Sensors and Materials, Vol. 11, No. 6 (1999) 329–337
MYU Tokyo

S & M 0376

Manufacturing Processes for LIGA Spinnerets

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(Received August 5, 1999; accepted August 10, 1999)

Key words: LIGA, deep X-ray lithography, spinneret, synthetic fiber

LIGA process, which includes X-ray lithography, electroforming and injection molding, was used to manufacture spinnerets with various geometries for functional fiber production. To satisfy the ultradeep requirement of spinnerets, a special process of deep X-ray lithography was developed to generate a LIGA die with a capillary 2 mm deep and 70 μm wide. Mass production of spinnerets is then achieved by injection molding and electroplating. Production of new generation fibers with extrafine sizes and new functionality at a low cost can be expected.

1. Introduction

The polyester industry has existed since the 1950's, and technological advances are now allowing the industry greater room for growth. One area with great potential is that of microfibers that breathe like natural fibers and have a softer feel than traditional polyester fibers. Polyester fibers, which melt typically at 260°C, can be divided into two types: one is staple (fibers cut into lengths of 0.45 m or longer), which is primarily used for blended yarns and fibers; the other is filament, which is used in outer garments, linings and other applications. The size of filaments is measured in denier. One denier is defined as one gram of polyester raw material at a length of 9,000 meters. Larger denier numbers mean thicker fibers. Fine filaments under 0.3 denier are termed extrafine denier filaments or microfibers, and 1.0–0.3 denier fibers are called fine denier filaments.

The polymers are fed into a spinneret with 24–48 holes (72–144 holes in the case of high-count filaments) to produce filaments at a speed of over 3,000 m/min. The capillary width of the microfiber spinneret is usually larger than 100 μm to prevent blocking during the direct spinning process. Therefore, making the capillary deeper is much more important than making the capillary smaller for microfiber production. From the theoretical point of view, the aspect ratio of the shaped capillary should be larger than 6 to extend the fully developed flow in the capillary. The spinnerets are normally fabricated by a micro-EDM (Electric Discharge Machining) technique. However, this method cannot satisfy the requirements to produce complexly shaped, high-aspect-ratio spinnerets at a low cost. Innovative machining technology should be developed for spinneret fabrication.

2. LIGA Spinnerets

In recent years, many micromachining technologies have been developed as extensions of microelectronic fabrication. Among these techniques, LIGA is known as a powerful method to fabricate high-aspect-ratio microstructures (HARMS) with high precision. LIGA is the abbreviation of German words of "Lithography," "Galvanik" and "Abformung," which mean lithography, electroforming and molding, respectively, in English.[1] Highly intense and collimated synchrotron radiation is used as the light source in deep X-ray lithography (DXL). Polymethylmethacrylate (PMMA) is commonly used as the X-ray resist due to its high contrast and low surface roughness after developing. After die electroforming, microstructures are mass-produced by molding and plating. Various materials (metal, alloy or composites) could be used to replicate the microstructures according to the applications.

Spinnerets manufactured using LIGA have the following advantages: (1) high aspect ratio, (2) high uniformity, (3) low surface roughness, (4) high level of hardness, and (5) any lateral geometry. Such a LIGA spinneret will have direct impact on 0.5 denier fiber production due to its high spinning speed and uniformity.

Microfibers are currently obtained by splitting the fibers extruded from a conjugate spinneret. However, the production speed is low and the cost is high. In contrast, fine fibers of 0.5 denier are produced by single-component spinning without splitting the fibers. The spinning speed is about 1,500 m/min. Although this spinning speed is lower than the normal production speed, it is still more cost-effective than the conjugate technology. In this paper, the manufacturing process of LIGA spinnerets is presented. Very deep (2 mm) and shaped capillaries with a minimum feature size of 70 μm were fabricated successfully by this process. The issues on X-ray lithography, electroforming and microinjection molding are discussed in the following section.

