a conductive layer on the entire polymer. Thus an electrode must be provided which acts only at the bottom of the individual microstructure areas. In the case of a coherent plastic structure, this problem can, in principle, be solved as follows: The self-supporting plastic structures produced by irradiating and developing on the resist and subsequently laminated on a plating base. Due to resulting inevitable structural distortions, however, it is usually preferred to firmly connect the resist layer with a metallic substrate suitable for being used as galvanic electrode prior to irradiation and development of the polymer layer. For details see the description in Section 2.3. Apart from the so achieved higher structural accuracy, this method has the advantage of being applicable for noncoherent structures as well.

The use of a solvent-containing developing agent insures that the surface of the substrate in the gaps between the structures is completely free of grease. The surface then serves as a plating base without needing any activating process.

3.2. *Results of galvanoforming*

For the fabrication of separation nozzles, nickel was selected as structural metal mainly because of its excellent corrosion resistance against uranium hexafluoride. Nickel equally proved to be highly suitable for the fabrication of other microstructures with high aspect ratios, since the nickel sulphamate electrolytic bath has an excellent microthrowing power at current densities on the order of 1 A/dm^2. Also, the deposited microstructures exhibit only minor internal stresses [8].

The nickel sulphamate bath contains 400 g/l nickel sulphamate. Small quantities of an anion-active wetting agent and 40 g/l boric acid as a buffer are added. The electrolytic bath is operated at a temperature of 52 °C and a pH-value of 4.4. Metal deposition is done at current densities ranging between 1 and 2 A/dm^2. To keep the bath in a clean condition, it is circulated by pumping through a membrane filter with 0.3 μm pore opening.

Galvanic metal deposition with an external current source never produces a completely flat surface. Therefore, slight variations in the structural height and the microroughness of the surface facing the anode are removed by finish-grinding of the metal structure with the polymer still in place. Subsequently, the polymer is stripped out of the metal structures by immersion in a solvent. When using a cross-linked PMMA, the structures are exposed to synchrotron radiation before the resist is stripped, thus guaranteeing sufficient solubility.

To demonstrate the accurate replication of the shapes obtained by galvanoforming, the PMMA honeycomb structure shown in Fig. 5 and a complementary structure were filled with nickel by electrodeposition. The metal structures shown in Fig. 8 indicate that the structures defined by the PMMA are replicated with almost no defects. This applies even to features as small as 0.1 μm.

Figure 10(a) is a detail of a nickel separation nozzle chip produced by galvanoforming with a primary template as is illustrated in Fig. 6. Galvanoforming using secondary plastic templates is dealt with in Section 4 of this paper.

