A NOVEL FABRICATION PROCESS FOR HIGH-ASPECT-RATIO AND CO-AXIAL MULTI-LAYER NICKEL MICROSTRUCTURES

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ABSTRACT

A novel process of high-aspect-ratio metallic microstructures is proposed. The process combines protective film coating, laser drilling, swelling of polymers, electroforming and demolding. The pattern accuracy of metallic microstructures is controlled not only by laser drilling but also by swelling of polymers, because the diameter of drilled holes decreases to a certain value after the treatment of swelling. Using this process, a micro-post-array nickel mold and a precisely co-axial multi-layer nickel microstructure with a high aspect ratio of about 100 and a thickness of 5mm is produced. The advantages of this process include low cost, simple procedures, and easy demolding.

1. INTRODUCTION

For the conventional LIGA-process, a microstructure is fabricated using very complex procedures including photoresist coating, photolithography (photoresist baking, X-ray exposure, photoresist developing), electroforming and demolding, which were described elsewhere [1-2]. Using the LIGA-process, the height and pattern accuracy of fabricated microstructures is determined by the penetrating depth of exposure light and lithography respectively. In practical, the pattern accuracy, roughness, height, aspect ratio, and wall angle of microstructures can be less than 0.5μm, some ten nanometers, more than 2mm, 200, and 90° respectively [1-2]. However, some disadvantages of LIGA-process strongly limit itself in the industrial applications like expansive X-ray source, few types of useful photoresists, complicated and time consumable manufacture of X-ray mask, and simple-geometry microstructures.

In order to lower the fabricating cost or to simplify the manufacturing procedures, LIGA-like and excimer laser LIGA processes were developed [3-4]. For the LIGA-like process, exposure source and mask are using UV light and IC-mask instead of synchrotron source and X-ray mask in LIGA-process respectively [4]. For the excimer laser LIGA process, the exposure source, mask and patterning mechanism are using excimer laser, IC or metal mask, and laser ablation respectively [5-6], which are very different to those in LIGA-process. Therefore, the costs of exposure equipment and mask decrease significantly. In addition, the take time and procedures for mask preparation are strongly shortened and simplified. Using these two alternative processes, however, the height and aspect ratio of microstructures can be achieved to only some hundred micrometers and less than 20 respectively. Furthermore, the microstructures have less pattern accuracy and roughness than those made using the LIGA-process.

Though the above mentioned methods are frequently used to generate precise micro-mechanical structures and micro-components, they are difficult to form complex geometrical or co-axial multi-layer microstructures due to many repeating procedures and layer-to-layer misalignment.

In this study, a novel process for the fabrication of high-aspect-ratio micro-post-array nickel molds is proposed. This low-cost process is very simple and easy, which combines protective film coating, laser drilling, swelling of polymers, electroforming and demolding. A micro-post-array microstructure with a diameter of 50μm and with a height of 5mm was produced using this technology. Furthermore, the difficulties for the manufacture of co-axial multi-layer microstructures, which have a diameter of 50μm and an aspect ratio of 100, have been successfully overcome by applying this simple method to a multi-layer specimen.

2. SWELLING OF POLYMERS

General speaking, the mass transfer of organic solvent in polymeric materials is determined by their chemical potential and induced mechanical stresses in bulk materials [7]. The mass transfer of solvent in polymers occurs only if there does exist the gradient of chemical potential. Therefore, molecules of solvent will diffuse into polymers and then result in mechanical stresses in bulk materials. However, mechanical stresses can be released either by the swelling of polymers or by the movement and rearrangement of molecular chain of polymers [8]. As a result, the mass transfer of solvent in materials will be stopped when the equilibrium state between chemical potential and mechanical stresses is achieved.

In this study, high-aspect-ratio and co-axial multi-layer microstructures are fabricated using the concept of swelling, which is performed in an electrolytic solution. Due to the swelling phenomenon, the diameter of drilled holes in a hydrophilic polymeric workpiece will strongly reduce. The aspect ratio of drilled holes will thus be significantly improved. If holes are drilled in a hydrophilic/non-hydrophilic laminate structure, the diameter of drilled holes in hydrophilic layers will decrease after treatment of swelling, while that in non-hydrophilic layers not. Therefore, co-axial multi-layer cavity can be generated.

