

Micro-layered-photolithography for Micro-Fabrication and Micro-molding

Y. Tang¹, H.T. Loh^{1,2}, J.Y.H. Fuh², L. Lu², Y.S. Wong², S. C. H. Thian²

¹Singapore-MIT Alliance, National University of Singapore,

²Department of Mechanical Engineering, National University of Singapore

Abstract—A novel process based on the principle of layered photolithography has been proposed and tested for making three-dimensional micro-structures. An experimental setup was designed and built for doing experiments on this micro-fabrication process. An ultraviolet (UV) excimer laser at the wavelength of 248 nm was used as the light source and a single piece of photo-mask carrying a series of two dimensional (2D) patterns sliced from a three dimensional (3D) micro-part was employed for the photolithography process. The experiments were conducted on the solidification of liquid photopolymer from single layer to multiple layers. The single-layer photolithography experiments showed that certain photopolymers could be applied for the 3D micro-fabrication, and solid layers with sharp shapes could be formed from the liquid polymer identified. By using a unique alignment technique, multiple layers of photolithography was successfully realized for a micro-gear with features at 60 microns. Electroforming was also conducted for converting the photopolymer master to a metal mould of the micro-gear, which proved that the process is feasible for micro-molding.

Index Terms—Electroforming, Micro-fabrication, Micro-molding, Photolithography

I. INTRODUCTION

Highly innovative micro-fabrication techniques have emerged from the laboratory environment during the last decade, creating a new method for developing and producing microstructures in various application areas. For

Manuscript received November 18, 2004. This work is partly funded by National University of Singapore under Grant: R-265-000-129-112.

Y. Tang is with Singapore-MIT Alliance, E4-04-10, Engineering Drive 3, Singapore 117576 (phone: 65-68744857; fax: 65-67795922; email: smatyx@nus.edu.sg).

H. T. Loh is with Singapore-MIT Alliance and Mechanical Engineering Department, National University of Singapore, 9 Engineering Drive 1, Singapore 117576 (email: mpelht@nus.edu.sg).

J. Y. H. Fuh is with Mechanical Engineering Department, National University of Singapore, 9 Engineering Drive 1, Singapore 117576 (email: mpefyh@nus.edu.sg).

L. Lu is with Mechanical Engineering Department, National University of Singapore, 9 Engineering Drive 1, Singapore 117576 (email: luli@nus.edu.sg).

Y. S. Wong is with Mechanical Engineering Department, National University of Singapore, 9 Engineering Drive 1, Singapore 117576 (email: mpewys@nus.edu.sg).

S. C. H. Thian is with Mechanical Engineering Department, National University of Singapore, 9 Engineering Drive 1, Singapore 117576 (email: mpetchs@nus.edu.sg).

example, structures with micron features and tolerances in the submicron range are being used in optical systems as waveguides, switches or connectors, read-write heads used in miniaturized disk drives, and micro-structured orifices used for ink-jet printing and fuel injection applications. Based on various purposes, micro-fabrication could be divided into several sorts: surface micromachining for thin films and functional coatings, bulk micromachining (deep silicon RIE) for sub-conducted silicon micro-structures, photolithography for polymer or biomaterial microstructures (tissues), micro-molding for micro-parts via injection or casting, etc. The most successfully developed micro-fabrication process is the well-known LIGA, a German acronym stands for deep-etch x-ray lithography, electroplating and molding [1]-[3]. With this technique it is possible to produce microstructures with very high aspect ratios (up to 100), very small structures (in the submicron range) and very smooth sidewalls (surface roughness less than 5nm). The standard fabrication steps in a LIGA process are: mask layout, mask fabrication, substrate (PMMA) preparation, X-ray exposure, X-ray resist development, etching, electroless-plating, high aspect ratio electroplating, planarization and replication. The whole process is relatively complex, and very expensive. And although the fabrication in z direction could be very deep, only two dimensional (2D) or two and half dimensional (2.5D) structures can be fabricated by LIGA because of the deep x-ray lithography. The high cost, the limitation in 3D structure and the “time to market” factor have forced most of the manufacturer to give up this X-Ray based LIGA technique.

