Digital Micromirror Device Based Microstereolithography for Micro Structures of Transparent Photopolymer and Nanocomposites

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Abstract: This paper describes a Digital Micromirror Device (DMD) based ultraviolet (UV) microstereolithography (μ-SL) system developed for rapid prototyping and manufacturing of micro 3D structures. Characterization experiments show that the developed the DMD-based imaging system irradiates an entire photopolymer layer at once, providing reasonable curing speed and good resolution at a low cost. 2D and 3D micro parts were fabricated. High frequency ultrasonic vibration (above 20 kHz) was experimented and verified that it can be used to significantly decrease the leveling time of viscous photopolymer. Furthermore, micro parts were also fabricated in nanocomposites, which were obtained by ultrasonic mixing of the transparent photopolymer and nano-sized ceramic particles. High quality micro models fabricated by this novel process could be used for micro scale investment casting, tooling, devices, and medical applications.

1. Introduction

Miniaturization is important in fabrication and commercialization of new industrial products that encompass complex geometries, high aspect ratios and complex microstructures. These miniature products can deliver a new generation of functionality and performance in a smaller volume. Smaller-size cellular phones and notebook computers, hearing aids, nozzles for ink-jet printers, and accelerometers for car air-bag system are some samples of products made possible by rapid development in micro fabrication. Beside the commercial/consumer products and applications, 3D microparts are also of great interest from research fields in microrobotics, micromechanics, and microfluidics.

Silicon-based microelectromechanical system (MEMS) techniques are very popular for the manufacture of micro sensors, electronics, actuators and other components in integrated microsystems. However, these MEMS techniques are two-dimensional (2D) processes involving multiple steps and requiring complicated processing procedures in a cleanroom environment. These 2D techniques are normally difficult, if not impossible, to fabricate arbitrary shape and composition without the use of microassembly. The investment costs of these processes are expensive, and the choice of material is somewhat limited. To name a few of those processes are surface and bulk micromachining, LIGA (X-Ray Lithography, Electroplating, and Molding), and RIE (Reactive Ion Etching) [Madou 2002].

Recently, microstereolithography (μ-SL) process emerged as a freeform process capable of creating 3D structures with complex geometries. Microstereolithography has its root from the stereolithography process rather than integrated circuit (IC) technology. Stereolithography is a process of creating 3D solid models in a layer-by-layer fashion from a 3D CAD model using

photopolymer as a based material. A focused ultraviolet (UV) laser, coupled with a galvano-mirror, is used to cure photopolymer in a vector-by-vector manner [Jacobs 1996, Beaman 1997, and Prinz 1997].

The core idea of microstereolithography processes is similar. A solid 3D model from any modeling software (Pro/E, Unigraphics, SolidWorks, etc) is tessellated into array of triangles, and output in STL (SteroLithography) file format. Using slicing software, this tessellated model is then sliced into layers according to the predetermined thickness. The software then creates some output files that will be read and used directly to build the part. The output build files are then used to build the part on the microstereolithography apparatus. The microstereolithography processes can be classified into two main categories, based on how each layer is build [Bertsch 1999 and 2000]:

1. Vector-by-vector process: a layer is formed by raster scan of a laser beam. The laser beam is stationary and focused precisely to a very fine spot on the surface of the photopolymer. The container and the material are moved horizontally in order to build the layer.
2. Integral process: each layer is cured by one irradiation only. A dynamic mask/spatial light modulator is used. For this type of process, the slicing software gives output in image files (usually monochrome bitmap files); each file contain the cross sectional image of one single layer. These files are then used to drive the dynamic mask.

After a layer is formed, a microstage holding the part is dipped into the photopolymer vat, allowing fresh layer of resin to coat the cured layer. Then the microstage is raised again, leaving only a thin layer of liquid photopolymer (usually in the order of several microns) between the cured layer and the surface of the polymer vat. The fresh layer is then cured, and then the recoating process repeats. Once building process is done, the part is washed with the appropriate solvent to remove the uncured polymer.