3. EXPERIMENTALS

3.1 MANUFACTURING PROCEDURES

In this study, micro-post-array and co-axial multi-layer nickel microstructures were generated using the same process, as shown in Figures 1 and 2. The main differences in manufacturing the two mentioned structures are sample preparation and demolding methode.

As shown in Figure 1, the fabricating process of the micro-post-array nickel mold can be divided into 6 steps. At first, A 5mm-thick hydrophilic polyurethane sheet is coated with a protective film to prevent absorption of electrolytic solution in the bulk material (Figure 1(a)). This protective film must not be dissolved in the electrolytic solution during electroforming. Secondly, 400μm-diameter holes are drilled in the sample using a laser beam (Figure 1(b)). Thirdly, the patterned sample is fixed on a nickel cathode and immersed in an electrolytic solution at mass transport temperature (Figure 1(c)). In this step, the absorption of electrolytic solution in the sample will stop when the sample is saturated. Fourthly, the saturated sample is electroformed in the same electrolytic solution at mass transport temperature (Figure 1(d)). Fifthly, the sample is taken away from the electrolytic solution and lapped to a desired thickness (Figure 1(e)). The patterned parts will then restore almost to their original dimensions due to desorption of the electrolytic solution. Finally, nickel deposits are easily removed without destroying the sample (Figure 1(f)). A micro-post-array nickel mold is thus created.

In this process, it should keep in mind that the treatment of swelling and electroforming are carried out in the same electrolytic bath at the same temperature. This means that no additional equipment is needed for the swelling of polymers.

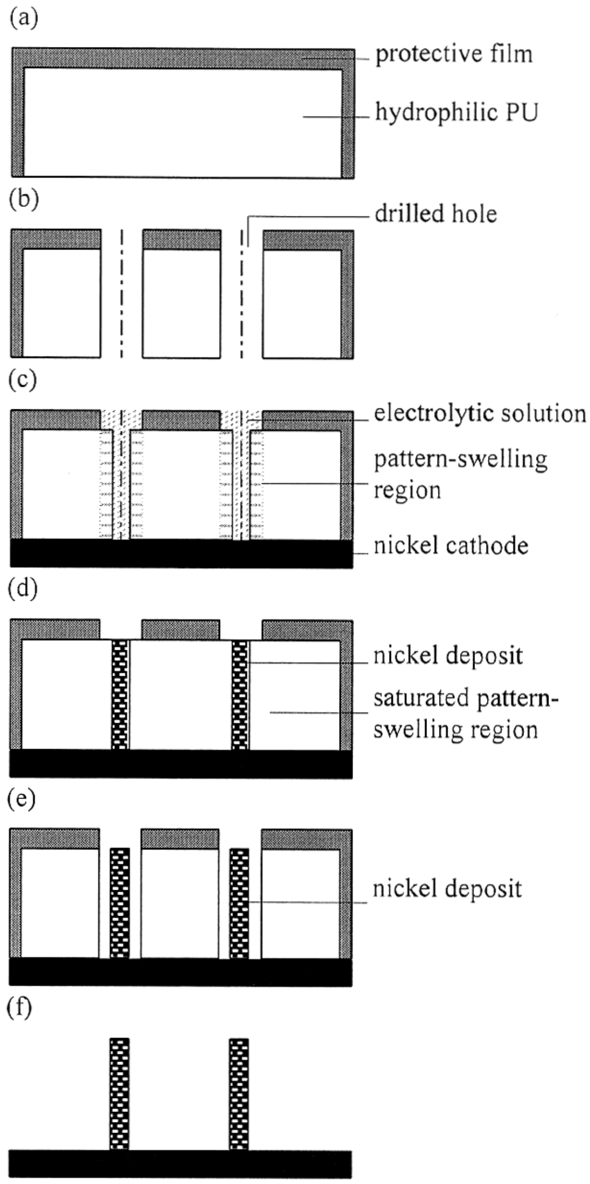

Figure 1: The process of manufacturing micro-post-array nickel molds..