As for 3D micro-fabrication, one recent thrust is focused on micro-rapid-prototyping, single or two-photon absorbed stereo-lithography, etc [4]-[8]. In these technologies, certain photopolymers (SU8, 2-photon initiative photopolymer) are specially developed that can be cured by UV laser. The laser beam should be focused to a very small spot (a few microns or less) with a very high intensity, and in some cases only femto-second laser can be used. The 3D structure is obtained by laser scan in which an ultra precise stage for the movements of focused laser spot in X, Y, Z axis is need. Hence these processes are still highly costly although the results from the research so far are encouraging.

One of the most important application for micro-

fabrication is micro-molding. Most micro-molding is used for micro-plastic injection which is very popular in watch, instrument and data storage industries. Presently the industry produces the micro-moulds by wire electric discharge machining (WEDM). For each level of a plastic structure the wire cuts out in a metallic plate the negative form of the shape. The plates are then assembled and mounted in the plastic injection machine for moulding. But WEDM has a limitation in wire diameter which is currently $30\mu\text{m}$, i. e., when the structure of the micro-parts is finer than $30\mu\text{m}$, WEDM cannot be applied. And only two and half dimensional shape can be fabricated by WEDM based on its principle. An alternative to WEDM technique is LIGA, with which very fine (microns or sub-microns) structures can be obtained. But the process is very expensive [9]. Recently, a process called MIMOTEC™ (MIcro-MOlds TEChnology) has been established and patented for the fabrication of metallic micro-moulds by H. Lorenz from Mimotec SA, Switzerland [10]. MIMOTEC™ is based on the UV photolithography of SU8 photo-resist and electroforming. The SU8 is spin coated to a metallized base with a certain thickness of layer, then it can be precisely photo-structured by UV irradiation to produce a master. The micro-mould is obtained by electroforming of the master. MIMOTEC™ became much cheaper than the LIGA process, but it has the limitation in thickness or depth for parts building, and only 2.5 D structure can be produced.

II. PROPOSED PROCESS

Our proposed process is illustrated in Fig. 1. In this approach, an excimer laser is used as energy source to solidify (cure or harden) the liquid photopolymer. When the laser beam pass through a photo-mask, the laser beam is regulated into a special shape and the size of the shape is reduced to a smaller scale with the use of an objective lens. With one exposure of the laser, the spot of the shaped laser beam acts on the surface of liquid photopolymer, and th layer of the liquid photopolymer will be solidified into th designed shape and stick to the substrate. Then with th movement of the mask, a series of 2D shapes will b created and stick to the substrate layer by layer wit controlled depths. Finally a 3D solid part can be created o the substrate. The 3D polymer-built pattern can then b replicated by electroforming using either nickel or coppers material. A final metal mold or part can hence be obtaine after dissolving the polymer pattern away.

Compared with other reported works, there are som distinct advantages for this proposal:

1) By using the excimer laser, ultra fine structures can b fabricated. The excimer laser has a high beam qualit (TEM00) and a very short duration time (nano-seconds). It is already proven in excimer laser ablation that the excime-

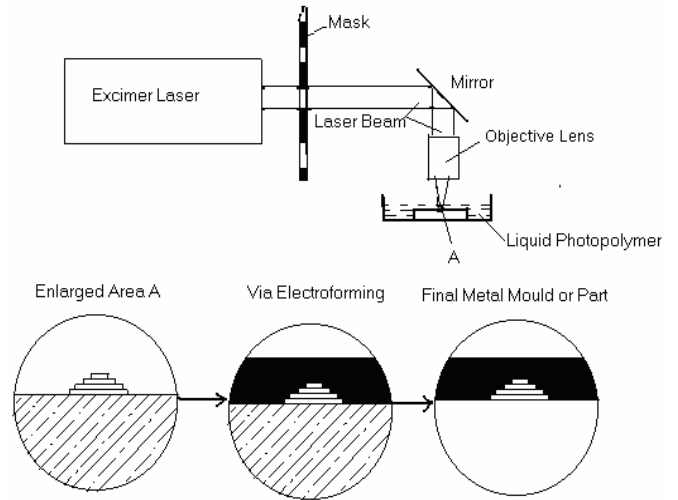


Fig. 1 Illustration of the proposed process

laser can remove material at a nanometer scale. And in this case, it also can solidify the photopolymer at nanometer or sub-micron scale.