3. Die Fabrication

3.1 *Ultradeep LIGA technology*

The key problem in fabricating a thick microstructure is the difficulty of forming trenches, not the exposure.(2) There are many methods, such as agitating, heating and elevating dosage to increase the developing rate in deep lithography. Among these methods, increasing X-ray dosage, which will efficiently break the chemical bonds in a polymeric material, is the safest way to accelerate developing process.(3)

Upon X-ray irradiation, the intensity attenuates as the penetration depth increases due to the absorption of the PMMA resist. To develop the resist in a reasonable time, the bottom dosage should be higher than ~4 kJ/cm^3, whereas the top dosage must be lower than ~20 kJ/cm^3; otherwise the gases induced upon irradiating X-rays will destroy the brittle PMMA structure. Under these two boundary conditions, it is difficult to elevate the X-ray dosage in the PMMA resist. The common method to fabricate a thick microstructure is using hard X-rays because of their high penetration power. However, the induced photoelectrons will scatter in the resist and then degrade the precision of the lithography.(4) The difficulties in mask fabrication and the accessibility of the light source together with the safety concerns make this method inappropriate for making very thick microstructure.

A new strategy, the "ultradeep LIGA process," was developed in this program to fabricate 2-mm-thick microstructures.(5) The principle involves carrying out DXL through successive exposure and developing processes. After the first lithography process, the dosage could be elevated beyond the constraint since the generated gases can escape through the porous surface. Total reflection of the X-rays during the second exposure prevents further photon deposition upon the sidewall. The dose distribution in the resist can be modified and the developing rate substantially accelerated. The strategy of successive exposures not only circumvents the problem of the shortage of hard X-rays but also overcomes the constraint on the developing time.

To eliminate the alignment procedure accompanying the multiple exposure processes, the idea of a conformal mask was adopted in this experiment. Although the conformal mask can only be used once, the tool for mass production is the die, not the mask in the LIGA process. Figure 1 shows the modified LIGA process using an X-ray conformal mask. As illustrated in the figure, a thin copper layer is sputtered or colaminated on PMMA. A thick resist (JSR 137N, Japan) is then patterned on the copper layer by UV lithography, followed by plating gold absorbers. After stripping the resist and the copper layer, the conformal mask is now ready for subsequent DXL and die electroforming (Fig. 1(c), (d), (e)).

There are several advantages of this successive exposure process combined with the use of a conformal mask: (1) no alignment is required, (2) no proximity gaps between the resist and mask occur, (3) thinner absorbers and less exposure time are required, (4) and a high developing rate is achieved. Very deep and high aspect ratio microstructure could survive after DXL process. Figure 2 is the scanning electron microscopic (SEM) image of a PMMA structure fabricated by the double exposures and developing procedure. No stepwise discontinuity was observed on the side wall. This figure also reveals that the Cu layer was slightly overetched to guarantee lithographic accuracy.

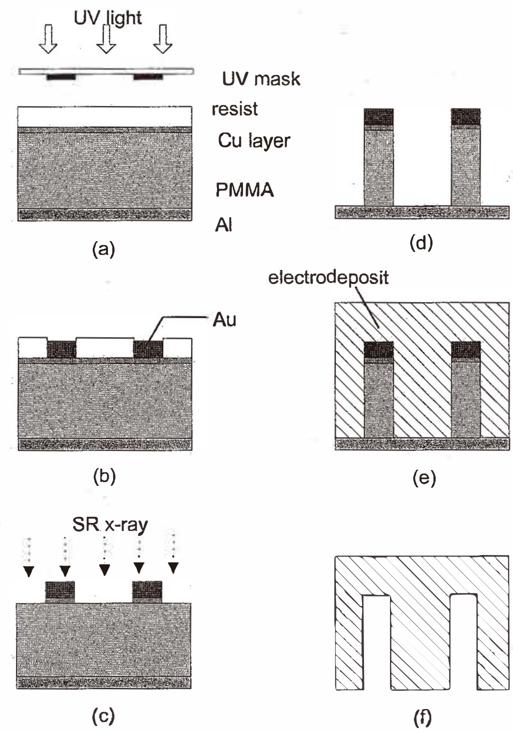

Fig. 1. Schematic diagram of the modified LIGA process. The dimensions in this figure are not in scale.