For generating co-axial multi-layer microstructures, the process can also be divided into 6 procedures, as illustrated in Figure 2. Since this process is very similar to the production process for micro-post-array except sample preparation and demolding, it will be simply described. At first, the sample is prepared by repeatedly coating 200μm-thick non-hydrophilic epoxy and 200μm-thick hydrophilic polyurethane layers, in order to form a polyurethane/epoxy laminate structure with a thickness of 5mm. The sample is then coated with a protective film (Figure 2(a)). Secondly, 400μm-diameter holes are drilled in the sample using a laser beam (Figure 2(b)). Thirdly, the patterned sample is fixed on a nickel cathode and immersed in an electrolytic solution (Figure 2(c)). Fourthly, the saturated sample is electroformed in the electrolytic solution (Figure 2(d)). Fifthly, the sample is taken away from the electrolytic solution and lapped to a desired thickness (Figure 2(e)). Finally, organic solvent or thermal decomposition is used to dissolve or to decompose the laminate structure, and then penetrated co-axial multi-layer nickel microstructures with 50μm-diameter posts are thus created (Figure 2(f)).

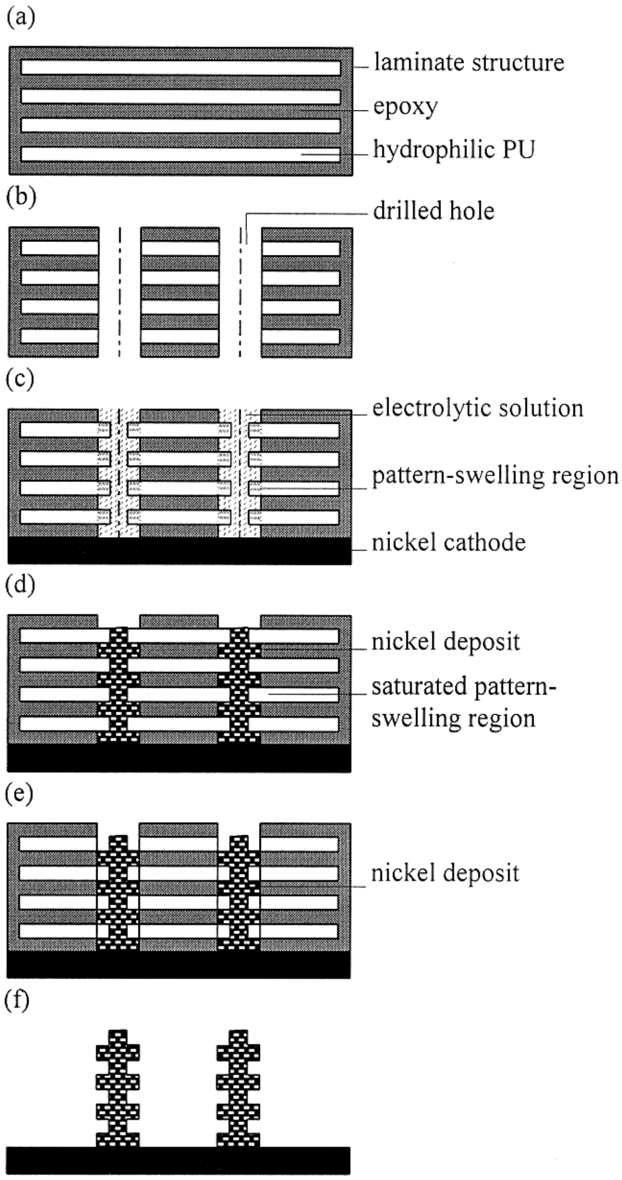

Figure 2: The procedures of fabricating co-axial multi-layer nickel microstructures.

3.2 SWELLING AND ELECTROFORMING

In the processes for producing micro-post-array and co-axial multi-layer nickel microstructures, electrolytic bath is used for the swelling of polymers and electroforming. The set-up of the electrolytic bath is illustrated in Figure 3. In these procedures, the sample is put on the cathode and immersed in the electrolytic solution. The electrolytic solution is made of nickel ammonium sulfate (40 parts), boric acid (2 parts), nickel chloride (1 part) and nickel brightener (1 part). The relative specific weight of the original electrolytic solution is 52 (the relative specific weight of water is 10). The original electrolytic solution is diluted with de-ionic water when it is used for the treatment of swelling and electroforming. The PH value of the solution should always be kept at approximately 4 by adding either sulfamic acid (to lower PH value) or nickel carbonate (to increase PH value) during swelling and electroforming. The temperature of the solution is set at 40°C, which is heated by an electrical heater and monitored by a thermocouple (Figure 3). In the step of swelling, no electrical current is applied. But in the procedure of electroforming, the applied voltage and current are 2.0V and 0.02A respectively.

