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LCD based Micro – Stereolithography: A Novel Technique for Rapid Prototyping

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ABSTRACT : *The LCD based Micro stereolithography (µSLA) can be developed to produce highly precise, three-dimensional (3D) microstructures from broad selection of functional materials, especially bio-compatible materials. In principle, µSLA utilizes focused light to scan over the surface of a photo-curable resin, which undergoes photo-polymerization and forms solid microstructures. It provides an engineering platform for various applications, such as Microelectromechanical Systems (MEMS), integrated photonics, tissue engineering, and Tetra hertz (THz) metamaterial synthesis. The µSLA fabricated devices, containing complex engineered microstructures which are covered with self-assembled functional groups, can work as a unique interface between the nanometer scale functional group and macro-scale bio-medical samples, therefore can find applications in Bio-MEMS. The basic concepts of LCD based Micro stereolithography and a case study of manufacturing a bevel gear using photosensitive resins reinforced with ceramic nanoparticles is presented in this paper.*

Keywords *– LCD, Micro – Stereo lithography, MEMS,*

I. INTRODUCTION

Stereolithography is an additive fabrication process utilizing a vat of liquid UV-curable photopolymer "resin" and a UV laser to build parts a layer at a time. On each layer, the laser beam traces a part cross-section pattern on the surface of the liquid resin. Exposure to the UV laser light cures, or, solidifies the pattern traced on the resin and adheres it to the layer below. After a pattern has been traced, the Stereo lithography apparatus (SLA) elevator platform descends by a single layer thickness, typically 0.05 mm to 0.15 mm (0.002" to 0.006"). Then a resin-filled blade sweeps across the part cross section, re-coating it with fresh material. On this new liquid surface the subsequent layer pattern is traced, adhering to the previous layer. A complete 3-D part is formed by this process. After building, parts are cleaned of excess resin by immersion in a chemical bath and then cured in a UV oven. Micro stereolithography (µSLA) can be developed to produce highly precise, three-dimensional (3D) microstructures from broad selection of functional materials, especially bio-compatible materials. In principle, µSLA utilizes focused light to scan over the surface of a photo-curable resin, which undergoes photo-polymerization and forms solid microstructures. It provides an engineering platform for various applications, such as Microelectromechanical Systems (MEMS), integrated photonics, tissue engineering, and THz metamaterial synthesis. The µSLA fabricated devices, containing complex engineered microstructures which are covered with self-assembled functional groups, can work as a unique interface between the nanometer scale functional group and macro-scale bio-medical samples, therefore can find applications in Bio-MEMS.

Ji Soon Choi [1] studied development of a more economical and simpler micro-stereo-lithography technology using a UV lamp as a light source and optical fiber as the light delivery system. The photo-polymer solidification experiments to examine the characteristics of the developed micro-stereo-lithography apparatus are presented. Ikuta [2] introduced micro stereolithography technology and developed several types of micro stereolithography apparatus. They also proposed a means of applying micro stereolithography in mass-production using an optical fiber array so that multiple microstructures could be fabricated in a single process. Bertsch [3] developed a micro stereolithography apparatus employing a pattern generator in which a UV laser and dynamic LCD pattern generator were used to generate the cross section of a 3D structure. While the substrate did not move in the x–y direction in the liquid photopolymer, an LCD pattern generation system was necessary and the resulting diffraction had to be considered. Lee [4] developed a micro stereolithography apparatus using a UV laser and a complex optical system. Kawata [5] developed raster scanning based nano-stereolithography technology using two-photon absorption of photopolymer. This nano-technology makes it possible to fabricate nanoresolution 3D structures. Ikuta [6] introduced vector scanning based nano-stereolithography technology, too. Nowadays, many researchers have applied this technology to various areas such as memory, bio-technology, and optical systems. However, this system shows its promise only to fabricate the micro-structures. Moreover, the technology needs expensive femto-second-pulsed laser systems, complex optical systems, and nano-stage systems. This paper focus on basic concept of LCD based micro–stereolithography technique used for rapid prototyping.

II. APPROACHES OF MICRO-STEREOLITHOGRAPHY

When Stereolithography is used to fabricate micro-parts, it is called Micro-Stereolithography. The principle of Micro Stereolithography is the same as Stereolithography, i.e. “Writing a cross section on a photopolymer surface by means of UV light”. However, the resolution required of a Micro-Stereolithography process is much finer. Micro-Stereolithography systems developed so far can be divided into two categories:

- Scanning Micro Stereolithography Systems and
- Mask projection Micro Stereolithography Systems, or Integral Micro-Stereolithography Systems.

