DIRECT WRITING FOR THREE-DIMENSIONAL MICROFABRICATION USING SYNCHROTRON RADIATION ETCHING

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ABSTRACT

This paper presents rapid three-dimensional microfabrication technologies for PTFE by direct writing with the TIEGA process, a LIGA-like process which replaces hard x-ray lithography with synchrotron radiation (SR) direct photo-etching. The etching rates of this process are of the order of 6-100 μm/min, depending on the photon flux of the SR light.

An X-ray lathe has been modified into an SR etching lathe to form cylindrical, helical, pyramidal, ellipsoidal, and other nonplanar objects. A metallic wire covered with a PTFE sheet is rotated and/or moved while being irradiated with SR through a mask. Moreover, direct writing without using any masks has been developed, by combining a scanning stage with a high degree of freedom under an He atmosphere, for creating any microstructure. The capabilities of these technologies and initial fabrication results are described here.

INTRODUCTION

Three-dimensional (3D) microstructures with well-defined curved and inclined surfaces are of great interest for current microparts applications, including mechanical, optical and electronic devices and subsystems. Several approaches to meet such requirements have been performed. Fabrication technologies such as the multi-mask process and the gray-tone lithography process [1, 2], have been utilized to realize 3D microstructures. Deep X-ray lithography (DXL) in the LIGA (German acronym for Lithographie, Galvanoformung, Abformung) process has been tested in forming high aspect ratio 3D microstructures using sequential planar formation of individual levels [3], or moving mask technology to control a side-wall inclination of PMMA (polymethylmethacrylate) [4]. These processes require several or modulated masks for LIGA, and elegant feedback systems, resulting in expensive and complicated processes. On the other hand, an X-ray lithography lathe, which rotates a cylindrical core coated with an X-ray-sensitive resist during exposures, has been reported as a simple 3D micromachining process [5]. However, uniformity of the resist layer and cracking of the resist during curing at elevated temperatures are serious problems for this method. Moreover, in the wet processes of lithography, there is a problem of sticking, due to the surface tension of the developer.

The ideal method for 3D microfabrication is direct writing, enabling the formation of any microstructure without using masks such as in dry etching processes. The SR etching in the TIEGA (Teflon Included Etching and Galvanicforming) process might meet these requirements [6]-[8]. This can be applied to Teflon polymers such as PTFE (polytetrafluoroethylene) and optical crystals like NaCl that could not be fabricated previously by other methods. Due to its thermostability, resistance to chemicals and its very low adhesion, and its especially high etching rate (of the order of 100 μm/min.), PTFE may be one of the most suitable materials for microparts in many fields. Processing for a 1000 μm height microstructure takes about 10 minutes, much shorter than that needed for the DXL.

Here we present our study for 3D microfabrication with TIEGA based on the X-ray lathe and mask-less direct writing and discuss the potential of these technologies.

TIEGA PROCESS

A schematic diagram of the steps in the fabrication of basic TIEGA microstructures is shown in Figure 1. In the first step the absorber patterns on an X-ray mask are transferred into a thick PTFE layer (200-2000 μm) on the metallic substrate by SR etching. A compact SR source, which is described later, is used here. The exposed regions of the PTFE are selectively etched. Our detailed studies about etching mechanisms of PTFE are shown elsewhere [9]. The unexposed regions, covered during irradiation by the absorbers of the mask, form the primary microstructures. These microstructures may