The integral stereolithography process is much faster than the vector-by-vector process. By employing a dynamic mask, e.g. Liquid Crystal Device (LCD), this process presents a technical breakthrough in the field of rapid prototyping. As an emerging dynamic mask, the performance of Digital Micromirror Device (DMD) is better than that of the LCD since DMD's fill factor of each pixel (85%) and its reflectivity (71%) are much better than those of the LCD (64% fill factor and 21% light transmission) [CRL Opto, DLP Technology]. In other words, when a pixel is in "active" or "on" state, the DMD can pass light more efficiently than the LCD. LCD-based μ-SL technology has been extensively studied [Bertsch 1999 and 2000]. EPFL (Swiss Federal Institute of Technology) at Lausanne, Switzerland, University of Sussex in United Kingdom, INPL (Lorraine National Polytechnic Institute) in France, and Saitama University in Japan are to name a few. Long layer settling time remains a difficult issue. Research team from Saitama University in Japan used DMD-based μ-SL to build 3D parts [Kaneko 2001]. A vibration generator working at frequency of 50 Hz was sued to reduce the leveling time and enhance the z-resolution by reducing layer thickness [Akahane 2001]. However, its layer thickness was still at approximately 100 μm. It should also be noted that Stanford Research Institute (SRI) has developed a projector-based imager system for ceramic-polymer prototyping [SRI 1999]. However, the system uses visible light, which is prone to interference and the system developed is suitable only for macroscale applications.

2. Experiment Apparatus

A microstereolithography (μ-SL) apparatus has been developed, as shown in Figure 1. The system employs a Digital Micromirror Device™ (DMD) as a dynamic mask/spatial light modulator, which eliminates the need to produce multiple masks to cure different layers of polymer. This apparatus uses an economical broadband UV light source to initialize polymerization of the molecules of the liquid polymer and thus form a solid layer. Detailed information of important elements of the system is described as follows.

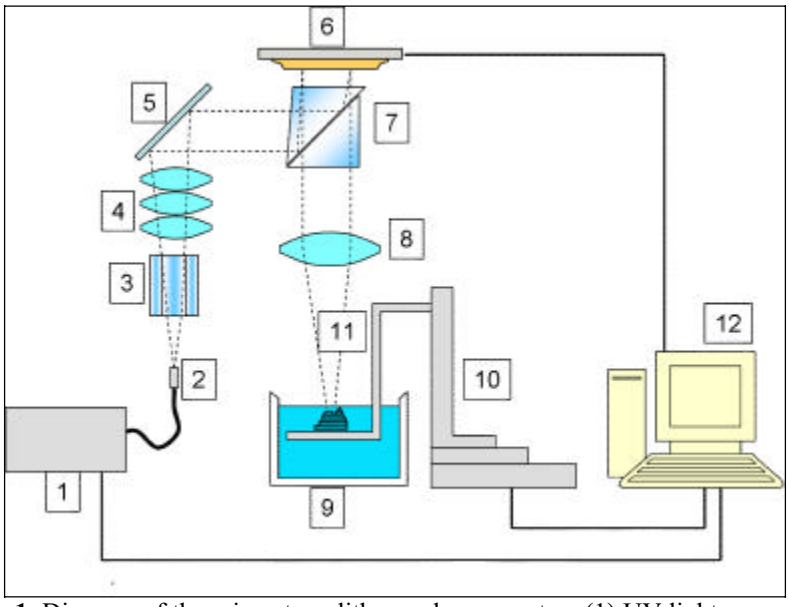

Fig. 1. Diagram of the microstereolithography apparatus: (1) UV light source; (2) light guide; (3) light pipe; (4) condenser lens system; (5) fold mirror; (6) DMD™; (7) TIR prism pair; (8) focusing lens system; (9) photopolymer bath; (10) x-y-z movable stage; (11) building platform; and (12) computer controller.

2.1. Optical System

The light path on the apparatus begins from the UV light source, identified by number 1 in Figure 1. The light is then transmitted using a UV light guide (number 2 in Figure 1) into a modified DMD-based multimedia projector (BenQ DX550). The light path starts at the light pipe (number 3 in Figure 1) and ends at the TIR (total internal reflection) prism pair (number 7 in Figure 1). A set of focusing lenses, identified by number 8 on Figure 1, is placed outside of projector to focus the reflected image from DMD onto the surface of polymer bath in a suitable size.