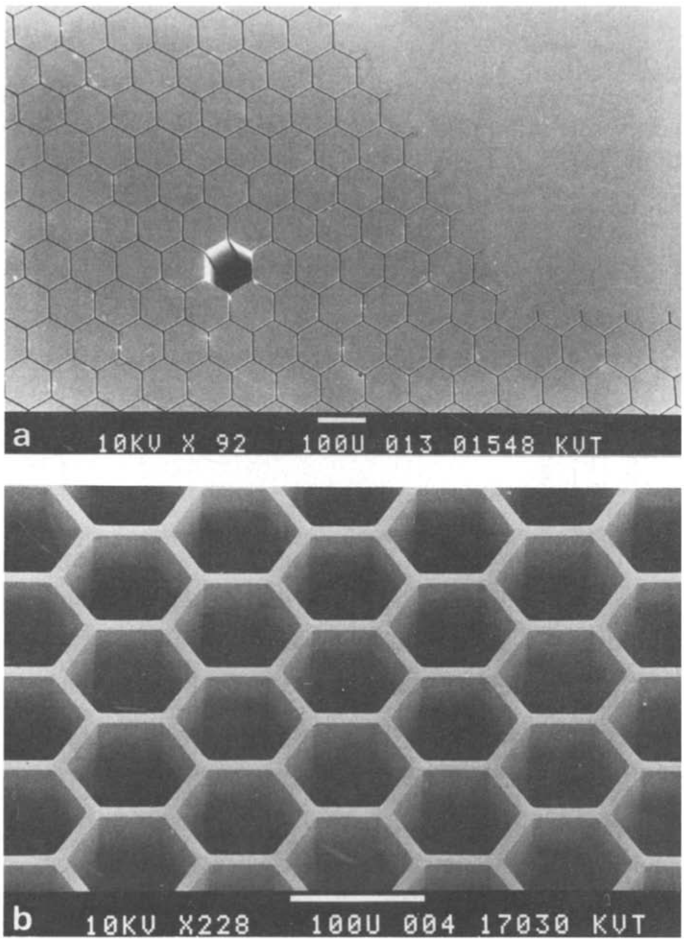


Fig. 8. Scanning electron micrographs of (a) hexagonal prisms, and (b) honeycomb structures, of nickel produced by galvanoforming using PMMA templates which are fabricated by synchrotron radiation lithography. The sizes of the prisms or the honeycomb, respectively, are 80 μm, the structural height is 330 μm. The gap width between the prisms and the wall thickness of the honeycomb are 4 μm. A view of the deep regions is given in the prism structure (a) where one unit was removed. The length of the bars at the bottom micrograph edges corresponds to 100 μm.

3.3. *Developments in galvanoforming equipment*

As soon as the key parameters for galvanoforming of microstructures with high aspect ratios had been determined on the basis of laboratory experiments, construction of an automated galvanoforming facility was started.[3] It is designed for producing nickel microstructures on a commercial scale. On this facility, the microstructure substrates arranged on carriers are processed automatically. A computer-controlled transport system moves the individual carriers through the process stages where the substrates are degreased, rinsed, pickled, electroplated, and dried and are then placed in a magazine. The facility is designed as clean room equipment since contamination of the microstructures must be prevented.

Figure 9 is a schematic drawing of the galvanoforming unit. It comprises the galvanoforming cell and an auxiliary tank in which auxiliary equipment required for the process is accommodated. This arrangement has the advantage that only the components necessary for metal deposition such as the substrate carrier and the nickel anodes are accommodated in the galvanoforming cell. Thus, it is achieved that the galvanoforming process is no longer exposed to contamination or damages caused by auxiliary equipment. To

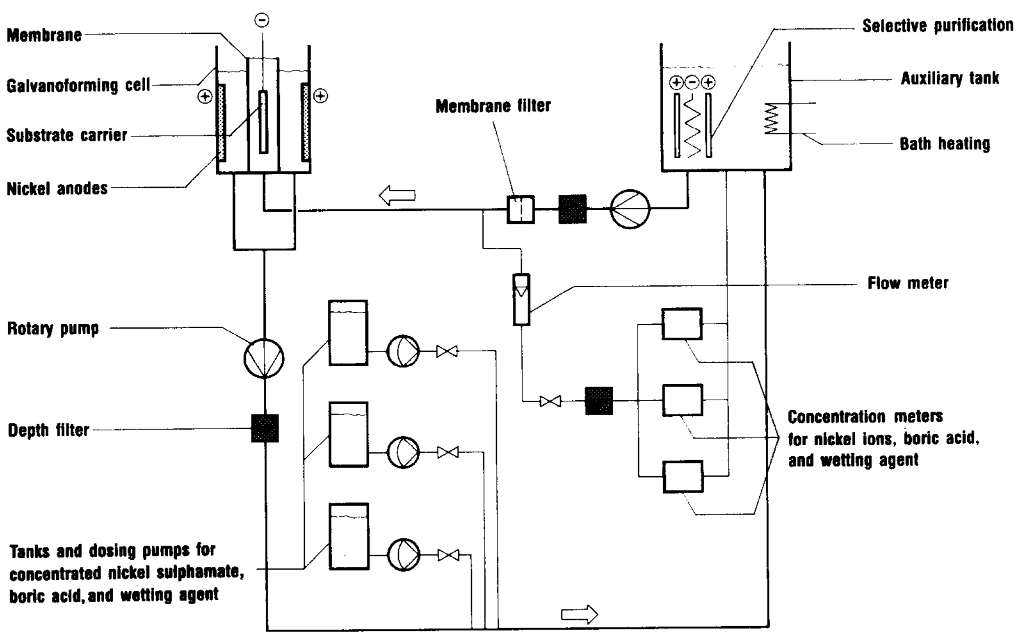


Fig. 9. Schematic drawing of the galvanoforming unit, part of an automatic galvanoforming facility for fabrication of nickel microstructures.

