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ORIGINAL ARTICLE

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Micro-stereolithography photopolymer solidification patterns for various laser beam exposure conditions

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Abstract Micro-stereolithography is a novel micromanufacturing process that fabricates 3D microstructures by solidifying the photopolymer using a UV laser in a layer-by-layer fashion. In this paper, variation in the photopolymer solidification pattern due to the scanning pattern and pitch of a focused laser beam was investigated experimentally. Also, experiments were conducted to determine the effects of the layer thickness on the solidification width and depth in multi-layer solidification. The experimental results were compared to numerical simulations. The results showed that a zigzag-shaped scanning pattern was faster and more stable than a crank-shaped pattern. It was also determined that the scanning pitch should be selected according to solidification depth and width for a given scanning pattern, and that the layer thickness has little effect on the solidification depth. Based on the results, several microstructures were successfully fabricated, such as a micro-tube with a helical separation wall and a microlink.

Keywords Microstereolithography · UV laser · Photopolymer · Focusing lens · Laser beam · Solidification

Nomenclature

P_L	The power of the laser beam
λ	The wavelength of the laser beam
f	The focal length of the focusing lens
z	The depth from the surface of photopolymer
V_S	The scanning feed of the laser beam
$W_0(z)$	The Gaussian half-width of the focused laser beam at a given depth z
E_C	The critical exposure of the photopolymer
D_P	The penetration depth of the photopolymer
$W_{0\ min}$	The Gaussian half-width at the focal point
R	The Gaussian half-width of the laser beam that passes into the focusing lens
w	The scanning width of the laser beam
L	The solidified width of the photopolymer
h	The solidified depth of the photopolymer
D_1	The layer thickness
D_2	The total solidified depth in a multi-layer solidification

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1 Introduction

More progressive and innovative technologies are required as the needs of modern society and individuals become more varied and complex. Microsystem technology (MST) has been developed to meet those needs and is regarded as one of the twenty-first century's leading technologies.

Surface micromachining, bulk micromachining, and lithography galvonoforming abforming (LIGA) are representative microsystem technologies. These technologies are based on the semiconductor manufacturing process, and can be mass-produced and easily integrated with signal processing circuits. However, it is very difficult to fabricate the required high aspect ratio 3D structures with complex cross-sectional shapes. LIGA was introduced to overcome the high-aspect ratio problem, and was followed by several other technologies. It is, however, still not possible to construct a 3D structure that has complex cross sections.

Microstereolithography technology, which made it possible to fabricate a freeform 3D microstructure, was first introduced by Ikuta [1, 2]. This technology is based on conventional stereolithography, in which a UV laser beam irradiates the open surface of a UV-curable liquid photopolymer, causing it to solidify. In microstereolithography, a laser beam that is a few μm in diameter is used to solidify a very small area of the photopolymer. This is one of the key technological elements, and can be achieved by using a focusing lens. Thus, the solidification phenomena of the liquid photopolymer must be carefully investigated.

Research into the solidification of liquid photopolymers in microstereolithography has focused mainly on the single line radiation of a laser. Maruo et al. [3, 4] demonstrated the solidification depth and width of a single line laser radiation in two-photon absorption microstereolithography. Zissi et al. [5] and Scheffer et al. [6] developed a theoretical model of photopolymer solidification that considered the concentration of the nonreactive photoabsorber. They also examined the effects of the photoinitiator concentration, the irradiation flux and the irradiation time on the solidification depth and width of single line laser radiation. Zhang et al. [7] introduced ceramic micro-stereolithography and measured the solidification width and depth of seven overlapped lines of laser radiation, as well as a single line. Nakamoto et al. [8] developed a photopolymer solidification model for a focused single line laser beam, and compared their results with other experimental data.

In real micro-stereolithography systems, however, many UV laser scan lines are overlapped to fabricate a given cross-sectional area. These are stacked together to form the desired 3D shape. The solidified depth and width of the cured photopolymer largely depend on the scan pattern and pitch of the laser beam, yet despite being essential to the development of micro-stereolithography technology, little research has been reported on these aspects.

In this paper, we experimentally investigate the photopolymer solidification pattern in response to variations in the scanning pattern and pitch of a focused laser beam. These results are compared with those obtained from a photopolymer solidification model of a focused laser beam developed using analysis software. The effect of layer thickness on the solidification width and depth is also examined in the multi-layer solidification.