2) With the photo-mask to regulate laser exposure, the fabrication actually happens within a very small spot. Together with a high numerical aperture (NA) objective lens, the pattern brought by the laser beam from the mask will be reduced into a very small scale (micron or sub-micron level) on the fabricating surface.

3) True 3D micro structures can be fabricated by using the layered manufacturing mechanism. It has already been proven by normal RP techniques.

4) Micro-scale metal parts can be fabricated by using high-aspect-ratio electroforming. It can also be applied to micro-molding for mass production.

III. EXPERIMENTAL SETUP

Based on the above principle, an experimental rig has been set up as illustrated in Fig. 2. An UV laser mirror is

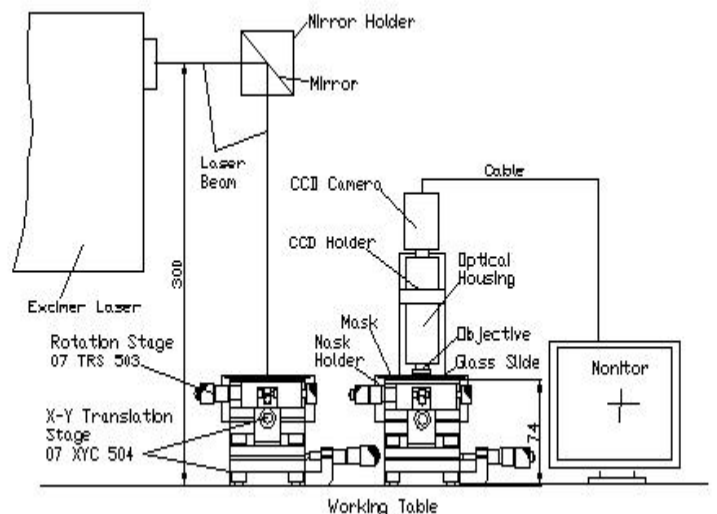


Fig. 2 Experimental setup

used to reflect the laser beam downwards onto the photo-mask with the substrate placed below it. Two linear (x , y axis) and one rotating stage positioner are used to align the substrate with the photo-mask while a machine vision system is used to view the alignment process.

A. Laser

A Lambda Physik COMPex 205 multi-gas (KrF) excimer laser is used for the experiment. The wavelength of the laser is 248nm, which is in the deep UV range. This laser is usually used for precision machining, producing features down to 40nm in resolution with virtually no heat-affected zone. Therefore, medical doctors make use of this property to correct myopia in refractive eye surgery, such as LASIK (*Laser in situ Keratomileusis*). In principle, shorter wavelength allows the beam to be focused to smaller spots and thus, excimer lasers have also been used in high-resolution material processing and surface modification.

The maximum energy output of this laser is 600 mill joules per pulse with pulse duration of 25 nanoseconds (ns). Hence the peak power can achieve as high as 24 Megawatt (MW). With a rectangular beam of 24×6mm, the power density achievable is 16.7MW/cm². The energy level of the laser is powerful enough to induce photopolymerization for most UV liquid photopolymers.

B. Photo-mask

Fig. 3 (a) shows the three-inch square photo-mask of a micro-gear. The whole photo-mask includes 30 patterns; 5 rows by 6 columns. The enlarged view of one pattern is shown in Fig. 3 (b). The pattern is a 1 mm diameter (measured from tooth to tooth) gear with 16 teeth and 4 alignment marks at its corners. The alignment marks are to assist in the alignments with the previous layers. The width of each tooth is 60 μ m. It is in fact a pattern for a 3D micro-gear (central area). For the central gear (shown in Fig. 3 (c)), there is a rotating angle of 0.5 degree for the second layer to the first layer. Therefore, the whole gear has a rotating angle of 15 degree for the total of 30 layers in the 3D structure.