2.1 Scanning Micro-Stereolithography Systems

It is believed that, in conventional Stereolithography, too many mobile optical elements lead to focusing errors and thereby, poor resolution. Also, the spot size doesn’t remain constant throughout the layer cross-section. As a result, lateral resolution is dependent upon the distance of a feature from the center of the vat. In scanning Micro-Stereolithography, this drawback is eliminated by keeping the light beam focused onto a stationary light spot and scanning the layer by moving the work piece under the spot. The principle of Scanning Micro-Stereolithography is shown in Fig.1.

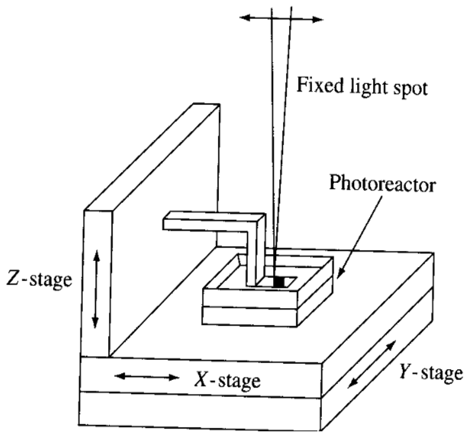

Fig.1 Principle of scanning micro-stereolithography (Beluze et al. 1999)

The following specifications of a typical scanning Micro-Stereolithography process have been presented by Gardner (2001):

- 5 µm spot size of the UV beam.
- Positional accuracy is 0.25 µm (in the X-Y directions) and 1.0 µm in the Z-direction.
- Minimum size of the unit of hardened polymer is 5 µm x 5 µm x 3 µm (in X, Y, Z).
- Maximum size of fabrication structure is 10mm x 10mm x 10mm.

2.2 Mask Projection Micro-Stereolithography

In Mask projection Micro Stereolithography, also called Integral Micro-Stereolithography, a complete layer is polymerized in a single radiation. The principle of Mask projection Micro Stereolithography is shown in Fig.2.

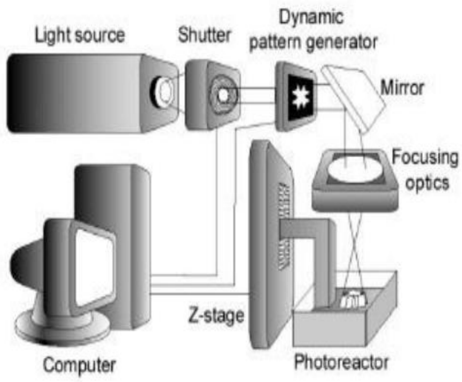

Fig. 2 Schematic Diagram of a Mask Projection micro stereolithography (MPμ SLA) [9]

The three dimensional CAD model of the object to be cured is scaled, oriented and sliced at uniform increments by horizontal planes. Each slice is converted into a bitmap file. This bitmap file serves as an input to the mask, which displays a pattern corresponding to the layer to be cured. As shown in Fig.2, the beam coming from a light source is shaped by this pattern so that it contains the image of the layer to be cured. Focusing optical components are used to reduce and focus this image onto the surface of a liquid photopolymer, held in a vat. This cures a layer of the cross-section corresponding to the pattern displayed on the mask. Once the curing of a layer is complete, the already polymerized part of the object is immersed deep in the photopolymer vat so that the polymerized surface is totally covered by fresh photopolymer. It is then lifted up a certain height such that there remains a layer of resin between the last polymerized layer and the free surface of photopolymer. The process then repeats over the same sequence of operations for the next layers until the object is finished. The polymerized layers are stacked onto one another by the interpenetrating polymer networks. When all the layers have been built, the polymerized part is removed from the vat and washed with the appropriate solvent.