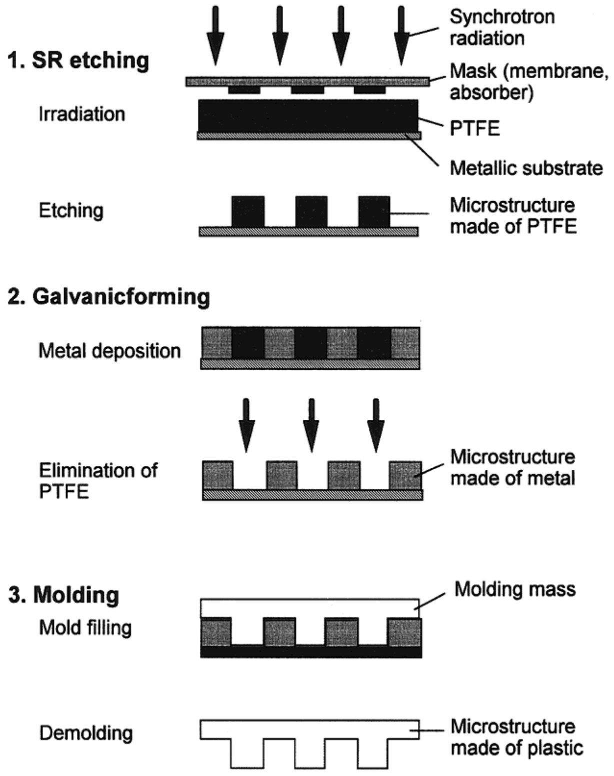


Figure 1: Principle process steps for the fabrication of microstructures by TIEGA process.

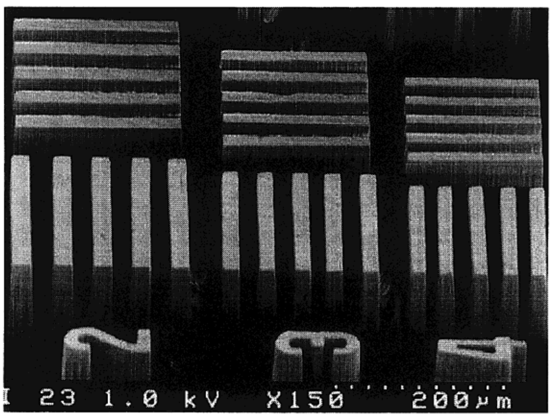


Figure 2: SEM picture of microstructures made of PTFE created by SR etching with LIGA mask.

be the end products of the process, for example in biomedical applications taking advantage of the characteristics of PTFE, but other options are available. Metallic microstructures, necessary for many micromechanical applications, are fabricated by filling the PTFE template with metal by galvanicforming. After eliminating the PTFE template by SR etching, these metallic microstructures may also be the end product. Alternatively, the electrodeposition process may be extended, adding metal 3-5 mm thick above the height of the microstructures. In this case direct elimination of the PTFE template can be available because of non-adhesion of PTFE to the metal. A stable mold insert suitable for the mass production of microstructures is produced. Mold inserts may then be used in different molding processes to produce secondary polymer structures. Compared to the LIGA process, the TIEGA process has the following advantages:

- Only one step is required to make a template for electroforming, due to the etching process.
- Being a dry process, It is free from problems of sticking due to the surface tension of the developer.
- The faster processing speed results in reducing the cost of photons.
- It needs neither a high-energy SR source nor a high-contrast X-ray mask.

The maximum aspect ratio we achieved was 75 and the minimum pattern feature was of the order of a few micrometers. The quality of the microstructures that we made using TIEGA in PTFE was very close to that obtained using the LIGA process in PMMA [6]. We have applied LIGA masks developed by ourselves [10] to SR etching for two-dimensional (2D) micro structuring, since X-ray masks for TIEGA have not been developed. The mask was composed of a 3-7 µm thick Au as an absorber and a 2 µm thick SiC as a membrane. As shown in Figure 2, using a LIGA mask, microstructures have been successfully created in PTFE with an etching rate of about 100 µm/min.

EXPERIMENTAL AND FABRICATION

SR source and spectra

Some experimental details (such as the SR source, beamline, experimental station, sample preparation and etching processing) can be found in our recent publications [6], [11]. The SR source was our home-made compact superconducting electron storage ring, AURORA (575 MeV energy), now installed in the SR center at Ritsumeikan University. Its SR had a continuous spectrum from IR (infrared) to X-ray with a critical wavelength of 1.5 nm (0.84 keV) and the bunches had a duration of 170 ps with a repetition rate of 191 MHz. Its routine starting beam current was about 300 mA. Different metallic filters were used to select SR X-rays in different wavelength ranges optimized for the processes