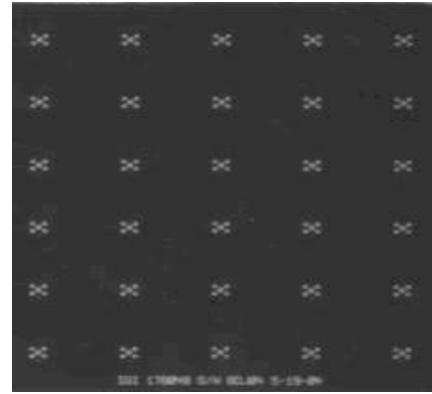
The photo-mask is made of quartz coated with chrome instead of soda lime glass, even though it is more expensive because only quartz has high transmission for wavelength of 248 nm. The base material of quartz is for the laser beam to pass through, and the chrome film is to reflect the laser beam, allowing the laser beam can be regulated to the shape of the pattern on the photo-mask.

The quality and accuracy of the photomask is extremely important, since it will affect the dimension of the developed pattern.

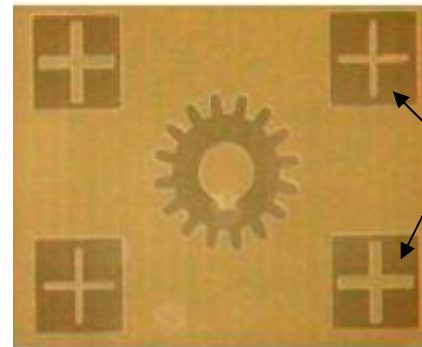
C. Positioner

Manually actuated linear micro-positioner of 3 μ m resolutions is used to position the substrate in the x , y axis for alignment with the photo-mask. An additional rotation positioner is placed on top of the linear positioner to correct any misalignment due to rotation. The whole

process of the alignment can be monitored by the machine vision system.



(a) Three-inch square photo-mask



(b) Magnified view of one pattern with four alignment marks



(c) Center of one pattern-a gear with 16 teeth

Fig. 3 Photo-mask of the micro-gear

D. Machine vision system

Semi-conductor industries use either expensive automatic alignment system or split-field microscope to do alignment. Automatic alignment system is expensive and is meant for large volume of production, while using microscope will strain the eyes even for low-volume productions. In our setup, a machine vision system, as shown in Fig. 2, comprising of an objective lens, a CCD

camera and a high resolution monitor screen for display, is used for assisting to do alignment.

IV. EXPERIMENTS

The experiments included both single layer and multiple layers lithography. The single layer lithography experiments were conducted to test the material suitability for the 3D micro-RP. The parameters for the single layer lithography have been optimized by a series of experiments, with a view to using the parameter values for multiple layer lithography.

Two kinds of liquid photopolymers were tested. They are Norland Optical Adhesive-NOA 60 and Vantico SL5510. The liquid photopolymer was coated onto a normal rectangle microscope glass slide (to act as substrate) using a spin-coating machine, and a thin layer of about 1 μm thickness could be formed. The thin layer of liquid photopolymer was then solidified when exposed to the excimer laser. After the layer is solidified, the glass slide was put into the alcohol for developing. The un-solidified liquid photopolymer would then be dissolved by the alcohol, leaving the solidified pattern stuck to the glass slide. The solid pattern was then observed and analyzed using a microscope.

The experiment for multiple layers' lithography was based on the result of the single layer experiment, after the optimum parameters for the solidification of the photopolymer were obtained. Again, the glass slide was spin coated with the first layer of photopolymer followed by exposure to the excimer laser using the optimum parameters. After ensuring that the first layer of photopolymer was well solidified and stuck to the glass slide, the substrate was spin-coated again with the second layer of liquid photopolymer without developing at this stage. The substrate was then exposed to the laser again and the second solidified layer would be obtained. The process was repeated until a 3D solid gear was created, layer by layer, in the liquid photopolymer. Finally, the substrate was put into the alcohol for developing, where the uncured liquid photopolymer was dissolved, displaying a solidified 3D micro-part. For a clearer view of the 3D micro-part, the sample was observed and analyzed under a scanning electronic microscope (SEM).

The 3D micro-gear was also built on a brass substrate using the same process, and the sample was sent for electroforming experiment. As the brass substrate is conductive, it can be deposited with nickel directly by electroplating, and a cavity will be formed to surround the photopolymer master.