Based on the results, typical examples of microstructures, such as a micro-pipe with a helical separation wall and a micro-link, were successfully fabricated.

2 The photopolymer solidification model

A UV laser is used as the light source in most microstereolithography. A focusing lens is used to obtain the very small focal point diameter. When the laser beam irradiation has a Gaussian distribution and is focused on the surface of the photopolymer, the Gaussian half width of the beam changes along the optical axis after passing through the focusing lens. According to the Beer-Lambert law, when a beam passes through a certain medium, part of its energy is absorbed by the medium, and thus the irradiance decreases along the optical axis. Generally, a liquid UV-curable photopolymer solidifies by absorbing the UV light. When the photoinitiator in the photopolymer is activated by a photon of UV light, the monomers in the photopolymer are cross-linked and become polymers. To make a desired cross-section, the focused laser beam must follow a given path; thus, the light-absorbing pattern inevitably changes according to the laser power and scanning speed of the laser beam.

Suppose that a continuous wave (CW) laser beam of wavelength λ and power P_L passes through a focusing lens of focal length f as shown in Fig. 1. The laser beam radiates vertically and becomes focused on the surface ($z=0$) of the photopolymer. Let the scanning speed of the laser beam be V_S. Then the solidification shape along the laser-moving axis can be expressed as follows [8, 9]:

$$y = \frac{2}{W_0(z)^2}\sqrt{\ln\left(\sqrt{\frac{2}{\pi}}\frac{P_L}{W_0(z)^2 V_S E_C}\right) - \frac{z}{D_p}} \tag{1}$$

where D_P is the penetration depth of the photopolymer and represents the depth at which the irradiance becomes 1/e times that at the surface. E_C is the critical exposure of the photopolymer, and represents the energy level as the photopolymer changes from liquid to solid. D_P and E_C are properties of the photopolymer, and can be evaluated through experiments. $W_0(z)$ is the Gaussian half-width of the laser beam, which varies along the optical axis because of the focusing lens.

As shown in Eq. 1, the solidified shape of the photopolymer is gourd-shaped and thus symmetrical with respect to the beam axis. And it is also found that the material properties (D_P and E_C), laser scanning speed and laser power have influence on the solidification depth.

A numerical simulation program was developed based on the above result to give the solidified shape of the polymer due to the laser beam irradiation. The input parameters to this program are the material properties (D_P and E_C) and optical values (λ, P_L, V_S, and f). We used this program to compare our experimental data to numerical results. Figure 2 shows a captured screen image of the developed program.

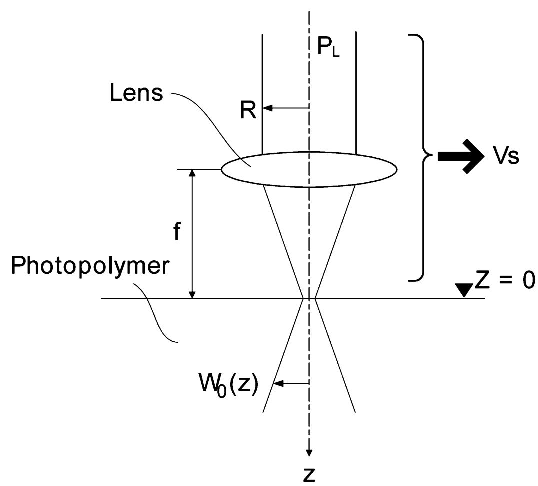


Fig. 1 The scanning of the focused laser beam by a focusing lens on the surface of a photopolymer

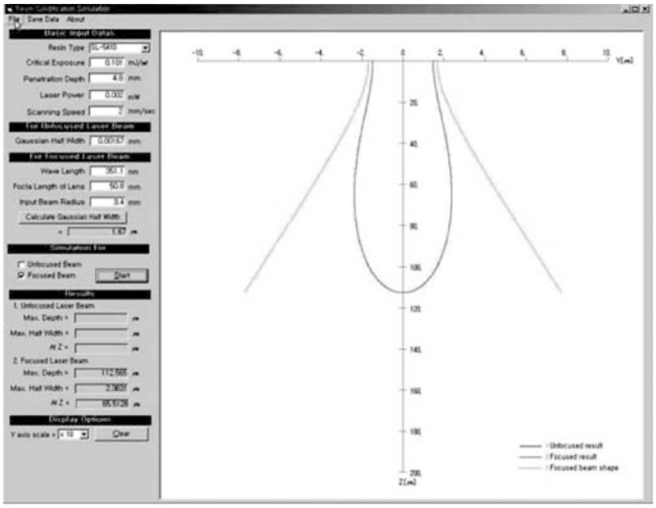


Fig. 2 A screen image of the developed software for the solidification shape analysis of photopolymers