To supply UV light, a broadband GreenSpot™ UV Spot Curing System from UV Source, Inc. was used. The UV Spot Curing System consists of a high-pressure mercury lamp, a 100W power supply and ballast system, and a programmable shutter. The shutter is electronically controlled, and can be adjusted in increments of 0.01 second up to 99.99 seconds. The spectrum of the broadband UV light ranges from 300 and 470 nm, and has a peak at 365 nm. This external UV light source was selected to avoid difficult modifications required to integrate the stand-alone high-pressure mercury bulb into the projector. The light guide assembly was also supplied by UV Source, Inc. The light guide is liquid-filled, and provides good UV transmission between 300 and 500 nm.

The DMD has a resolution of 1024x768. It provides rapid change of image patterns (up to 10,000 paterns/s). It consists of thousands of micro mirrors, each with a size of 13.7 μm x 13.7 μm. Each individual mirror element can be rapidly electronically switched (up to 10,000 Hz) between "on" and "off" state. The light is thus selectively reflected, according to a designed image pattern, out of the projector into the focusing lens. For this study, the lens system was designed to provide approximately 1:1 ratio between the DMD pattern and the focused image. Silica lens was used since silica has good transmission in the UV region.

2.2. Photopolymer

Suitable photopolymers are critical for the μ-SL process. Important characteristics, such as viscosity, sensitivity, and wavelength response need to be considered. After UV curing, polymers will also exhibit different thermal, mechanical, and optical properties.

Several photopolymers from companies that specialize on stereolithography were evaluated. The DSM Somos 10120 WaterClear™ was selected because of its low viscosity (~130 cps @ 30º C), its relatively low critical exposure (E_c = 9.7 mJ/cm^2), and its transparency in both liquid and cured state. The transparency in the cured parts is of interest since transparent micro molds could be used for a visual monitoring of mold filling in micro-casting or channel filling in electroplating. Other properties of the polymer are presented on Table 1.

DSM Somos 10120 WaterClear 10120 Specification			
Physical Properties - Liquid		**Mechanical Properties**	
Appearance	Optically clear	Tensile Strength	3736 psi
Viscosity	~130 cps at 30º C	Elongation at Break	32%
Density	~1.12g/cm^2 at 25º C	Elongation at Yield	4.20%
Optical Properties at 355nm		Modulus of Elasticity	248 ksi
E_c (Critical Exposure)	9.7 mJ/cm^2	Index of Refraction, n	1.51
D_p (Slope of cure-depth vs. ln(E) curve)	0.16 mm (0.0063 in.)	Hardness (Shore D)	81
E_{10} (Exposure that gives 0.254 mm (.010 in.) thickness)	48 mJ/cm^2		

Table 1. Properties of DSM Somos WaterClear™ 10120 photopolymer. [Data from DSM Somos]

2.3. Motion Control

To provide an accurate linear movement of the building platform (number 11 on Figure 1), a PC-controlled three-axis micro-stage (number 10 on Figure 1) from Anorad Inc. was implemented. Two perpendicularly stacked LW-7 stages provide lateral (x and y directions) movements, while an Anoride 7-4 stage enables the platform to move vertically (in z direction). The stage system has a resolution of 30 nm and can travel in speed up to 200 mm/s.

2.4. Software

Two different types of software were used for the apparatus: CNC-2000, and Microsoft PowerPoint. The CNC-2000 controls the motion of the stages; manual input of a single command line is possible, as well as automatic input of a series of commands in G-code format.

Microsoft PowerPoint was used to create monochromatic patterns and images and transferring those to the DMD. Further software development is needed to automate the solid model slicing and image generating.

3. Experiment procedure

The experiments were performed to characterize the apparatus and evaluate its capability for fabrication of meso and micro-sized 3D objects. The results will be used in selecting important variables and optimizing the fabrication process.