Table 1 Results obtained using Mask projection Micro Stereolithography

Research Team	Light source	Mask	Component Size	Resolution	Reference
Bertsch	Laser 515 nm	LCD[1]	1.3 x 1.3 x 10mm3	5 x 5 x 5 μm	(Bertsch, Zissi,, 1997 Bertsch, Jezequel, 1997)
Chatwin	Laser 351.1nm	SLM[2]	Not reported	5 μm lateral resolution	(Chatwin,1998,Farsarial.,1999 Chatwin, 1999,Farsari,2000)
Monneret	Broad Band Visible	LCD	Not reported	2 μm lateral resolution	(Monneret et al., 1999; Monneret et al., 2001)
Bertsch	Lamp (Visible)	DMD[3]	6 x 8 x 15 mm3	5 x 5 x 5 μm	(Bertsch, 1999)
Bertsch	Lamp (UV)	DMD	10.24 x 7.68 x 20 mm3	10 x 10 x 10 μm	(Bertsch et al., 2000)
Hadipoespito	Lamp (UV)	DMD	Not reported	Not reported	(Hadipoespito et al., 2003)

III. LCD BASED MASK PROJECTION MICRO–STEREOLITHOGRAPHY

In mask projection LCD based micro-stereolithography, also called integral microstereolithography, a complete layer is polymerized in a single radiation. The principle of MPµSLA is shown in Fig.3. The LCD based MPµSLA is used to project and focus the patterned light, which is formed by a mask on the resin surface according to the binary image generated from the sliced 2D section. In this process, the light source, a laser or a UV lamp, is enlarged and illuminated to the mask. A shutter controls the duration of the irradiation step. Each layer is cured according to a sliced 2D section, and then the cured layer is immersed into resin and the refreshed resin is covered such that it reaches slicing thickness by the Z stage. The final 3D microstructure is produced through the accomplishment of these consecutive processes in all layers. In LCD based MPµSLA, the pattern generation part plays a distinguished role in making dynamic patterns without any physical masks. It takes a shorter time to cure each layer compared to that of a scanning micro stereolithography apparatus because the later uses a slower vector-by-vector scanning process. Moreover, the accuracy of MPµSLA is better, because it is free from the errors introduced by the *X-Y* translation. Due to these advantages, current research on micro stereolithography (µSLA) is focused on LCD based Mask Projection micro stereolithography (MPµSLA).

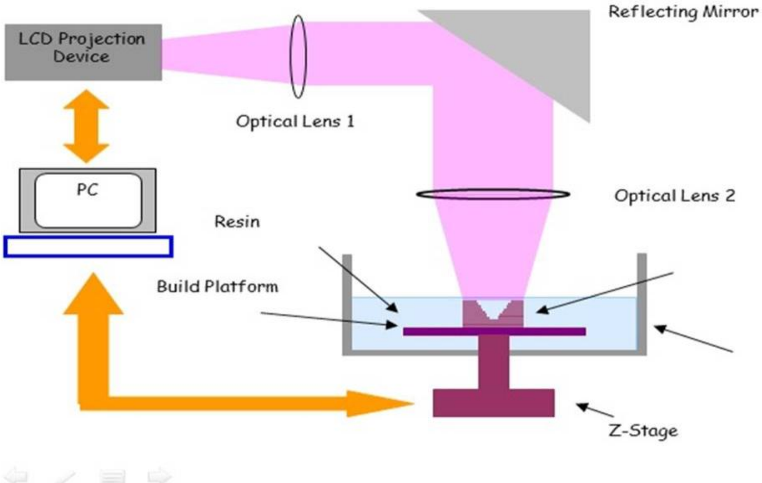

Fig.4 LCD based Mask Projection Micro-stereolithography.

Advantages of Mask Projection approach over Scanning approach

The Mask Projection Micro-Stereolithography process has the following advantages over Scanning Micro-Stereolithography:

1. Mask projection Micro Stereolithography is faster than the Scanning Micro Stereolithography
2. because vector-by-vector scanning is a slower process.
3. The accuracy of MPµSLA is better because the errors introduced by the X-Y translation stages are
4. avoided. The only mobile element in the MPµSLA systems is the Z-Stage. Due to these advantages,
5. current research on Micro Stereolithography is focused on Mask projection Micro-stereolithography.