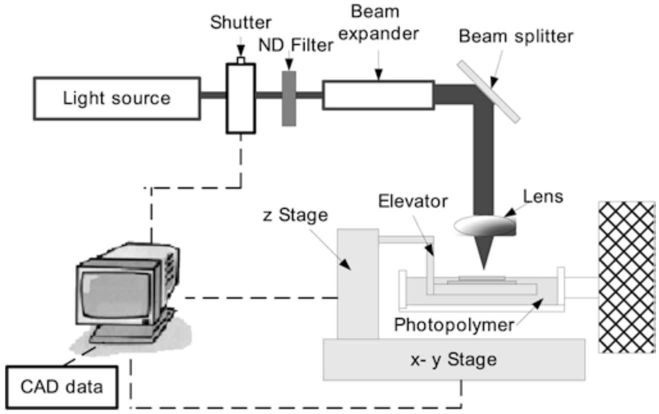


Fig. 3 A schematic drawing of the developed microstereolithography apparatus

A beam expander was used to increase the beam diameter R.

3 The construction of the microstereolithography apparatus

Figure 3 shows a schematic drawing of the developed micro-stereolithography apparatus. An Ar+ laser was used as the light source, which had a wavelength λ of 351.1 nm and Gaussian half width R of 0.85 mm. To attenuate the power of the laser, a neutral density (ND) filter was used. Beam splitters and mirrors changed the laser beam path, and a lens with a focal length f of 50.8 mm was used to focus the beam on the surface of the photopolymer. In our system, the substrate moves in three orthogonal directions (termed an elevator) in the photopolymer container by the x-y-z stage and a fixed laser beam is irradiated onto.

In microstereolithography, the UV laser beam must be focused to within a few μm. When a focusing lens with a relatively long focal length is used, the Gaussian half-width at the focal point $W_{0\,\min}$ increases as:

$$W_{0\,\min} = \frac{f\lambda}{\pi R} \tag{2}$$

4 Photopolymer solidification experiments

We experimentally investigated the solidification pattern of the photopolymer in response to the variation of the scanning pattern and pitch of a focused laser beam. The effects of layer thickness on the solidification width and depth in multi-layer solidification were also examined. Table 1 summarises the experimental conditions. The photopolymer used in this experiment was SL 5410 (3D Systems), of which the penetration depth and critical exposure were 4.8 mils and 10.1 mJ/cm^2, respectively.

4.1 The laser scanning pattern

To develop and advance micro-stereolithography technology, it is essential to study the effects of various laser beam scanning patterns on the solidification of the photopolymer. The scanning path of the laser beam depends largely on the cross-sectional shape of the structure, which can affect its scanning pattern or pitch.

Table 1 Experimental conditions

Experiment conditions	Laser scanning conditions			Layer thickness
Type of experiment	Pattern	Width (μm)	Pitch (μm)	(μm)
Laser scanning pattern	Zigzag shape	300	1∼8 (step size 1)	–
	Crank shape	300	1∼8 (step size 1)	s
Laser scanning pitch	Zigzag shape	200	1∼8 (step size 1)	–
		300	1∼8 (step size 1)	–
		400	1∼8 (step size 1)	–
Layer thickness	Zigzag-shape	300	4	10∼60 (step size 10)

Laser power = 1 μW, scanning speed = 1 mm/s

The most commonly used scanning pattern in conventional stereolithography scans parallel to only one direction. Our experiments indicate that this also works well for micro-stereolithography, and that the built structures tend to collapse easily when any other type of scanning pattern is used. Two typical scanning patterns of this type were considered: a zigzag-shaped pattern and a crank-shaped pattern (Fig. 4). For each pattern, the solidified depth and width of the scanned area were measured.

The experimental setup is shown in Fig. 5. A bridge shape was fabricated between two support posts to examine the solidification depth and width for each scanning pattern. The scanning pitch was varied between 1 and 8 μm with a step size of 1 μm to examine its effect on the solidification shape. The scanning width of the bridge shape w was 300 μm, the thickness on the support post t was 40 μm and the distance between the two support posts was 350 μm. The power of the laser P_L was attenuated to 1 μW, and its scanning speed V_S was set to 1 mm/s.