3.1. Experiment on curing depth and exposure time experiment

This series of experiments was carried out to better understand the relationship between the exposure time and cured layer thickness. The experiment was conducted by fully curing a support polymer layer on top of a silicon wafer, as shown in part 2 in Figure 2. A circular part on this layer was intentionally left uncured for top layer measurement purpose. Then a fresh layer of liquid polymer was recoated above the cured layer by dipping and raising the building platform. Finally, this top layer was exposed to a focused UV light within a predetermined period of time (part 3 in Figure 2). The cured thickness was then measured by use of a microscope, as illustrated in part 4 in Figure 2. The relationship between exposure time and cured layer thickness can be determined.

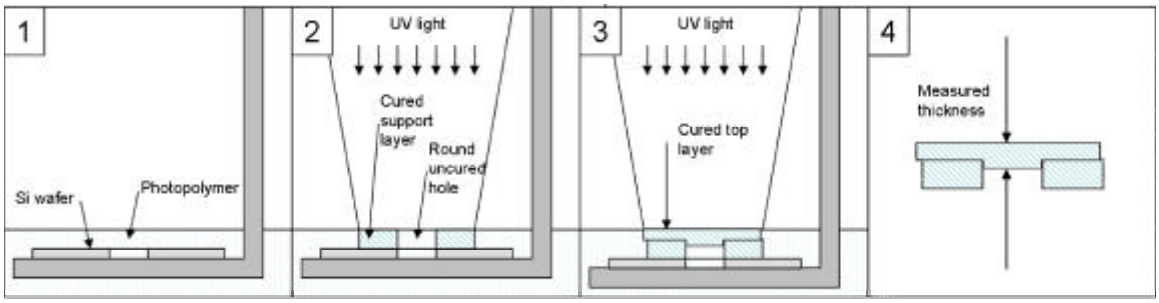

Fig. 2. Experiment on curing depth versus exposure time

3.2. Experiment on settling time

The apparatus builds microparts by stacking thin layers of photopolymers, preferably 5-micron thick for each layer. Conventional stereolithography apparatus normally utilizes a blade to achieve a desired layer thickness, normally 50~100 μm. However, this technique can not be applied on a μ-SL apparatus since the blade will destroy the micro part being built. A μ-SL apparatus usually relies on gravity to settle the polymer layer into a thin layer.

The experiment was conducted by lowering the building platform, and then raising it within the polymer bath up to height that is 10.0 μm below the surface of the photopolymer. Once the platform is raised, UV light was turned on periodically to cure a different small part of the settling polymer. The cured layer thicknesses were measured by a Tencor Alpha-Step 200 profilometer.

3.3. Experiment on resolution

There are two different resolutions on a μ-SL apparatus: lateral resolution, and vertical resolution. Lateral resolution is decided by the size of the individual mirror on the DMD as well as the focusing lens system. Vertical resolution is simply determined by the layer thickness; the smaller the layer thickness, the better the vertical resolution. However, thinner layer thickness demands more layers to build a 3D part.

The experiment was carried out to quantify the lateral resolution of the system. The experiment was conducted by curing a pattern of lines with different widths. After the sample was developed, the narrowest line width indicated the resolution of the apparatus.

3.4. Fabrication of Micro Parts

2D and 3D patterns/parts were fabricated to assess the capability of the apparatus. A microgear was of interest because it is a mechanical component containing small features. A microgear with 1.5mm lateral diameter was designed to be built using the apparatus, as shown in Figure 3a. To increase the complexity of the micropart, a cylinder and a second, smaller gear with fewer teeth (Figure 3b) were to be built on top of the base microgear.

A micropart with overhanging feature was also of particular interest. One attractive capability of the μ-SL process is that it is able to build overhanging features without the need of supporting structures. Hence, a micropillar with 1mm x 1mm lateral dimension with an overhanging section was designed, as shown in Figure 3c.