IV. CASE STUDY: BEVEL GEAR MANUFACTURING BY LCD BASED MICRO-STEREOLITHOGRAPHY

The schematic diagram of the continuous lamination microstereolithography method using an LCD mask is shown in Fig.5. The micro bevel gears are first designed using a 3D CAD system. Next, a series of 2D cross-sectional data is generated from the 3D CAD model of a micro bevel gear. These cross-sectional data are used as the dynamical mask pattern for the LCD mask. The experimental apparatus mainly consists of a uniform illumination system, an LCD mask system, an optical reduction system, and a fabrication system with a Z-stage for the lamination procedure. An Hg-Xe lamp is used as the light source; this source provides the strongest light intensity at a wavelength of 436nm. The photosensitive resin used in this experiment is highly sensitive to this wavelength. The irradiation from the light source is collimated by passing it through the collimating lens A; the collimated beam then uniformly illuminates the LCD mask, which is placed between two quarter-wave plates. Next, the gear pattern displayed on the LCD is reduced to 16% of its size by using the optical reduction system that comprises the condenser lens B and the imaging lens C. The reduced image is then focused onto the glass plate at the bottom of a resin container. Synchronizing the Z-stage movement with the cross-sectional data of a gear makes the successive lamination procedures from the first layer to the final layer possible. The 3D micro bevel gear is finally fabricated by using this system.

4.1 Evaluation of the μ-STL processability of the photosensitive resin reinforced with ceramic Nanoparticles

4.1.1 Photopolymerization characteristics of the photosensitive resin reinforced with ceramic Nanoparticles

The chemical composition of the photosensitive resin reinforced with ceramic nanoparticles is as follows.

- Particles
  - Al_2O_3-SiO_2
  - (50wt%, average diameter, 98 nm)
- Dispersant
  - Hydrophobic polymer (1.5wt%)
  - Phosphate ester monomer (1.5wt%)
- Photosensitive resin
  - KC1042 (9.4wt%, urethane-acrylic)
  - KC1162 (37.6wt%, made of a monomer with a highly dense acrylic functional group)

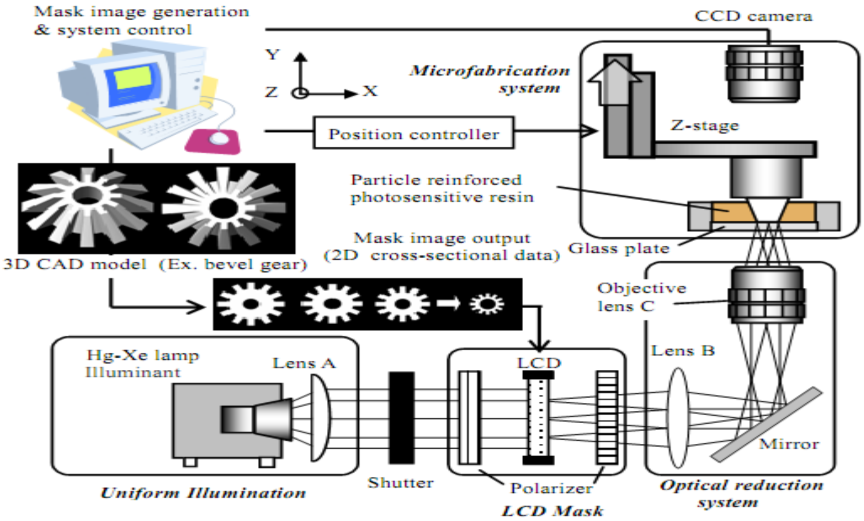

Fig.5 Experimental set–up for manufacturing Bevel Gears

Basic experiments are conducted to examine the photo polymerization characteristics of the developed resin. Fig.6 shows the relationship between the cure depth and the exposure energy for the photosensitive resin reinforced with ceramic nanoparticles and the dispersant. The cure depth is 28.9 µm at an exposure energy of 5 mJ/cm2; this is almost equivalent to the minimum exposure energy used in this method. The developed resin thus has a cure depth sufficient to fabricate 3D microparts because the layer thickness is usually less than 10 µm in microstereolithography. The cure depth is calculated from equation (1) according to the Beer-Lambert law.

$$C_d = D_p \ln (E / E_p) \tag{1}$$

Here, C_d is the cure depth; Dp, the penetration depth of the beam; and E, the exposure energy per unit surface area of the resin. The quantity Ec is the critical exposure energy for the resin. The incident light is widely scattered and absorbed within the photosensitive resin reinforced with ceramic nanoparticles.Thus, it is considered that the solidification of the gear shape is not completed in the case of the photosensitive resin reinforced with ceramic particles. Therefore, a higher exposure energy is required for the fabrication of the micro parts as compared to that of the photosensitive resin without nanoparticles.