The solidified polymer was cleaned with methyl alcohol and Rapid Rinse (Green Power Chemical), and its width and thickness were measured using an optical microscope. A CCD camera was installed to the microscope to capture the image of the optical microscope, and the number of pixels corresponding to the width and depth of the captured image were counted. The relation between the number of pixels and real length was calibrated in advance. A commercially available scale, which is graduated in 10 micrometers, was used to calibrate the relation between the number of pixels of the CCD image and real dimension.

Figure 6 shows the width L and depth h of the solidified photopolymer for the two types of laser scanning patterns given in Fig. 4. The figure indicates that the solidified width and depth of the photopolymer decrease as the scanning pitch increases, regardless of the scanning pattern. However, the rate of the decrease differs. As shown in Fig. 6a, the crank-shaped pattern requires a relatively small scanning pitch (2 μm) to obtain a solidified width $L = 300$ μm compared to the zigzag-shaped pattern (4 μm). Thus the zigzag-shaped scanning pattern substantially reduces the fabrication time. Furthermore, as the scanning pitch increases to a certain value for the crank-shaped scanning pattern, the solidified photopolymer tends to get lost during the

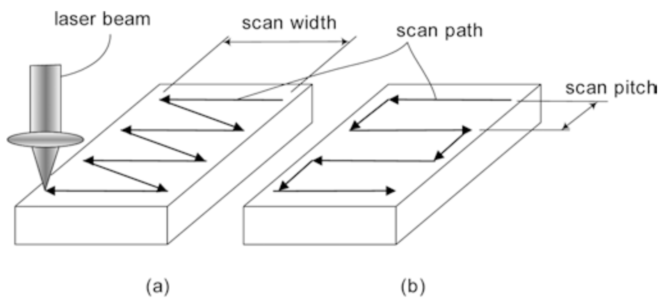


Fig. 4a,b Two different scanning patterns of the laser beam: **a** zigzag-shaped and **b** crank-shaped