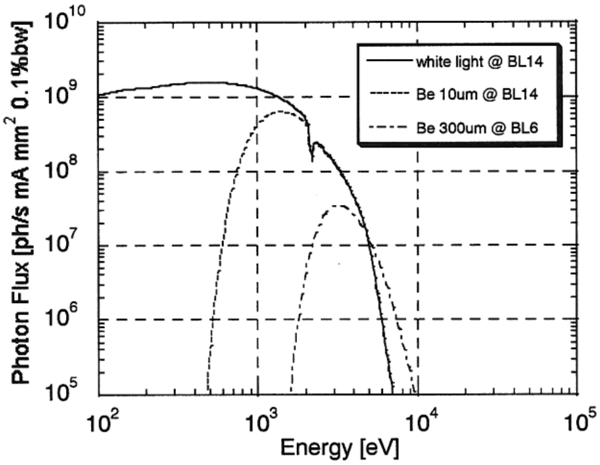


Figure 3: SR spectra BL14 for SR-stimulated process including TIEGA and BL6 for LIGA process.

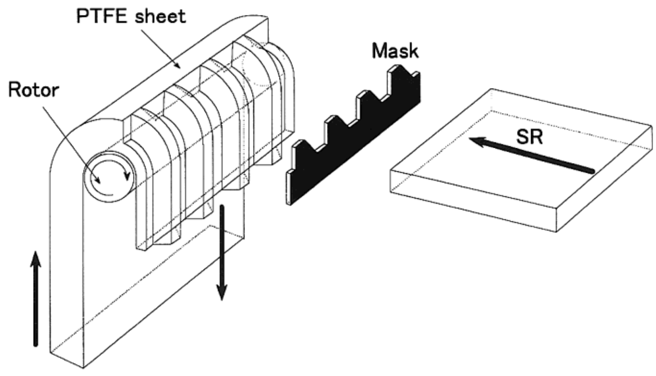


Figure 4: Schematics of SR etching lathe for 3D microfabrication.

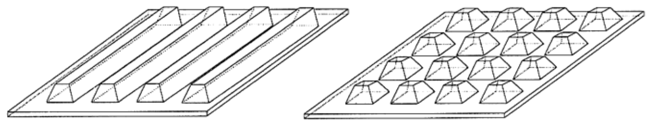
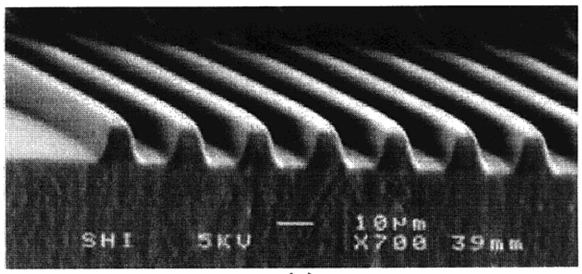


Figure 5: Schematic of PTFE microstructures; (a) line and space of trapezoidal shape, (b) pits of trapezoidal shape.

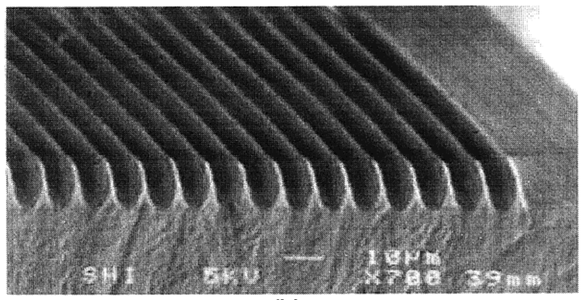
at each station. Figure 3 shows the SR spectra for both stations used in our experiments. At BL14 for SR stimulated processes including TIEGA, a 10 μm-thick Be filter was used to select the X-rays mainly in the spectral range 0.4-6 keV which peaked at about 1 keV. The photon flux in the sample surface was calculated to be $3x10^{12}$ photons s^{-1} mA^{-1} mm^{-2} at 4 m distance from the light source. Note that a focussing mirror system was installed in BL14 and fabrications were performed in a vacuum at this station. If the mirror is not used, the photon flux is reduced by about one order of magnitude. At BL6 for the LIGA process in an He atmosphere, a 300 μm-thick Be filter was used to select in the spectral range 2-10 keV which peaked at about 4 keV, and the photon flux was calculated to be $5x10^{10}$ photons s^{-1} mA $^{-1}$ mm^{-2} at 3 m distance from the light source.