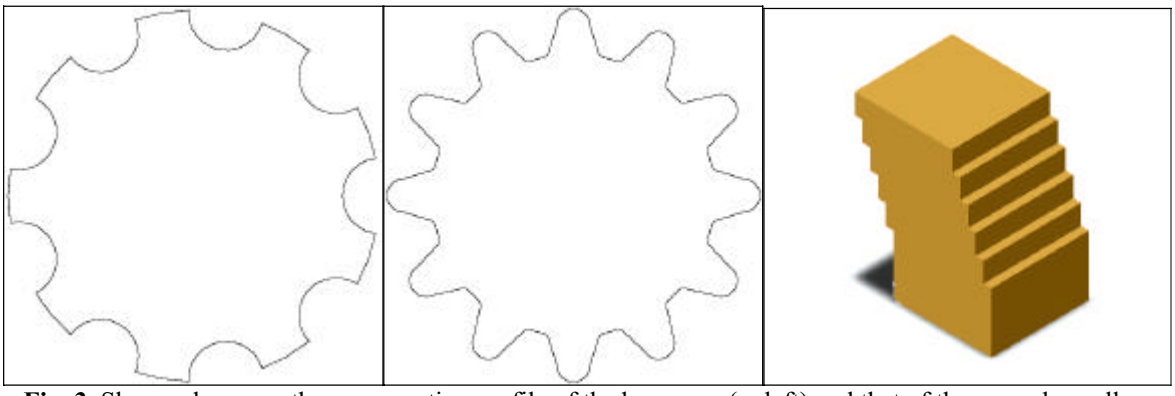

Fig. 3. Shown above are the cross-section profile of the base gear (**a**, left) and that of the second, smaller gear (**b**, middle) (the pictures are not in the correct scale). A CAD model of a micropillar with overhanging section was to be built using the apparatus (**c**, right).

3.5. Experiment on ultrasonic-assisted layer settling

High frequency ultrasonic vibration (above 20 kHz) was experimented in order to significantly decrease the leveling time of photopolymer. As shown in Figure 4, the experiment setup includes a 20 KHz ultrasonic ultrasonic transducer, a vibration table, and a silicon wafer. The thickness of the droplet of photopolymer on top of the silicon wafer was measured against time. A droplet of photopolymer of 14.6 μl was placed on top the silicon wafer under ultrasonic vibration. By measuring the diameters of settling droplets, the average thicknesses of the settling droplet layers were determined.

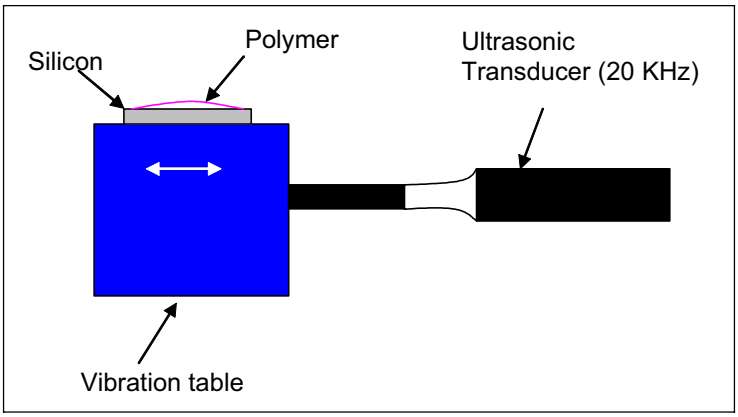

Fig. 4. Diagram of ultrasonic-assisted layer settling

3.6. Nano-composites preparation

The experiment was carried out to determine the feasibility of mixing polymer with nano-sized ceramic particle. Polymer-nano-composite material was of interest because it had the potential of improving mechanical properties of the fabricated parts.

High intensity ultrasonic waves were used to mix nano-sized Si_3N_4 (30 nm) with the photopolymer. A viscometer was used to measure the viscosity of the resulting polymer-nano-composite mixtures. The measurement result was plotted and used to determine the suitable nano-composite content in the mixture.

4. Results & Discussions

4.1. Curing depth and exposure time

Figure 5 shows the result of the curing depth versus exposure time. The linear fit of the data points on the plot suggests the cured layer thickness is proportional to the exposure time. The plot suggests that the polymer would not start to cure if the exposure time is less than 1.67 seconds in this μ-SL system. Other experiments verified this behavior. It might be attributed to the use of broadband UV light source and the fact that the photopolymer used is optimized for curing at 355nm wavelength. It might be better to use low power UV laser at 355nm to obtain optimized performance for this particular polymer. However, currently these UV lasers are expensive. One possible solution would be to find or develop photopolymers that have better response curve with respect to the spectrum of the broadband UV light.