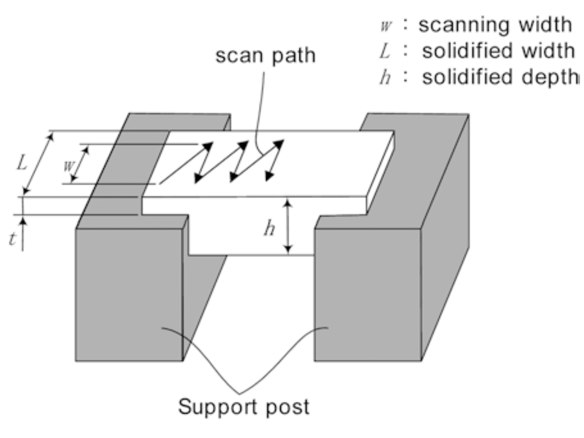


Fig. 5 The experimental setup

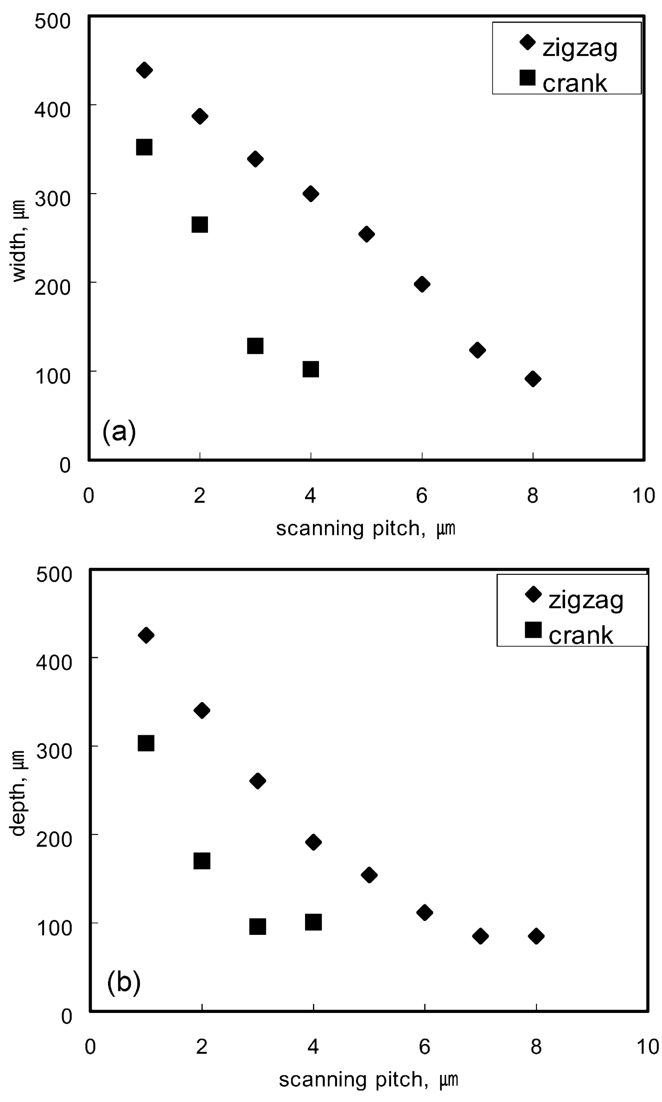


Fig. 6 **a** The width and **b** depth of the photopolymer solidified by a focused UV laser beam with two types of laser scanning patterns

cleaning step, whereas the zigzag-shaped scanning pattern maintains the shape of the microstructure.

4.2 The laser scanning pitch

An identical bridge shape was used in a test to examine the change of the solidification width and height caused by various scanning widths and pitches of the laser beam. In this experiment, the zigzag-shaped scanning pattern was used. The experiment was performed at scanning widths of 200, 300 and 400 μm. For each scanning width, the scanning pitch of the laser beam was varied from 1 to 8 μm with a step size of 1 μm. Figure 7 shows the solidification depth and width of the photopolymer for each condition.

As shown in Fig. 7a, the solidified width increases as the scanning pitch decreases, regardless of the scanning width. When the scanning pitch is smaller than a certain value for each scanning width, the solidified width is larger than the scanning width. At a small scanning pitch, a voxel near the edge of the scanning width tends to receive more radiation energy repeatedly, thus increasing the solidified width. This can be explained by either diffraction effects, fluorescence emissions from the solidified area or changes in the refractive index [6]. On the other hand, the solidification width decreases as the scanning pitch increases. It is conjectured that when the laser scanning pitch increases, the radiation energy absorbed by the photopolymer at a voxel near the edge of the scanning width decreases and the solidified polymer chain is relatively loose. Thus the solidified photopolymer can easily be attacked by the cleaning solution.

Figure 7b shows the solidification depth for each test case given in Fig. 7a. The solidification depth rapidly increases as the scanning pitch decreases for all scanning widths. According to the analytical results, the solidification depth for this condition ($P_L = 1$ μW, $V_S = 1$ mm/sec) with a single line laser radiation is 146 μm. This variation is also due to the difference in the energy absorbed by the photopolymer, diffraction effects, fluorescence emissions or changes in the refractive index.