[3] Construction and testing of the galvanoforming facility are carried out in collaboration with DEGUSSA AG, Frankfurt/Main.

protect the microstructures from being contaminated, the electrolyte is flowing up vertically in the centre channel of the galvanoforming cell to which the substrate carrier is introduced from the top. The electrolyte is drained off downwards in the two neighbouring channels which contain the nickel anodes. The centre channel is separated from the outside channels by plastic membranes. This design of the galvanoforming cell prevents the substrates from being contaminated by particles either entering the cell from above or being produced by insoluble parts of the nickel anodes.

The electrolyte is circulated between the galvanoforming cell and the auxiliary tank by two pumps and is filtered by two depth filters and a membrane filter. The auxiliary systems required for temperature control and selective purification of the electrolyte are accommodated in the auxiliary tank. The effect of selective purification of the electrolyte is that at low current densities in the range of 0.2 to 0.5 A/dm^2, foreign metal ions are preferentially deposited on an auxiliary cathode, thus being removed from the electrolyte. A portion of the electrolyte flow to the galvanoforming cell is branched off and fed to three concentration meters. The concentration meters determine the three electrolyte components online and without any preparation of samples. Measuring of nickel ions and boric acid is done by photometers in the visible and the infrared spectral range, whereas the concentration of the wetting agent is determined electrochemically. The concentrations are adjusted automatically by adding via metering pumps the respective concentrates stored in tanks. The complete system is computer-controlled.

4. Fabrication of secondary plastic templates by moulding with metallic microstructures

4.1. *Specific requirements imposed on the plastic moulding process*

Likewise, the application of plastic moulding within the LIGA process generates new problems as compared to the moulding process applied for the production of records and video disks [7]. They are caused by the several orders of magnitude higher aspect ratio. Furthermore, the secondary plastic templates produced by moulding do not normally represent the final product, but are supposed to be filled with a metal by electrodeposition as is done with the primary templates produced by synchrotron radiation lithography. This means that, in general, the secondary plastic templates, too, must be provided with an electrode or plating base.

Even high aspect ratio microstructures can be moulded with polymers quite easily, if a polymer is used as moulding mass which has small adhesive powers and rubber-elastic properties, for example, silicon rubber. However, it is the nature of rubber-type plastics that they have a very low stability of shape which makes them unsuitable for moulding of free-standing microstructures having high aspect ratios.

Polymers which preserve their shape after hardening require a mould with extremely smooth inner surfaces to prevent form-locking between it and the hardened polymer. Since the use of an external mould release agent for microstructures with high aspect ratios is related to considerable difficulties, it is reasonable to facilitate unmoulding by applying an internal mould release agent.

4.2. *Results of plastic moulding*

Secondary plastic templates designed for serial production of separation nozzles are produced by the process of reaction injection moulding as is shown in Fig. 1. There, advantage is taken from the fact that fine nozzle structures are linked with considerably wider gas conduits. The mould insert is covered in a tool by means of a gate plate into which injection holes to the gas conduits are drilled which are needed for introducing the moulding polymer. After hardening of the moulding polymer, a form-locking connection between the produced part, i.e., the secondary template, and the gate plate is established at the injection holes permitting the unmoulding of the produced part from the insert.

The gate plate can be used directly as galvanoforming electrode for the deposition of metal in the secondary plastic templates. Safe sealing between mould insert and gate plate is achieved by the use of soft-annealed aluminium gate plates into which the insert is slightly pressed when closing the tool.

Moulding experiments were performed with a methacrylate-based casting resin. An internal mould release agent was added to the casting resin reducing the adhesion between the produced part and the inside surface of the mould insert.