SR etching lathe

Based on the X-ray lithography lathe, the modifications presented here extend TIEGA into a variety of 3D structures. Figure 4 shows the experimental set up for the SR etching lathe. A PTFE sheet (thickness of 50-200 μm) was attached to a cylindrical rotor with a small radius. This sheet and the rotor rotate simultaneously during SR etching, with a mask set in front of the PTFE surface. This method could not be applied If the material for processing is less flexible than PTFE, eg. PMMA. Using the mask shown in Figure 4, long, in principle, line and space (L&S) patterns of trapezoidal shapes can be created parallel to the SR light (Figure 5(a)). After this process, the PTFE sheet again is set to the rotor perpendicular to the direction of the former processing.



(a)



(b)

Figure 6: SEM pictures of L&S patterns of (a) trapezoidal and (b) saw-toothed shape.

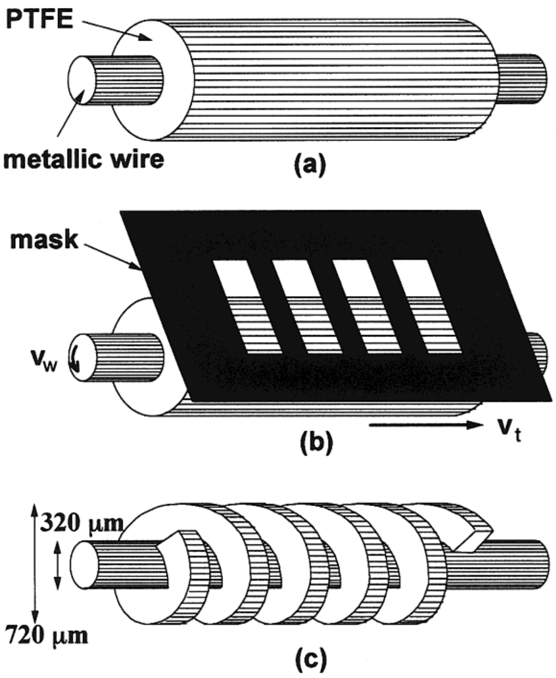
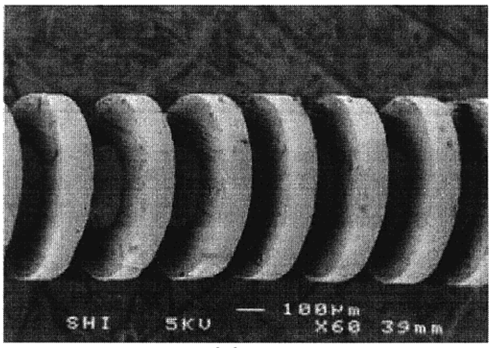
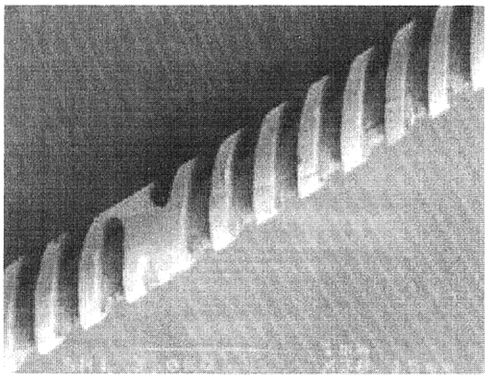


Figure 7: Schematic of SR etching lathe for helical structure; (a) metallic wire covered with PTFE, (b) SR etching process, (c) helical structure.



(a)



(b)

Figure 8: SEM pictures of 3D microstuctures by SR etching lathe; (a) cylindrical symmetry structures, (b) helical structures.