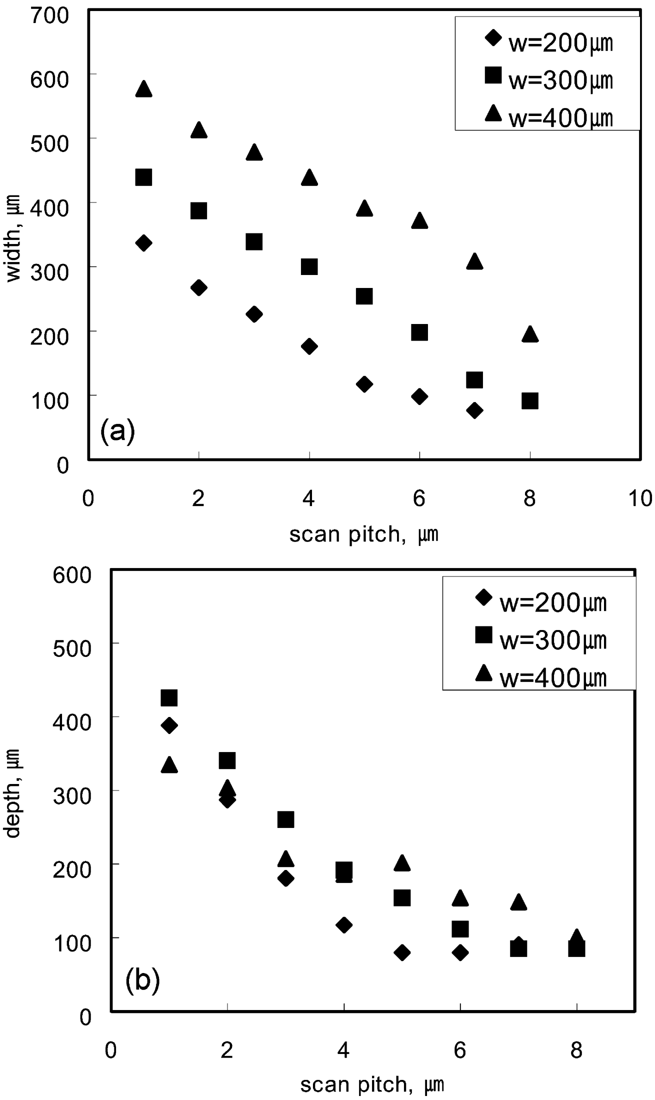


Fig. 7 **a** The width and **b** depth of the solidified photopolymer according to the scanning width and pitch of a zigzag-shaped laser scanning pattern

4.3 The layer thickness

Micro-stereolithography is a layer-by-layer laser-induced polymerisation technology. The laser beam is focused on the open surface of the liquid to turn it into a solid. The layer thickness was varied from 10 to 60 μm with a step size of 10 μm, to examine its effect on the solidification width and depth. These results were compared to the single-layer results.

The laser scanning width and pitch were fixed at 300 μm and 4 μm, respectively, to observe the effects of the layer thickness with the other fixed conditions and the zigzag-shaped scanning pattern was used. The power of the laser was 1 μW, and its scanning speed was set to 1 mm/s. As shown in Fig. 8, the thickness on the support post was 40 μm. Subsequent layers were added to this bridge shape, changing its layer thickness. To

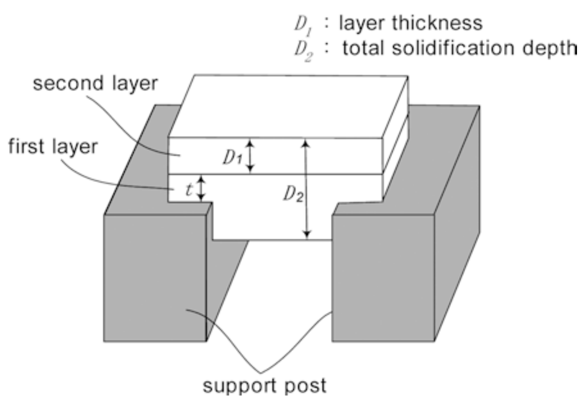


Fig. 8 The experimental setup for the multi-layer polymerisation

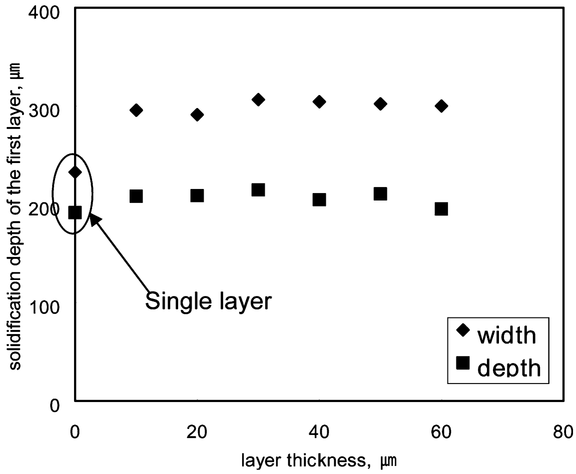


Fig. 9 The effect of the layer thickness on the solidification of the photopolymer

examine the effect of the layer thickness on the solidified depth, the layer thickness D_1 was subtracted from the total solidified depth of the photopolymer D_2.

As shown in Fig. 9, the solidification depth of the first layer (D_2-D_1) remained almost constant, even though the layer thickness increased. However, the solidified width of the multi-layered shape was larger than was observed in the single layered case. The single layered shape appeared to be attacked more easily by cleaning solutions such as methyl alcohol.