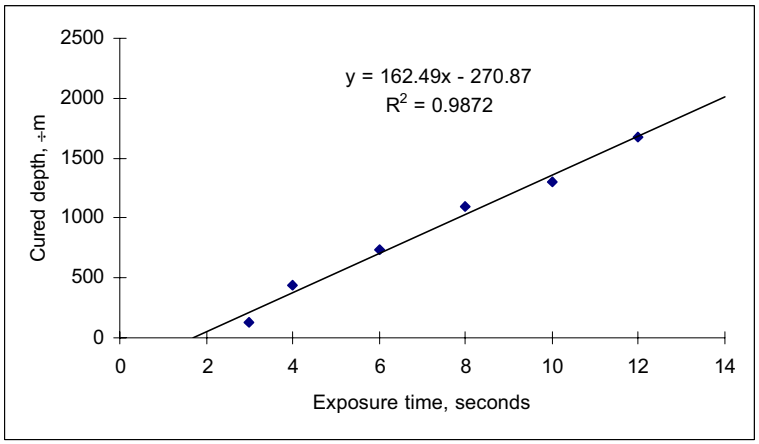

Fig. 5. Cured depth (cured layer thickness) versus exposure time on DSM Somos WaterClear 10120.

4.2. Settling time

Figured 6 shows how the polymer surface settled naturally (decreased in thickness with respect to the building platform) on top of silicon wafer as time elapsed. The plot suggests that the settling polymer layer thickness is proportional to the elapsed time. However, the settling time of the polymer was surprisingly long to reach 100 μm. The result suggests that 895.36 seconds would be necessary to obtain a polymer layer of 10 μm thick. Such a long settling time is not satisfactory for a rapid prototyping system. Further study is needed to find a more suitable photopolymer or to develop other means to spread thin polymer layer in this μ-SL system.

To overcome this settling problem, ultrasonic vibrations could help to achieve a significantly shorter layer settling time. Preliminary settling time experiments with ultrasonic vibrations were conducted, and results are presented in the subsection 4.5.

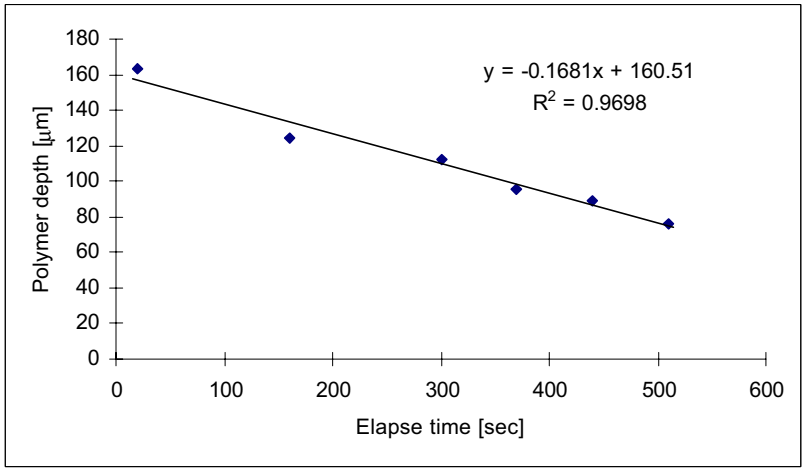

Fig. 6. The height of the polymer surface measured from the building platform versus elapsed time.

4.3. Resolution

By comparing the line widths on the computer screen to the cured line widths, the image ratio can be determined. A ratio of 1:20.3 can be achieved between the line width on the screen and the actual cured line width.

By use of microscope and SEM, the lateral resolution of the apparatus is determined to be approximately 20 μm. It dictates the smallest feature possible in X-Y plane to be built.

