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Microstereolithography: Concepts and Methods

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Abstract- Microstereolithography (Micro-SLA) is a fabrication process emerged from the 3D printing industry. The first attempt in manufacturing micro level objects was made in 1993. Different researchers around the world have developed micro-SLA machines since then. All the micro-SLA systems are based on the fabrication of parts by UV light incited layer-stacking. Micro-SLA incorporates an integral curing approach creating complex 3D micro-objects. These objects can be used in the fields of microsystems, microfluidics, and micro-robotics. The most promising application field of this technology is still the rapid prototyping that faces an increasing demand of high-resolution small-size prototypes. The paper reviews the prime micro-SLA processes developed until now.

Keywords-Additive manufacturing, Microstereolithography, Photopolymerization, Collective Microstereolithography

I. INTRODUCTION

The advance of Additive Manufacturing (AM) techniques has significantly improved the ability to fabricate structures with precise geometries. These techniques include fused deposition modeling, selective laser sintering, stereo lithography, etc. originally, AM techniques were developed to create prototypes in the process of product designing and development. The ability of AM to create an object from a computer-aided design within hours significantly speeds up the product development. Stereo lithography, being the first commercially available AM technique, was developed in 1986 by 3D systems [1]. Stereo lithography is especially versatile with respect to the scales at which objects can be built: submicron-sized structures and the freedom of designing structures.

Micro-SLA is related to rapid prototyping technologies, more precisely to Stereo lithography (SLA), allowing the manufacturing of 3D objects by layer-by-layer curing of a photopolymer resin with an ultraviolet (UV) laser [2]. Concepts and apparatuses of micro-SLA were developed by various research teams mostly in an academic context.

In this paper, we review the major Micro-stereo lithography processes. The principles of operation of the micro-SLA technique are discussed.

II. CONCEPTS

Micro-stereo lithography (micro-SLA) is a micro fabrication technology that is different from the techniques commonly used for the manufacturing of Micro Electro Mechanical System (MEMS) components [3]. Micro-SLA is undoubtedly the one among all micro fabrication techniques developed up to now, that can manufacture small objects with the most intricate details and high-resolution complicated shapes. Micro-SLA is also known as micro-photo-forming, spatial forming, optical forming, micro-stereo photolithography, 3D optical modeling etc. corresponding to design variations in the apparatuses [4]. However, all these machines allow building high-resolution, small-size 3D objects, by polymerization of a liquid resin into a solid polymer. Micro-SLA technique can be classified into three major categories: Scanning micro-SLA, Projection micro-SLA, Sub micrometer micro-SLA.

2.1.Scanning Micro-SLA

The first micro-SLA machines based on scanning principle were presented in 1993. One machine was presented by Ikuta and Hirowatari [5] and another by Takagi and Nakajima[6].

2.1.1. Constrained surface technique or fixed surface method.

The solidification of the photopolymer occurs always on the fixed boundary between the window and the resin. This technique is based on a vector by vector tracing every layer of the object with a light beam. The light beam is tightly focused on the photopolymer through a transparent window. No scanning mirrors are used to deflect the light beam.

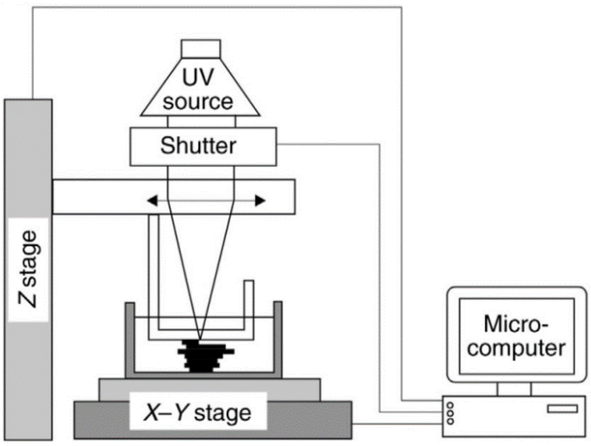

Figure 1: Schematic of scanning Micro-SLA machine with constrained surface technique

The vector by vector fabrication is obtained using x-y translation stages to move either the whole optical system targeting the light beam on the resin surface or the photopolymer container in which the object is made while the focus point remains fixed [7]. The light beam occulted with the help of the shutter during translation without polymerization or when a new layer is made. The system uses glass window to persist the liquid to avoid the problem of spreading the fresh photopolymer on the already polymerized part of the object. The main disadvantage of this method is the polymerized object sticks to the transparent window. This adhesion can lead to a partial or total destruction of the object during the manufacturing process.