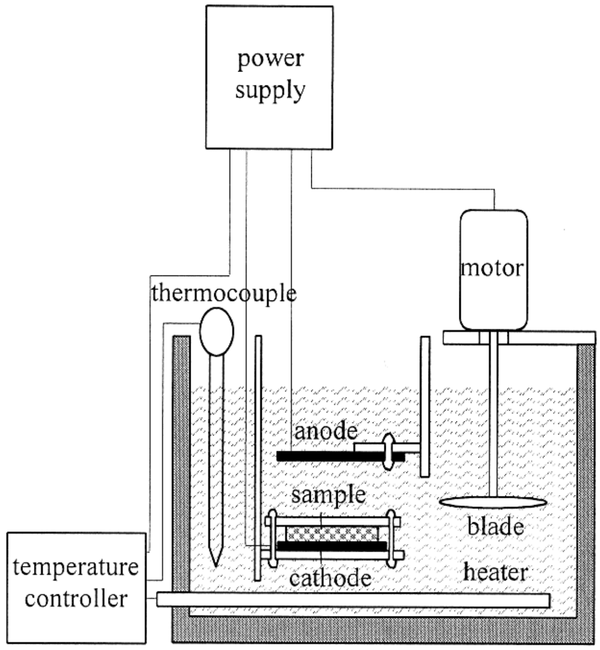

Figure 3: The set-up of electrolytic bath.

3.3 MEASUREMENT

The surface morphology of samples after laser drilling and those after the treatment of swelling was performed using an optical microscope (OM). The morphology of nickel microstructures was photographed using a scanning electron microscope (SEM) or OM. The diameters of drilled holes were measured using OM or SEM. The PH value and relative specific weight of the electrolytic solution were measured with a PH meter and Baumé meter respectively.

4. DISCUSSION AND RESULTS

4.1 MATERIAL REQUIREMENTS

In this study, the aspect ratio of microstructures is strongly improved by the swelling of polymers. Therefore, the bulk material should absorb a certain amount electrolytic solution, but not dissolved or

destroyed in the solution. For this purpose, hydrophilic polyurethane is used as specimen, which is one of the best candidates.
In order to produce co-axial multi-layer microstructures, laminate structure with different materials was used. This laminate structure can be constructed from hydrophilic materials and non-hydrophilic materials, or from hydrophilic materials with different amounts of absorption of electrolytic solution when saturation. Thus, hydrophilic polyurethane and non-hydrophilic epoxy was used in this study, in order to build up the laminate structure for co-axial microstructures.

4.2 LASER DRILLING

For the polymer micromachining, holes with a diameter of 50μm and an aspect ratio of more than 5 are frequently drilled using excimer lasers. Utilizing these lasers, however, the machining depth and aspect ratio are limited to less than 500μm and smaller than 20 respectively. Thus, it is almost impossible to drill holes with a depth of 5mm in polymeric substrates.
If the diameter and depth of drilled holes in polymers increase to some hundred micrometers and to some millimeters respectively, CO_2 lasers seem to be the better choice than excimer lasers. Therefore, in this study, a CO_2 laser was used to drill holes with a diameter of 400μm and a depth of 5mm in hydrophilic polyurethane sheets and laminate structures, as seen in Figure 4(a).