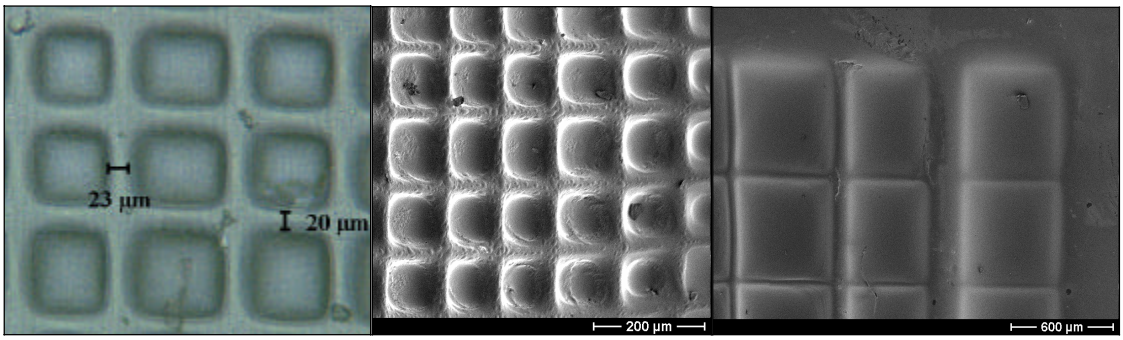

Fig. 7. Shown above are a microscope capture and SEM pictures of lines and grids patterns generated using μ-SL apparatus.

4.4. Fabrication of 3D Micro Parts

Figure 8 shows SEM pictures of 3D microparts fabricated with the μ-SL apparatus. Individual tooth can be distinguished on both micro-gears; however it seems some features were over cured. It is believed that optimization of process parameters will be necessary to solve this problem.

The last image in Figure 8 shows the micro-pillar. It seems no obvious overhanging feature appears. It is likely that the overhanging feature was washed out, possibly due to the recoating process. Further experimental study and process optimization are being carried out to obtain more sophisticated parts.

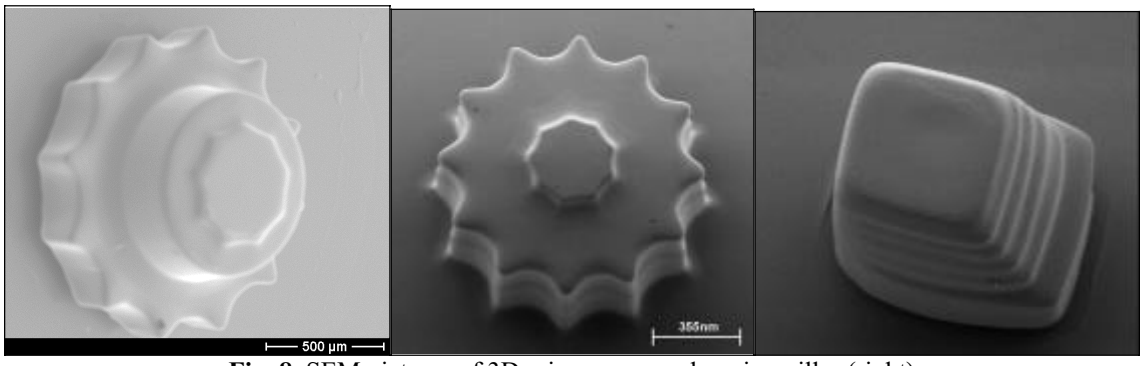

Fig. 8. SEM pictures of 3D microgears, and a micropillar (right)

4.5. Ultrasonic-assisted Layer Settling

Comparison between the results with and without ultrasonic vibration indicates that ultrasonic-assisted settling is very effective. It shines light for the future implementation of ultrasonic-assisted layer settling mechanism in the developed DMD-based μ-SL system.