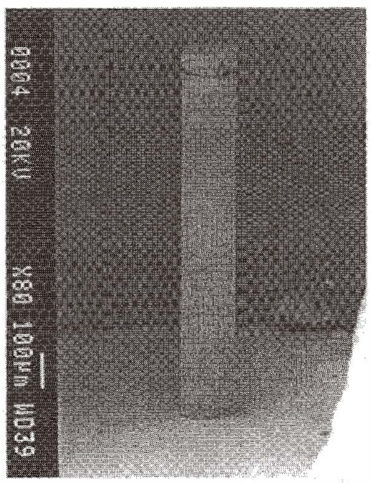

Fig. 2. SEM image of the PMMA microstructure fabricated by double exposures to achieve 1 mm depth. The diameter of the column is 160 μm.

3.2 *Die electroforming*

Nickel is one of the most popular electrodeposits for protective and decorative applications. Among various electrolytes for Ni plating, the sulfamate bath is the best choice for micro-electroforming due to its low-stress deposit. Figure 3 shows the plated Ni capillaries with various geometries. The surface was ground without obvious damage and the polymer inside the orifice has been removed. Compared with EDM technique, LIGA is especially suitable for those spinnerets with complexly shaped capillaries as illustrated in Fig. 3. The uniformity and the aspect ratio of the capillaries, which are very important for high speed spinning, can be controlled well and the capillaries can be fabricated by the LIGA process without any difficulties.

The Vickers' hardness of Ni deposits ranges from 400 to 150 at current densities of 1 and 5 ASD (A/dm^2), respectively. However, high plating rate is more appreciated in production. To improve the duration of the LIGA die, a NiCo alloy-plating technique with a high deposition rate (5 ASD) was also developed. In this study, the cobalt ion was supplied by dissolving Co metal in the sulfamate electrolyte. As illustrated in Fig. 4, the hardness first increases and then saturates (Hv~420) as the cobalt sulfamate concentration is higher than 20 g/l. This indicates the possibility of plating wear-resistant dies at a relatively high deposition rate. However, the residual stress accompanying Co addition must be carefully controlled.

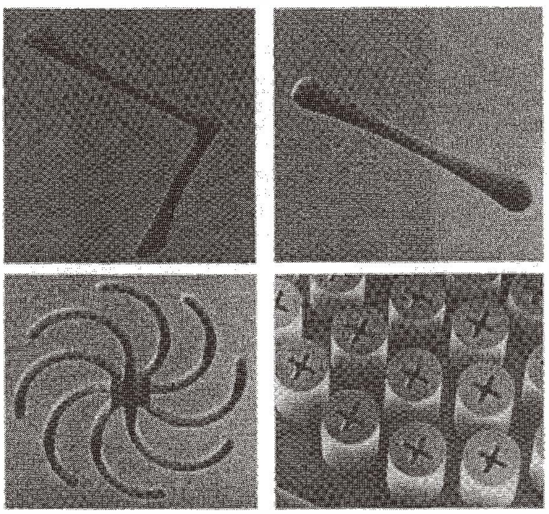

Fig. 3. Electroformed Ni capillaries with various geometries. The depth is 1 mm and the minimum feature size is 100 μm.