4.3 SWELLING OF POLYMERS

The treatment of swelling is the main issue in this study. Before the specimen is immersed in the electrolytic solution, the specimen should be coated with a protective film. The function of this film is to avoid mass transport of the electrolytic solution into the bulk of specimen from unwanted surfaces. This will avoid the dimension variation of the specimen during swelling.
If the specimen is not coated with this protective film, the electrolytic solution will mass transport into the bulk of specimen from all surfaces of specimen. The dimensions of specimen (length, width and height) will increase until saturation. This means that the volume of specimen will increase due to absorption of the solution in the specimen. Additionally, the diameter of drilled holes may also increase. Therefore, the aspect ratio of electroformed structures may not increase.
In contrary, if the specimen is coated with the protective film, the electrolytic solution can not diffuse into the bulk of specimen from outer surfaces, except from the surfaces of drilled holes. The dimensions of specimen are thus constrained and can not be varied during swelling. In fact, the volume of specimen will increase due to absorption of electrolytic solution from the surfaces of drilled holes. As illustrated above, the dimensions of specimen are constrained by the protective film. The increasing volume of polymers during swelling will thus force the surfaces of drilled holes to move toward the cavity of drilled holes. As a result, the diameter of drilled holes will decrease after the treatment of swelling. This means that the aspect ratio of drilled holes will be improved.

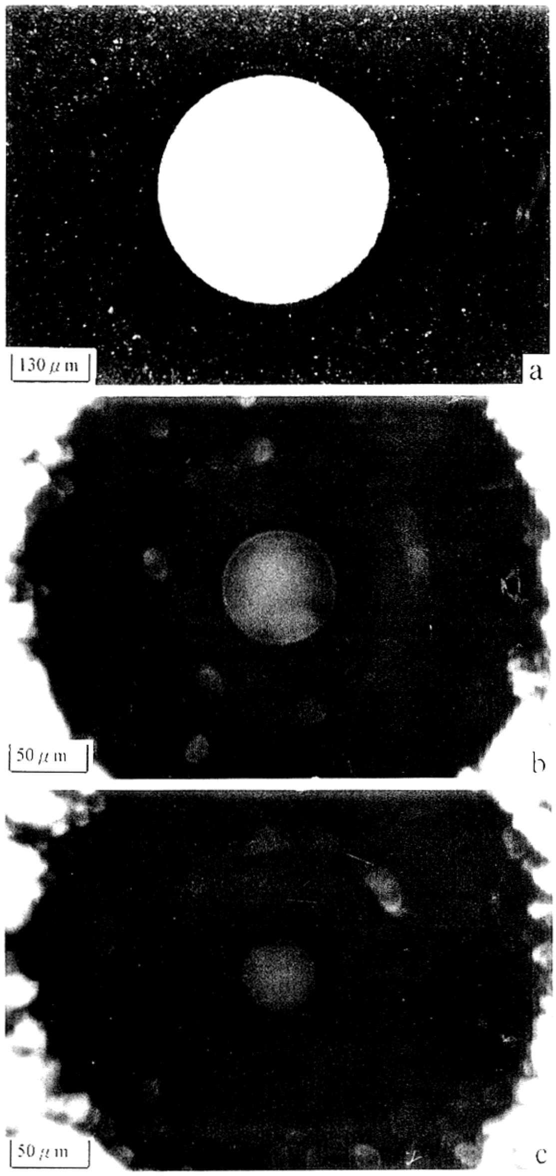

Figure 4: Sequence of optical microscopes of hole with different uptake time (a) 0 hr, (b) 23 hr, and (c) 40 hr.

Figure 4 shows surface morphology of drilled holes in the specimen before, during and after the treatment of swelling. The diameter of drilled holes is 400μm before the treatment of swelling, while 50μm after the treatment. This indicated that the aspect ratio of drilled holes strongly increase by 8 times.
During the swelling step, the relationship between the diameter of drilled holes and uptake time can be seen in Figure 5. At the beginning of swelling, the diameter of drilled holes decrease very rapidly, but the decreasing rate reduces with increasing uptake time. After 40

hours treatment, the diameter does not decrease any more. This means that the specimen is saturated. Therefore, the electrolytic solution will stop to mass transport into the bulk of specimen.

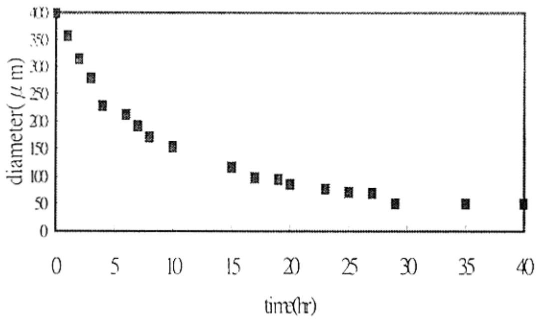

Figure 5: Diameter of hole as a function of uptake time.