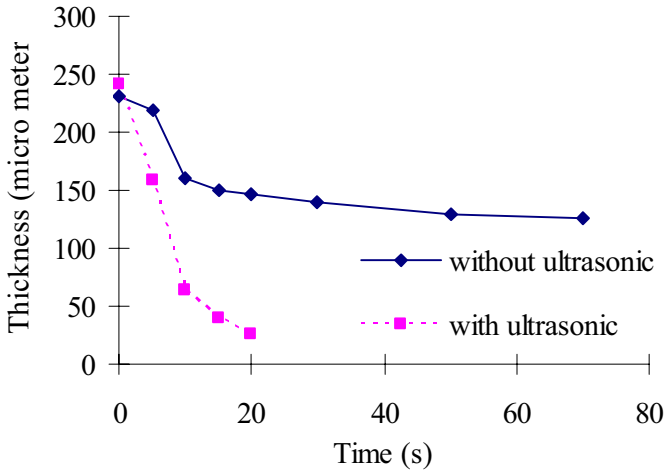

Fig.9. Polymer settling time on top of silicon wafer

4.6. Polymer Nanocomposite Parts

Figure 10 shows the viscosity trend of the photopolymer matrix nanocomposite as the nanoparticles content is increased. Based on the result, the nanocomposites having 1.0 weight % nanoparticles might have the combination of good strength improvement and their viscosity still remains low enough for recoating process. Thus photopolymer was mixed with 1.0 weight % by use of ultrasonic mixing. The resulting mixture was then used to fabricate a micro-gear shown in Figure 11. Visual observation under a microscope suggests that the nanoparticles within the microgear were dispersed quite uniform.

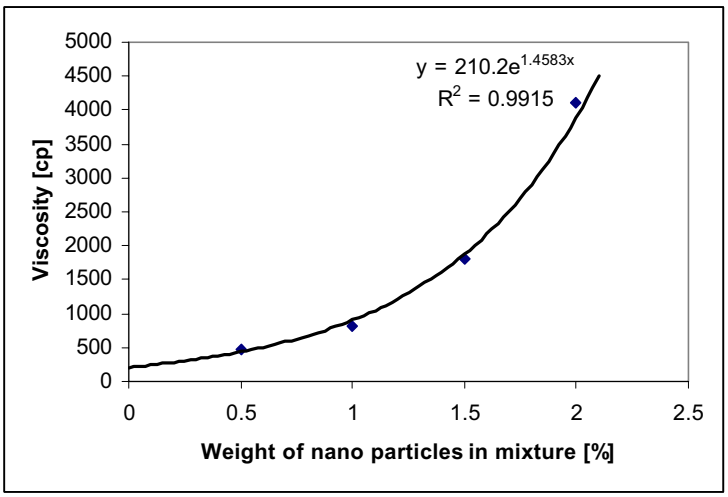

Fig. 10. Viscosity of photopolymer-nanoparticle mixture (measured at 1.0 rpm)

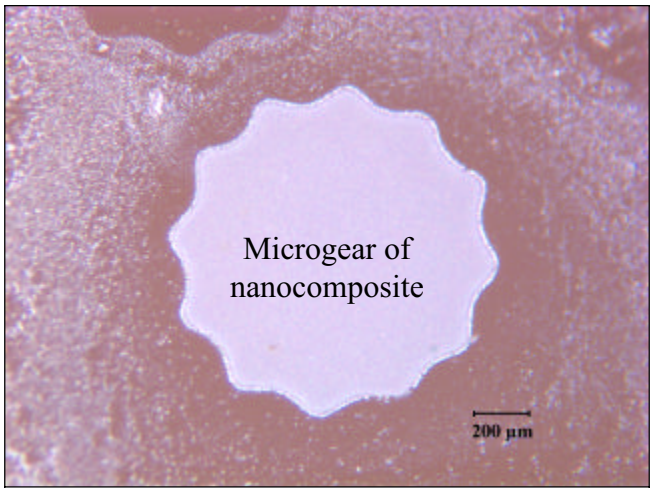

Fig. 11. A microscope picture of a microgear made of polymer-nano-composite.

5. Conclusion

A DMD-based microstereolithography apparatus has been realized. The apparatus attempts to combine the versatility of rapid prototyping, and the capability of fabricating high resolution micro structures. 2D and 3D microparts with 20 μm lateral resolution are realizable. Characterization experiments show that the developed the DMD-based imaging system irradiates an entire photopolymer layer at once, providing reasonable curing speed and good resolution at a low cost. Further study and process optimization will be needed to improve the quality of the micro parts.

High frequency ultrasonic vibration was experimented and verified that it can be used to significantly decrease the leveling time of viscous photopolymer. Uniform photopolymer matrix nanocomposites were obtained by ultrasonic mixing. The nanocomposites promise to improve properties of fabricated parts. Micro parts were also fabricated in nanocomposites.

6. Acknowledgements

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