Many pits of trapezoidal shape can be formed with SR etching using the same mask (Figure 5(b)). Usually, PTFE sheet is irradiated by SR with a L&S mask set in front of the surface as shown in Figure 1. In this case, the roughness of the processing surface (the bottom surface) becomes larger when the aspect ratio of microstructures becomes larger. In the case of the SR etching lathe, in principle, the roughness of the microstructures would be equivalent to the roughness of the mask edges since the processing proceeds along the SR direction. The results of the SR etching lathe are shown in Figure 8. L&S patterns of trapezoidal (Figure 6(a)) and saw-toothed (Figure 6(b)) shape were clearly created in 100 μm-thick PTFE sheets. The surface roughness of the microstructure is of the order of sub-microns.

Next, we tried to make a cylindrical symmetry and a helical structure in PTFE. Figure 7 shows the experimental set up for this SR etching lathe. A metallic wire 320 μm in diameter covered with a PTFE tube 720 μm in outside diameter was irradiated, with the mask consisting of L&S (100 and 150 μm). Cylindrical symmetry structures were fabricated by rotating the wire (Figure 8(a)). Helical structures were successfully fabricated by rotating the wire and simultaneously moving it parallel to the wire axis (Figure 8(b)). In figure 8(b), the vertical size of the SR light we used was 200 μm. To etch PTFE on a screw, the wire was rotated with an angular speed (v_w) of 16 degrees/min and moved with a translational speed (v_T) of 20 μm/min under an etching rate of 100 μm/min. Helical structures made of PTFE can also be formed by eliminating the wire core. Taking advantage of the chemical characteristics of PTFE, it is also possible to dissolve the metallic wire in some solvents. Moreover, metallic microstructures can be formed when the electroforming is carried out in the PTFE template using the TIEGA process.

We have already found that raising the PTFE temperature during processing results not only in significant enhancement of the etching rate, but also in improvement of the quality of the processing surface [6], [7]. In order to efficiently generate structures using the SR etching lathe, a heater installed inside the rotor in Figure 4 or the metallic core acting as a heater in Figure 7 would be used for these methods. The etching time can be reduced by 50 % with a mask that exposes both sides of the PTFE covered metallic wire simultaneously.

Mask-less direct writing

For ideal 3D microfabrication, we have been developing a direct writing system without any masks using SR etching in TIEGA as shown in Figure 9. A PTFE sheet

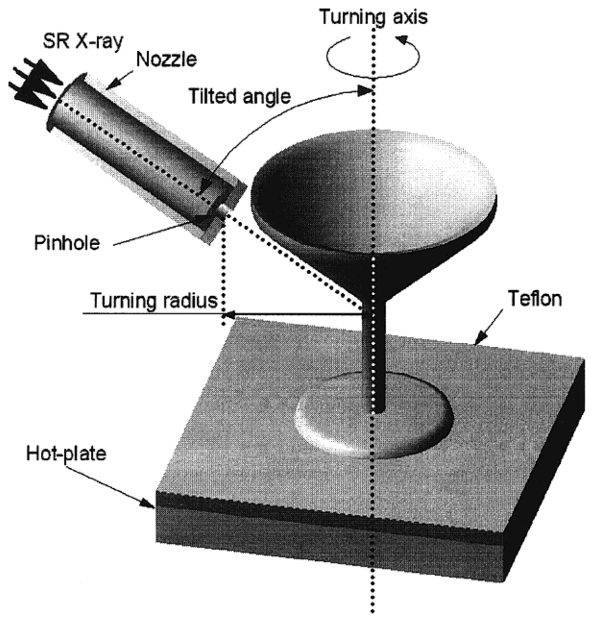


Figure 9: Schematic of experimental set up for direct writing without any mask.

Figure 10: SEM picture of 3D microstructure created in PTFE surface.