As illustrated above, diameters of drilled holes in hydrophilic specimens can be varied by the treatment of swelling. If a laminate structure constructed with hydrophilic/non-hydrophilic layers is drilled and treated with swelling, the co-axial multi-layer microstructure with different diameter cavities is then created, as seen in Figure 2(c).

4.4 ELECTROFORMING

In this study, electroforming starts just after the specimen being saturated. This hints that the diameter of drilled holes will not be changed if the temperature of electrolytic solution is kept at the same value. Since the working temperatures and electrolytic solution in the procedures of swelling and electroforming are the same, the dimension of drilled holes after treatment of swelling will not be varied during electroforming.

4.5 DEMOLDING

For the conventional LIGA-process, metallic molds are achieved by completely dissolving polymers and etching metallic seed layer. But the demolding in this study is much more easily than the conventional LIGA-process.

In the process for producing micro-post array nickel molds, demolding is carried out at 100°C in an normal oven by desorption of electroformed specimens. In this procedure, the saturated pattern-swelling regions in the sample will restore to their original dimensions due to desorption of the electrolytic solution, as shown in Figure 1(e). Nickel deposits is then easily removed without destroying the sample. The generated micro-post-array nickel structure is shown in Figure 6.

In the process for creating co-axial multi-layer nickel microstructures, demolding is performed using organic solvents to dissolve epoxy and/or polyurethane layers. The fabricated, penetrated co-axial multi-layer nickel microstructures with 50μm-diameter posts are shown in Figure 7.

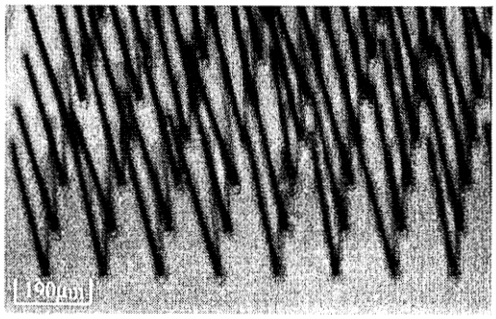

Figure 6: Photograph of the fabricated 3-D nickel post.

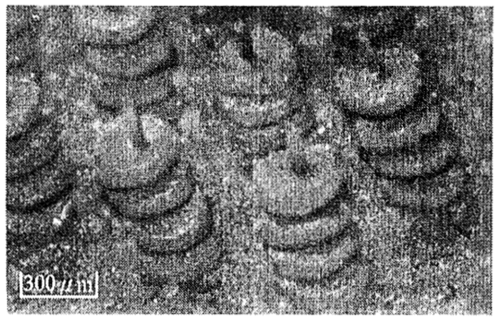

Figure 7: Photograph of the fabricated 3-D nickel multi-layer structure.

4.6 COST

As described above, only few machines are necessary for the proposed process, such as coater, CO_2 laser, electrolytic bath, oven and wet bench. The costs of these machines are much lower than those needed for LIGA-, LIGA-like and laser LIGA processes. CO_2 laser is widely used in industrial, it is causes of its low cost by using CO_2 laser can effectively reduce product cost.

Furthermore, the drilled samples are immersed in the electrolytic bath for both the treatment of swelling and electroforming. Finally, the samples are dried in an oven for demolding. Thus, the manufacturing procedures in proposed process are much easier and simpler than the conventional methods for creating high-aspect-ratio metallic microstructures.

5. CONCLUSION

A novel process for fabricating high-aspect-ratio nickel microstructures is proposed. Using this process, micro-post-array mold and co-axial multi-layer microstructures were successfully produced. The microstructures have a very high aspect ratio of about 100, a diameter of 50μm, and a height of 5mm.

The process can be divided into 6 procedures: protective

film coating, laser drilling, swelling of polymers, electroforming and demolding. The pattern is defined using a CO_2 laser. The high aspect ratio and pattern accuracy of metallic microstructures is achieved by the treatment of swelling.
Comparing this process with the conventional methods, the advantages of this process include low cost, simple procedures, and easy demolding.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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