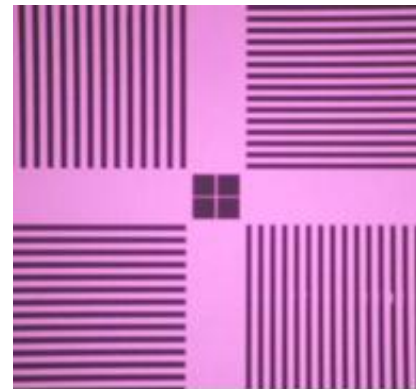
V. RESULTS AND DISCUSSION

A. Single layer lithography of NOA 60

The photopolymer Norland Optical Adhesive-NOA 60 was initially tried for the mask-based lithography. The photo-mask was a standard quartz photo-mask used as a

benchmark in semi-conductor industry. Fig. 4(a) shown below is the micro-structure of the pattern on the photo-mask under a microscope, which is used in a stepper machine for auto alignment. The whole pattern is made up of four squares of vertical and horizontal lines, diagonally to each other is 1.8 mm x1.8 mm. The width of each dark line is 23 μm .

The laser beam can only pass through the dark area (dark lines) in the photo-mask and therefore, will be regulated into a series of lines at micron scale. The parameters for this lithography were: 18KV, 10 shots, 100-110 mJ. After exposing to the excimer laser, a thin solid layer was formed and the substrate was developed in alcohol solution. After developing, the amplified microstructure of the solid layer is shown in Fig. 4(b).



(a) Pattern of the photo-mask



(b) Solidified layer of NOA 60

Fig. 4 Single layer lithography of NOA 60

From the figures, it can be seen that the material NOA 60 was photo-polymerized under the irradiation of excimer laser and a solid structure has been formed. The structure is also at the micron scale as it is duplicated from the photo-mask pattern. The dimensions of the solids lines were close to 23 μm . However, the solid structure is not sharp and clear, as there are still some uncured photopolymer left, covering the solid structure. A better solvent is still under seeking, which the uncured material could be washed away totally and allows a clearer solid structure to be developed out.

B. Single layer lithography of SL 5510

The material of photopolymer 5510 was also tried for the single layer lithography. This photopolymer is initially for RP process: stereo-lithography apparatus (SLA). It has been proven suitable for micro-lithography by our previous experiments. The single-layer experiments are for seeking suitable parameters for the mask-based lithography. The photopolymer was dropped on a glass slide and spin-coated to a thin layer about 10 microns. Using the excimer laser, three levels of energy have been tried for the lithography. They are 100-110mJ, 120-140mJ and 160-180mJ. The wavelength is 248nm, and the pulse duration is 25ns. After exposure, the photo-polymer was solidified at all energy levels. The solid layers were also developed by alcohol, and the optical microscope views of the solid layers are shown in Fig. 5. The results show that the low energy resulted in that the lithography is not enough (shown in Fig. 5(a)). And the high energy resulted in over reaction of the photopolymer and the shape of the solid layer became fuzzy (shown in Fig. 5(c)). The moderate energy of 120-140mJ was the best one for the lithography (shown in Fig. 5(b)), in which the photopolymer is completely solidified and solid layer had a sharp shape. It is proven that SL 5510 is suitable for the 3D micro-lithography. Besides that, the photopolymer SL 5510 has a low viscosity which is easy for spin-coating to multiple layers. Hence SL 5510 was selected as the suitable material for the multiple-layer experiment.