In layer-by-layer laser-induced polymerisation technology, the layer thickness is usually set in such a way that the lower part of the upper layer overlaps the upper part of the previous layer. Therefore, the remaining power of laser irradiation after solidifying the current layer (upper layer) goes into the previous layer. At this time, the laser irradiation weakens as the beam enters deeper into the previous layer in the *z* direction. When the laser power is lower than the critical exposure of the photopolymer at given wavelength, solidification no longer progresses. Therefore, the layer thickness has little effect on the solidification depth.

5 The development of freeform microstructures

Based on the above results, some freeform 3D microstructures with complex cross sections were fabricated. Figure 10 shows a micro-pipe with a helical separation wall. Figure 10a shows an optical microscopic view and Fig. 10b shows a scanning electron microscopy (SEM) picture of the cross-section. The inner and outer diameters of the pipe are 1 and 1.4 mm, respectively, and its height is 1.64 mm. The helical separation wall is 100 µm thick and twisted 180° along the centre axis of the pipe. It consists of 41 layers; each layer is 40 µm thick. The total elapsed time for the construction was 3.5 hours. The structure was cleaned using methyl alcohol. Figure 11 shows a SEM photo of a micro-link. It consists of 29 layers; each layer is 40 µm thick. The total development time was 5 hours. The structure was fabricated on a silicon wafer and cleaned using methyl alcohol and Rapid Rinse.

In these fabrications, the scanning parameters of the laser were properly selected since the complex structures were successfully fabricated.

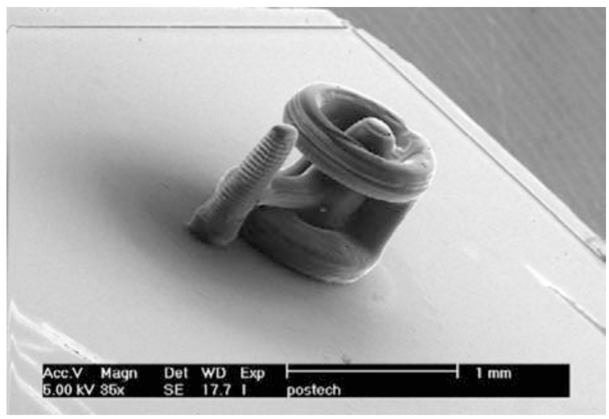
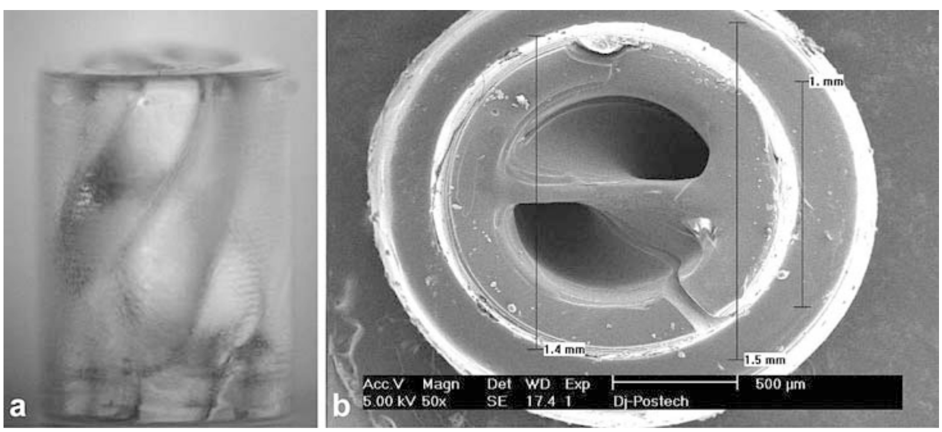


Fig. 11 A micro-link

Fig. 10a,b A micro-pipe with a helical separation wall
a a microscopic view
b a SEM picture of its cross-section



6 Conclusion

In this paper, a micro-stereolithography system and the associated photopolymer solidification simulation program were presented. A series of experiments were conducted to observe the solidification patterns for various laser beam exposure conditions. The following conclusions were drawn from the experimental and numerical results.

- To solidify a given cross-section, the zigzag-shaped scanning pattern requires a shorter fabrication time than the crank-shaped scanning pattern.
- The solidification width and depth of the photopolymer increase as the scanning pitch decreases, regardless of the scanning width.
- When the layer thickness is increased, the solidification depth of the first layer shows little change.

Based on these results, some 3D microstructures with complex cross-sections were successfully fabricated.

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