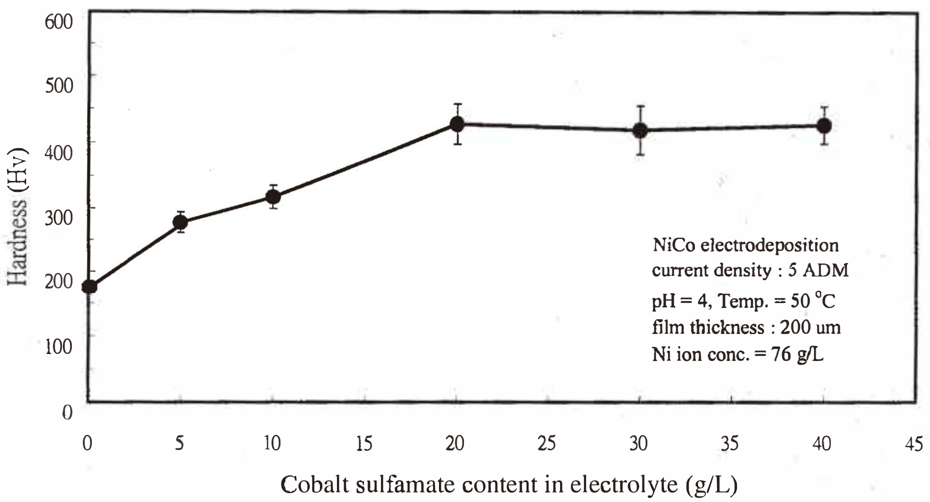

Fig. 4. Hardness of NiCo alloy deposit versus the cobalt sulfamate concentration in the plating bath.

4. Spinneret Duplication

4.1 *Injection molding and capillary electrodeposition*

Once the die was fabricated, microstructures were subsequently duplicated by injection molding as illustrated in Fig. 5. Polypropylene (PP) was used as the molding material. Figure 6(a) shows the photograph of the molded result with 72 shaped polymer structures on the stainless body. The width of the capillary was 70 μm and its depth was 2 mm. Electrodeposition process is conducted directly on the stainless surface to replicate the capillaries. As indicated in Fig. 6(b), the molded polymer structure exhibits smooth side walls and a well-defined geometry. The debris on the top surface is acceptable in the LIGA spinneret process because the complimentary electrodeposit will be ground to reveal the orifice.

Prior to capillary electroplating, the stainless surface was thoroughly cleaned to guarantee the adhesive strength of the deposit. Figure 7 shows the SEM image of a LIGA spinneret with 72 W-shaped capillaries. The top surface of the deposit was ground and the polymer inside was removed by mechanical and thermal methods. The depth and the minimum feature size of the capillaries are 2 mm and 70 μm, respectively. The performance of the LIGA spinneret is now under test for practical fiber spinning. As demonstrated in this report, such a high aspect ratio and high precision LIGA spinneret can be mass-produced at low cost. The geometry of the capillaries is not limited by mechanical machining ability; consequently, microfibers with new functionality can be explored using this technology.

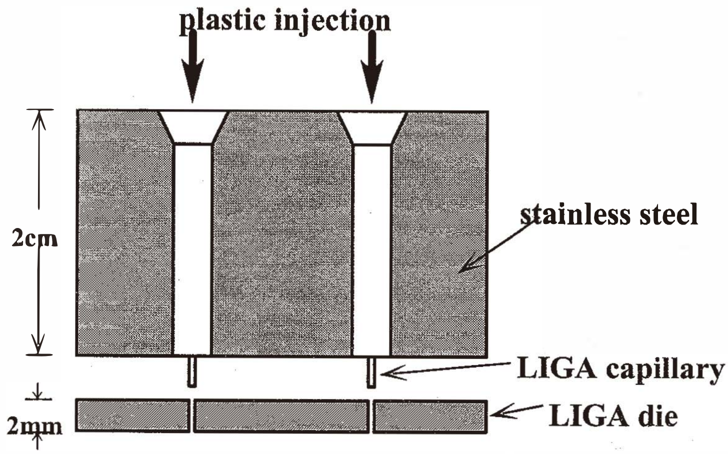

Fig. 5. Duplication process of LIGA spinneret.