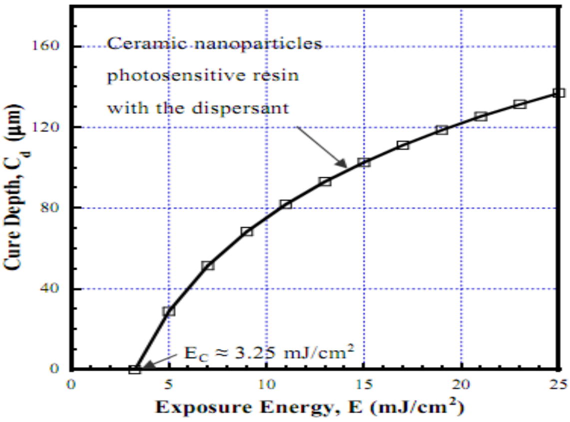

Fig.6 Relationship between the cure depths and the exposure energies and the influence of Dispersants

4.2 Investigation of the Z-stage movement on the fabrication characteristics

The partially solidified resin on the gear surface requires to be removed in order to reduce the surplus growth. This is accomplished by supplying fresh photosensitive resin between the gear surface and exposure plane. In spite of the high viscosity of the photosensitive resin reinforced with ceramic nanoparticles, this can be done as follows. First, the base plate in the resin container controlled by the Z-stage is moved higher upward and then allowed to descend to the desired layer thickness.

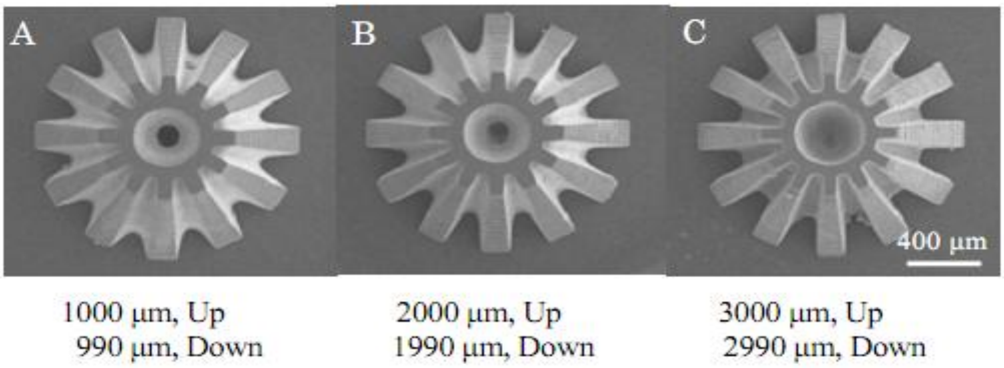

Fig.7 Fabrication results according to the distance through which the Z-stage is moved.

The experimental results of successive laminating fabrication of the micro bevel gears with varying distance of the Z-stage are shown in Fig.7. An exposure energy of 13.7 mJ/cm2 is used, which corresponds to the best processing accuracy. The thickness of each layer and the total number of continuous laminations are 10 μm and 50. The upward distances of the experimental conditions are 1000 μm, 2000 μm, and 3000 μm, respectively, and the descending distances are 990 μm, 1990 μm, and 2990 μm, respectively. The smooth supply of the resin with a high viscosity becomes easier by increasing the distance through which the Z-stage is moved. It is possible to generate a thin uniform resin layer with a thickness of 10 μm in this method. On the other hand, in spite of the reduction in the surplus growth on the tooth surface, the generation of the surplus growth in the center hole is not sufficiently retarded, as shown in Fig.7. Presently, the maximum velocity of the Z-stage in this experiment is 4 mm/s, and the total fabrication time of the experimental conditions are 11 min, 17 min, and 25 min, respectively.

V. CONCLUSIONS

Thus in LCD based MPμSLA, the pattern generation part plays a distinguished role in making dynamic patterns without any physical masks. It takes a shorter time to cure each layer compared to that of a scanning micro stereolithography apparatus because the later uses a slower vector-by-vector scanning process. Moreover, the accuracy of MPμSLA is better, because it is free from the errors introduced by the *X-Y* translation. A case study is presented for the fabrication of 3D microparts using photosensitive resin reinforced with ceramic nanoparticles. The resin that was developed satisfied the criteria of both good dispersibility and high fluidity. A repetitive lamination procedure for the formation of 50 layers is successively performed to obtain a layer thickness of 10μm. The exposure time for each layer is less than 0.15 s, and the micro bevel gear consisting of 50 layers can be quickly fabricated within error rates of 3.6% and with a high processing accuracy. Based on the above results, we confirmed the effectiveness of the LCD gray scale mask micro-stereolithography method using photosensitive resins reinforced with ceramic nanoparticles.

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