Figure 10(b) shows a detail of a 300 μm high secondary separation nozzle template. It is produced by the described moulding process using the nickel chip, shown in detail on Fig. 10(a), as mould insert. Even after using the mould insert 100 times, absolutely no damages to the insert are observed at the scanning electron microscope although there are micron features with a structural height of 300 μm. It is, therefore, anticipated that plastic microstructures having high aspect ratios and great structural heights can be mass-produced independently from a synchrotron radiation source provided that a suitable moulding tool is available.

Figure 10(c) illustrates that secondary plastic templates can actually be used for the fabrication of secondary metal microstructures. The nickel separation nozzle structure that is shown was fabricated by electrodeposition of metal into a secondary separation nozzle template, as can be seen from Fig. 10(b).

4.3. *Developments in plastic moulding equipment*

The secondary plastic template shown in Fig. 10(b) was fabricated on a simple laboratory equipment. Figure 11 shows a flow diagram of a recently completed two-component mixing and metering facility. On this facility, it will be analyzed, whether different resins are suitable for microstructure moulding.

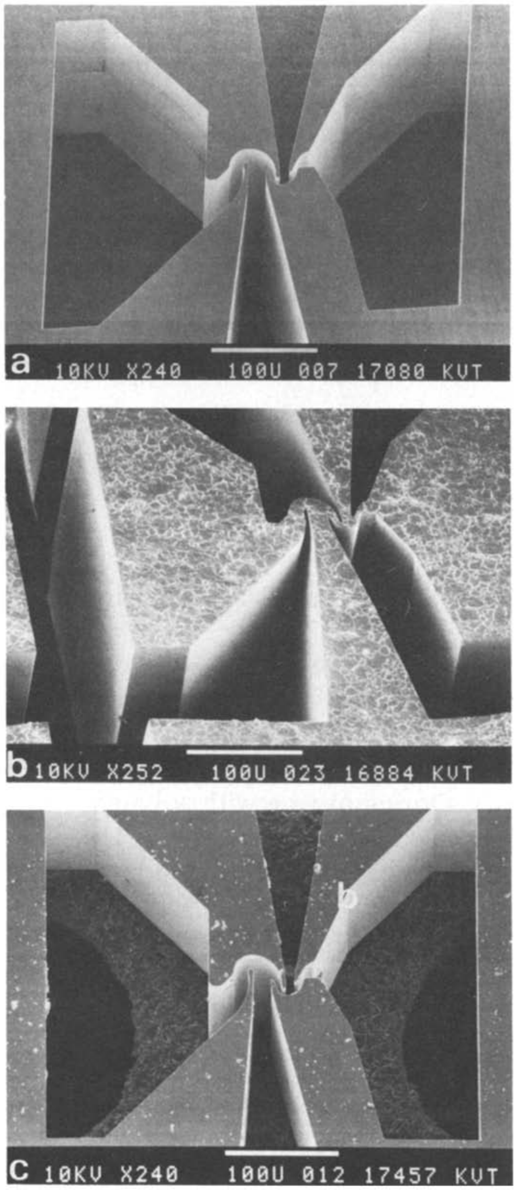


Fig. 10. Scanning electron micrographs showing details of (a) a primary separation nozzle structure made of nickel ("mould insert") produced by synchrotron radiation lithography and galvanoforming, (b) a secondary plastic template fabricated thereof by modulating, and (c) a secondary separation nozzle structure of nickel which was produced by electrodeposition of metal into the secondary plastic template. The length of the bars at the bottom edges corresponds to 100 μm.