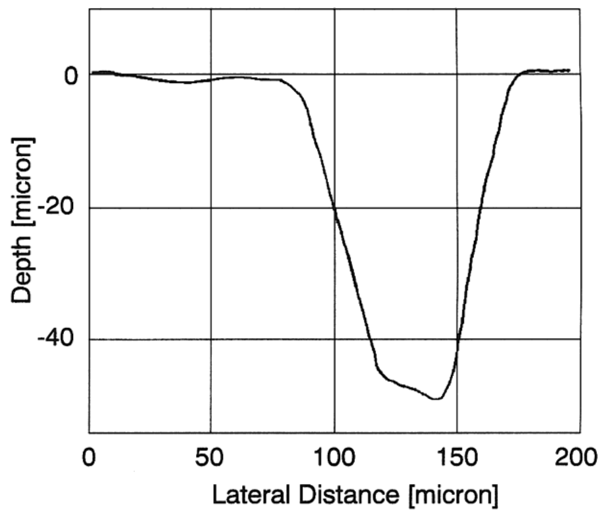


Figure 11: Cross sectional profile of the 3D structure of Figure 10.

is fixed on a scanning stage with a high degree of freedom and can be heated by a hot-plate attached to the rear side. One small pinhole is used as a collimator for the SR X-rays and set in front of PTFE as closely as possible. The PTFE is etched by the SR extracted from the pinhole. Free-microstructures can be formed by combination of turning and/or tilting PTFE and control of the irradiation dose. SR etching is suitable for direct writing. The problem is that although a higher etching rate can be achieved in a vacuum, gaseous products are evolved during SR irradiation of the PTFE [7]. It may be difficult to install a complicated stage with a geometrical freedom and flexibility in a vacuum. From a practical point of view, processing under an He atmosphere or atmospheric pressure are accessible for 3D fabrication dealing with such stages, their compositions and so on. We have checked the etching rate and the quality of the processing surfaces in an He atmosphere at BL6 for LIGA as described above [12]. The etching rate we achieved was about 6 μm/min, which was a reduction of one order of the etching rate at BL14. Fabrication of PTFE at 200 °C resulted in a smooth surface with a roughness of sub-microns. These results indicate that direct writing using SR etching still has advantages for 3D microfabrication.

We have carried out preliminary experiments using a rotatory stage around the turning axis under an He atmosphere. A PTFE sheet was fixed to a hot-plate (size: 3x3 cm^2) on the stage. A pinhole with 80 μm in diameter attached at the end of the nozzle was used for extracting SR X-rays. The surface of PTFE was tilted with angle of 15 degrees against the nozzle. Figure 10 shows the result of direct writing onto the PTFE surface with a turning radius of 300 μm. A cross sectional profile of this structure measured by stylus plofilometer is shown in Figure 11. Some deformation for a large area of the PTFE sheet occurred since the hot-plate heated a greater area than required. This deformation might have an influence on precision. On the other hand, a high degree of freedom of the scanning stage might be limited by the heater's size and its wiring. Local heating using a microheater-tip with a collimator for SR X-rays attached to the end of the nozzle may be an alternative method for heating during processing without deformation and limitations. We will test the capabilities of the microheater-tip for improving the tolerance of the processing.

CONCLUSION

Rapid 3D microfabrication technologies with the TIEGA process have been developed. The processing rates are of the order of 6-100 μm/min, depending on the photon flux of the SR light.

For the SR etching lathe based on the X-ray lathe as a relatively simple method for microfabrication, some experiments confirmed that microstructures such as cylindrical, helical, pyramidal, and other nonplanar objects could be created not only in PTFE but in metal using the TIEGA process. This method can offer large area processing for industry applications. For mask-less direct writing as an ideal method to form any microstructures, the initial trial to pattern curved structures onto a PTFE surface was successfully carried out in an He atmosphere with an etching rate of 6 μm/min. These demonstrate the possibility of applying SR etching in the TIEGA process to 3D microfabrication.

Future work will focus on the scanning stage with geometrical freedom optimized for mask-less direct writing using SR etching. Free microstructures will become feasible using this stage. Moreover we will apply these technologies to make devices such as fiber-optic lenses, waveguides, grating, and so on.

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