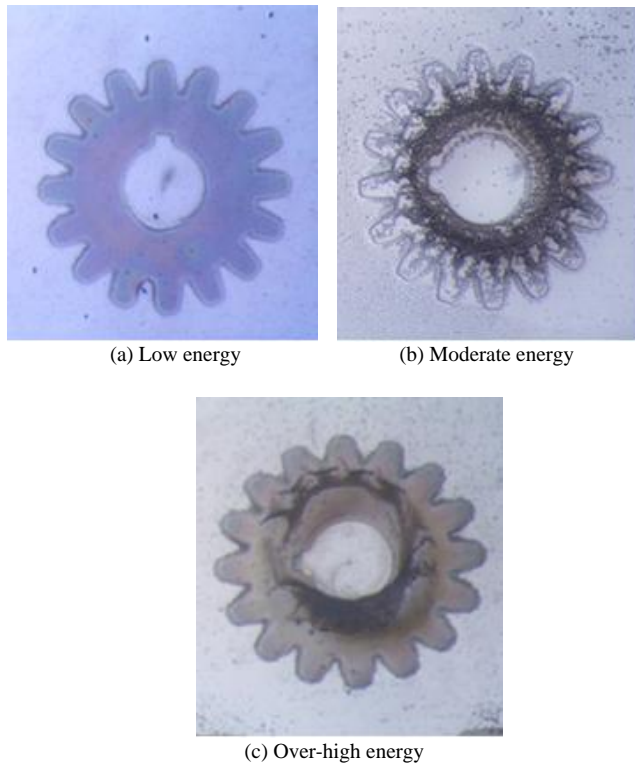


Fig. 5 Optical microscope views of single layer lithography for photopolymer 5510

C. Multiple-layer lithography for 3D micro-parts

Based on the single layer experiments, the multiple-layer lithography was therefore conducted using the photopolymer SL 5510 and the optimized parameters. The result is shown in Fig. 6.

As usual, a normal rectangle microscope glass slide was spin-coated with the first layer of SL 5510 photopolymer. After which, it was placed under the photo-mask for exposure between energy level of 120 to 140mJ. To ensure that the first solidified layer is well adhesive to the glass surface, this layer was exposed for three shots instead of one. After the first layer was solidified, the substrate was put recoated with the second layer of photopolymer and placed into the exact original position under the photo-mask by using a special fixture for another exposure.

The process was repeated and a total of 10 layers were cured in this case. After lithography, the sample was developed by alcohol, it was viewed under SEM. The result shows that the 3D structure of the micro-gear is rather good with sharp features like the gear teeth and the key slot. The alignment marks (in four corners) were also well formed in a 3D structure with a cross sign in the center. The total height of the part building is about 10 microns. This result proves that the mask-based lithography for 3D layered micro-fabrication is realized. Further experiments will be conducted for more layers of the lithography.

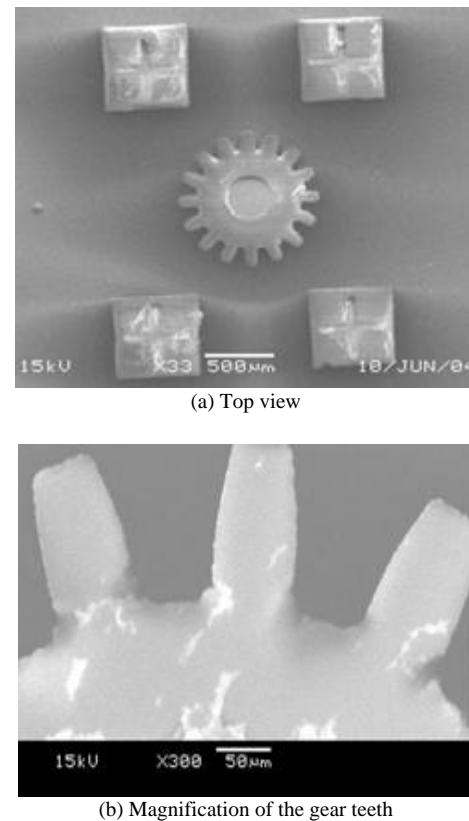
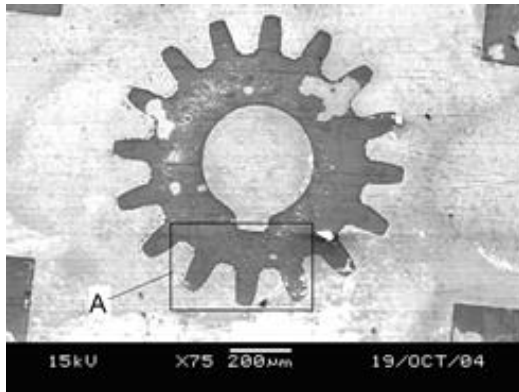