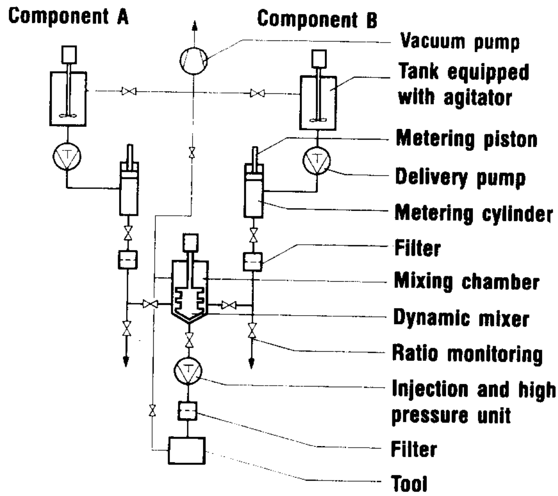


Fig. 11. Schematic drawing of the two-component mixing and metering facility for the fabrication of microstructures made of casting resins (manufactured by Kent-Moore (Europe) AG, Baar, Switzerland.

In addition, the facility is designed for optimizing the process parameters under reproducible conditions.

The two resin components, for example, resin containing an internal mould release agent and hardener, are processed in evacuatable 500 cm^3 tanks, each equipped with an agitator. The components are forced into metering cylinders via delivery pumps and are pumped at the desired ratio into the 30 cm^3 mixing chamber. During mixing with a dynamic mixer, the space above the resin can also be evacuated. The conduits to the mixing chamber are provided with filters of 3 μm pore width and one branch each for ratio monitoring.

The mixed material is drawn in by an injection unit and is then forced into the evacuated tool through another fine filter. Once the tool is filled, an additional amount of pressure up to a maximum of 100 MPa can be applied and maintained in order to compensate for shrinkage of the resin during hardening. After the injection unit has filled the tool, both the tool and the injection unit can be disconnected from the mixer without pressure release and be replaced by new ones.

5. Practical applications and future developments of the LIGA process

To utilize the total accuracy potential of the LIGA process, synchrotron radiation at a characteristic wavelength ranging between 0.2 and 0.3 nm is needed (see Section 2.1). Radiation of that kind will to a certain extent be available for research and development on the LIGA process at the Bonn University as soon as the stretcher ring ELSA currently under construction is put into service. Suitable synchrotron radiation can be generated at other places as well, for example, at the electron storage ring DORIS at DESY.[4] For use of the LIGA process on a commercial scale, it is, however, desirable that a radiation source is made available which is designed and primarily used for this special purpose. In the pursuance of this goal, an electron storage ring suitable to perform this task has been drafted [9]. The use of four superconducting deflection magnets reduces space and utility requirements of the machine. The aim is now to work that draft out in detail so that a decision on the construction of the radiation source can be made.

The universal applicability of the LIGA process is of benefit only if the required X-ray masks (see Section 2.2) are produced time-effectively and at reasonably low cost. At present, design and construction of a mask line is under way. All mask-making equipment will be accommodated in a clean room building.

Some applications of the LIGA process do not require all three process steps. It can be assumed that, in general, no plastic moulding is required, if the final product is made of metal, and if only small production quantities are demanded. Typical examples are metal grids having extremely small characteristic dimensions, high aspect ratios, and a great transparency for research and development purposes. Yet, even for small production quantities, plastic moulding can be indispensable, if, for example, the final product is made of a plastic that allows no lithographic structuring as might be the case with medical applications. If, in this particular process, unmoulding is found to be difficult and if the final product is of considerable value, it is possible to dissolve the mould insert from the plastic structure obtained by the moulding process.

Moulding of the primary or secondary metal structure can be done, if required, by other materials, too, that have the ability to flow or can be sintered, such as glass. These materials are considered for a project aimed at the fabrication of special microchannel plates [10].

More applications of the LIGA process are created by irradiating and developing the primary plastic template once again after electrodeposition of metal. This permits a partial uncovering of the metal structure while the remainder of the polymer fixes the structure. In this way, for example, microconnectors with extremely small pin-to-pin distance can be produced (Fig. 12) [11]. The same method is applicable with secondary plastic templates, if, as demonstrated in Fig. 10(b), a plastic is used for moulding which is sensitive to X-rays.

Plastic moulding of high aspect ratio microstructures and subsequent galvanoforming as has been developed within the LIGA process can also be performed with mould inserts not produced by synchrotron radiation lithography. A respective application is, for example, the replication of spinning

[4] Some of the experiments described in [1] were performed at the electron storage ring DORIS.