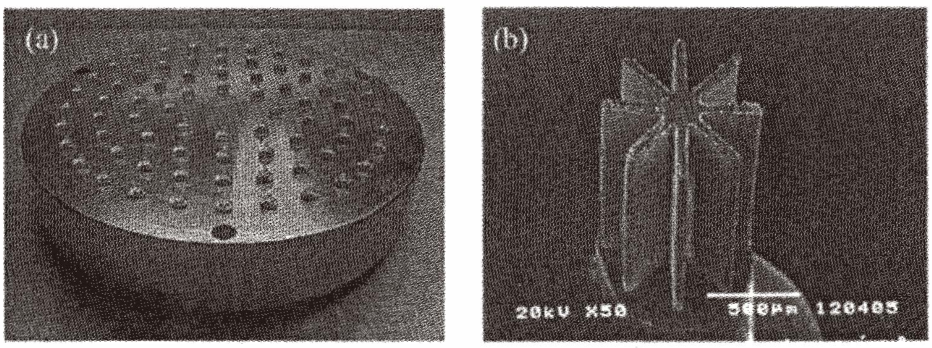

Fig. 6. (a) Optical photograph of the molding result, showing numerous polymer microstructures standing on the SUS substrate. (b) Magnified image of an individual polymer structure. The thickness and line width are 2 mm and 100 μm, respectively.

4.2 *Composite plating*

During fiber extrusion, the spinneret suffers harsh condition of high temperature (~280°C). Some inorganic additives, such as TiO_2, accelerate the wear rate in some extensions. Therefore, high temperature hardness is a particular concern for the durability of the spinneret. The hardness of NiCo alloy is similar to that of SUS 630 at room temperature; however, it degrades markedly at a temperature of 300°C. In order to improve the lifetime of the LIGA spinneret, a Ni/SiC composite plating technique was studied. The

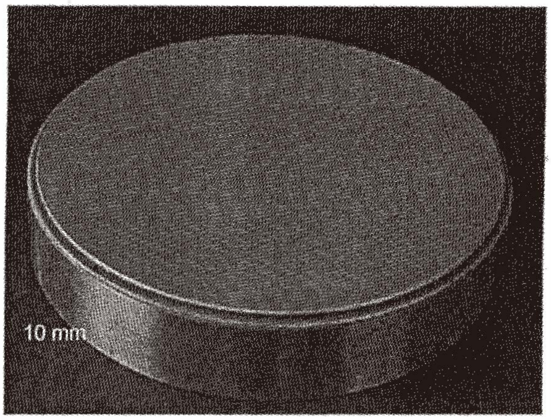

Fig. 7. LIGA spinneret with 72 W-shaped capillaries in NiCo electrodeposit.

uniformity of the nanoparticles along the depth direction is particularly important. Preliminary results showed that the composite coating maintains its hardness (~ Hv 500) up to a temperature of 500°C. In the future, this technique will be applied to fabricate capillaries that can extend the lifetime of LIGA spinnerets.

5. Summary

Today, polyester fibers are commonly used in daily life. Many functional fibers were developed to satisfy all the requirements in various applications. In such progress, the spinneret plays a very import role in producing extrafine fibers of high quality and new functionality. The spinneret is normally fabricated by a micro-EDM technique. However, this method cannot fabricate capillaries with complex shapes and high aspect ratio at a low cost. Innovative technology is therefore urgently needed to facilitate the fabrication of high performance spinnerets.

In this paper, LIGA was used to fabricate the spinneret. A precise die was first fabricated by deep X-ray lithography combined with electroforming technique. Spinnerets were duplicated by injection molding and plating. To meet the requirement in capillary depth, a new technique, termed the "ultradeep LIGA process," was explored to produce very thick microstructures with high aspect ratio. Instead of Ni deposition, NiCo alloy and Ni/SiC composite plating techniques were utilized to improve the wear resistance of the LIGA die and the spinneret. In this report, the manufacturing process for the LIGA spinneret was demonstrated. A spinneret with capillaries 2 mm deep and 70 μm wide was successfully fabricated by this method. New generation fibers can be expected as a result of this development.

Acknowledgements

The authors thank Prof. W.-C. J. Wei (Institute of Materials Science and Engineering, Taiwan University) for providing support in nickel composite plating. The authors also thank the National Science Council of the Republic of China for its financial support under contract no. of NSC-85-2622-E007-010.

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