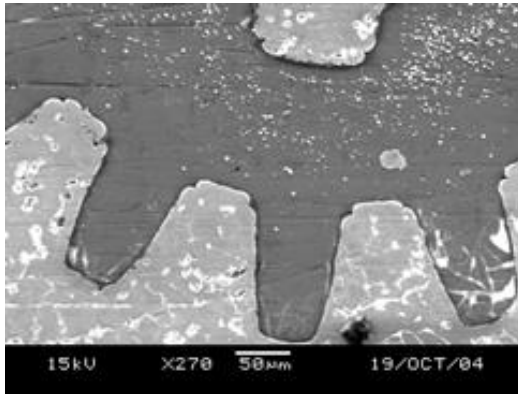
Fig. 6 SEM view of multiple-layer (10 layers) lithography

D. Electroforming

A micro-gear was also built on a brass substrate for 10 layers. Then the part was sent for electroforming of nickel using the standard process and parameters. After the electroforming, a nickel cavity was formed surrounding the photopolymer master. The SEM view of the electroforming cavity is shown in Fig. 7. From the view, it can be seen that the cavity was exactly duplicated from the master with clear and sharp features. The depth of cavity is also about 10 microns. This cavity can be used as an insert for the injection mould of the micro-gear.



(a) Top view



(b) Enlarged area A

Fig. 7 SEM view of electroforming cavity of the micro-gear

VI. CONCLUSION

Based on the principle of rapid prototyping that a 3D part is built layer by layer, a novel method was proposed to create a 3D micro-structure via the multi-layered photolithography. The process can be used for creating 3D micro-parts and even the metal micro-mould via electroforming. An experimental setup was constructed successfully according to the principle of the process. And a photo-mask which carries multiple layers' patterns sliced from a 3D part was built and used in the experiment. The single layer and multiple-layer lithography experiments demonstrate that the mask-based lithography for 3D layered micro-fabrication is realized. A ten layered gear of 1 mm in diameter with 60 μ m features has been fabricated

successfully using the proposed method. The electroforming of the micro-gear to a metal cavity was also successfully carried out, which proved that the proposed process is feasible for making micro-moulds for micro-molding.

REFERENCES

- [1] M. W. Borner, M. Kohl, F.J. Pantenburg, W. bacher, H. Hein, and W. K. Schomburg. Movable microstructures made by a sub-micron LIGA process. *Microsystem technologies*, Vol. 2, 1996, pp. 149-152
- [2] <http://www.imsas.unibremen.de/institute/institute.html>
- [3] T. Hattori, H. Mekaru, Y. Utsumi. An approach to three-dimensional micro-structure fabrication utilizing hard x-ray lithography of synchrotron radiation. *Review of Scientific Instruments*, Vol. 73, No. 3, 2002, pp1376-1378
- [4] V. Ya. Prinz, D. Grutzmacher, A. Beyer, et al. A new technique for fabricating three-dimensional micro- and nanostructures of various shapes. *Nanotechnology* 12 (2001), pp399-402
- [5] X. Zhang, X. N. Jiang, C. Sun. Micro-stereo-lithography of polymeric and ceramic microstructures. *Sensors and Actuators* Vol. 77, 1999, pp149-156
- [6] Shoji Maruo and Koji Ikuta. Three-dimensional micro-fabrication by use of single-photon absorbed polymerization. *Applied Physics Letters* Vol. 76, No.19, 2000, pp2656-2658
- [7] Hong-Bo Sun, Satoshi Kawata. Two-photon laser precision micro-fabrication and its applications to micro-nano- devices and systems. *Journal of Light-wave Technology*, Vol. 21, No. 3, 2003, pp624-633
- [8] Irène Wang, Michel Bouriau, and Patrice L. Baldeck. Three-dimensional micro-fabrication by two-photon-initiated polymerization with a low-cost micro-laser. *Optics Letters*, Vol. 27, No. 15, 2002, pp1348-1350
- [9] A. B. Frazier, M. G. Allen. Metallic microstructures fabricated using photosensitive polyimide electroplating moulds. *JMEMS*, Vol. 2, No. 2, 1993, pp87-92
- [10] H. Lorenz. Photo-fabrication of Ultra-Precise Micro-moulds. *Proceedings of the Injection Molding Technologies for the New Millennium Conference on Advance Plastic Technology*, Louisiana, USA, February 28 - March 1, 2000