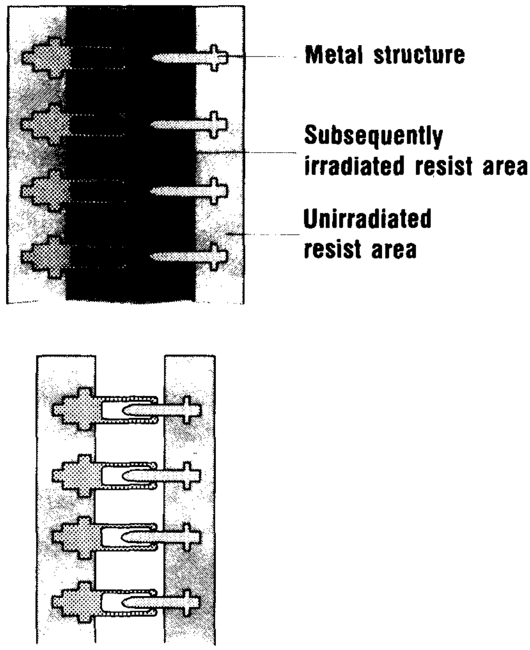


Fig. 12. Partial uncovering of metal structures produced by the LIGA process, which is achieved by a second irradiation step. This illustrates the formation of electronic microconnectors [11].

nozzle plates for the production of profiled filaments [12] whose primary spinning capillaries have been pierced into the plates by electroerosion.

But even if the structure to be moulded has no macroscopic regions adequate for injecting the moulding mass (see, e.g., the honeycomb structure in Fig. 5), moulding is possible, if the mould insert is covered by a liquid moulding mass or is impressed in a soft moulding mass. There, the plating base is produced by coating the outer surface of the mould insert, before it contacts the plastic, with an adhesion preventing layer followed by a metal (Fig. 13). During unmoulding, the metal layer remains stuck to the bottom of the secondary template where it serves as plating base. Unmoulding is preferably done by making use of the hardened polymer body which extends over the mould thickness and supports the microstructures. A further option is to impress the mould insert in a compound of an electrically insulating and an electrically conductive layer. The thickness of the insulating layer is selected in relation to the structural height ensuring that the impressed mould insert electrically contacts the conductive layer. After removal of the mould insert, the conductive layer is used as a plating base [13].

In large-scale production of secondary plastic templates, the rather long hardening time of casting resins hitherto used is a drawback. For that reason, respective experiments have been done on injection moulding of thermoplastics. Results achieved to date make this process very promising.

In commercial application, the LIGA process which is a combination of

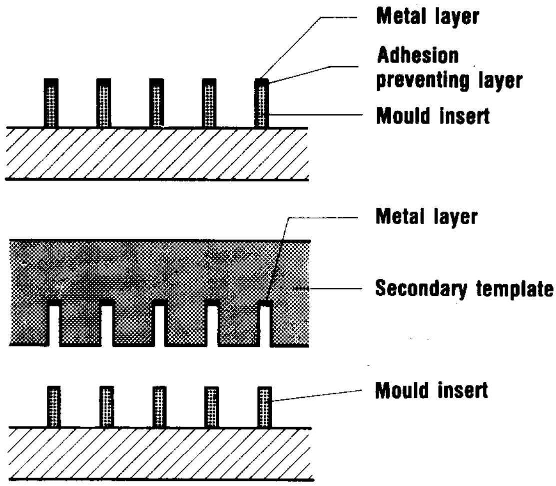


Fig. 13. Fabrication of a plating base by transfer of a metal layer from the outer surface of the mould insert to the bottom of the secondary template.

several process steps competes with other processes for the fabrication of microstructures with high aspect ratios, e.g., anisotropic etching of silicon [14] or the production of micropores in plastics or mica by etching tracks of high energetic heavy ions [15]. However, the LIGA process is expected to be superior to other processes, if, in mass production of microstructures with complex shapes as applies to the production of separation nozzles, specific requirements are imposed on the spatial resolution, the aspect ratio, the structural height, the parallelism of the structure walls, as well as the freedom of shape design.

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