2.1.2. Free surface technique.

The main differences between constrained surface and free surface based techniques are method of polymer curing and build orientation [8]. To avoid the problem of the object sticking to the window, many research teams promoted scanning micro-SLA processes where resin gets polymerized at the free surface of the liquid resin. In this process, the vector by vector fabrication is obtained by moving the photopolymer container with x-y-z motorized translation platform. The optical system targets the beam of light statically on the resin surface. Such types of machines are easier to build but it is difficult to control the thickness of the deposited resin layer. The rheological properties of photosensitive resin and the geometry of the last layer affect the time to get fresh layer of resin.
The first paper on scanning micro-stereo lithography with the free surface technique was described in 1994 by Zissi et al [4].Fresh layer of resin was obtained on the surface of the object under construction by immersing the object in resin container and bringing back close to the surface. To obtain stable beam intensity and small size spot, Laser was used instead of a lamp. The photopolymer used by them contained low viscosity monomer1,[6] hexanediol diacrylate (HDDA) and conventional UV initiator. A scrapping device was used by Kobayashi for actively spreading resin over the previous layer instead of waiting for gravity force for leveling [9].

2.1.3. Collective manufacturing using optical fibers.

With the micro-SLA techniques, objects are generally fabricated one object at a time because of limited build area. This is the major drawback for a micro-SLA system. Collective micro-SLA process was developed by Ikuta et al. in 1996 which allows collective manufacturing of small size components [10].

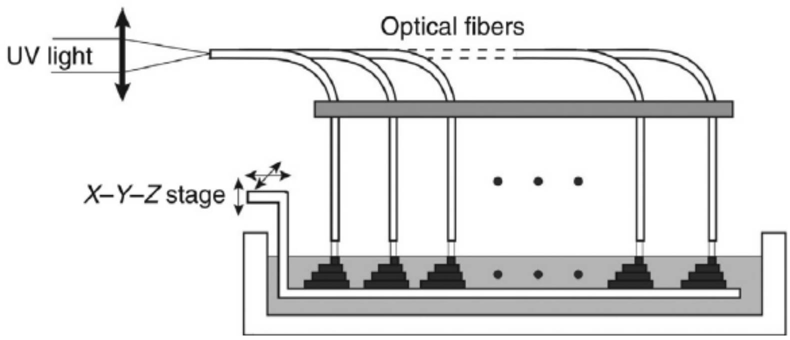

Figure 2: Schematic diagram of Collective Micro-SLA

The system presented by Ikuta et al. uses 5 single mode optical fibers as shown in Fig. 2, which are used to focus UV light beam in five different locations on the free surface of photopolymer. The optical system is held stationary and the vectors constructing layers are achieved by scanning the resin container using x-y-z-stages under computer control. Five objects with same geometry can be built simultaneously with this setup [4].

2.2.Projection Micro-SLA

Projection micro-SLA process is different than conventional AM processes that work on the vector by vector manner. The components used as dynamic pattern generator are the key components. 3D computer aided design (CAD) files obtained by CAD modeling software are oriented (if needed), scaled and sliced uniformly along the chosen plane(generally XY plane).The slices are converted into bitmap image files and used to operate dynamic pattern generator, beginning with the cross section corresponding the bottom of the object. The pattern generator shapes the beam coming from the source of light so that it comprises the image of the layer to be built. The image is focused on the surface of photopolymer to selectively cure the irradiated area and a thin layer of cured resin of required shape is obtained. The first layer of the object to be fabricated is cured at the surface of a platform [11]. Once the solidification of a layer is complete, the already polymerized part is immersed in the resin container, deep enough so that polymerized surface is totally covered with fresh resin. It is then lifted up to a certain height, such that there remains a layer of resin between the surface and the last polymerized layer. The same sequence of operations is performed until the object is completed. The polymerized layers are stacked to one another by the interpenetrating polymer networks. The completed object is taken out of the resin container and washed with suitable solvent.

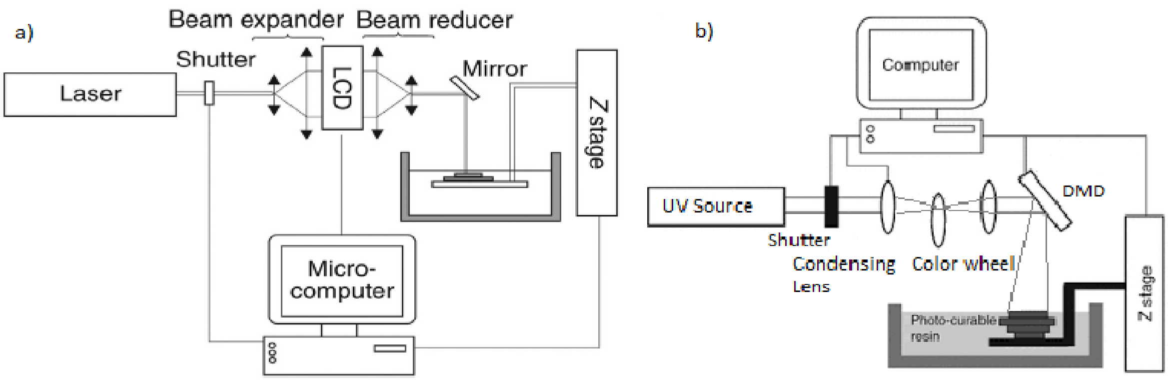

Figure 3: Schematic diagrams of Projection Micro-SLA systems

Projection micro-SLA show advantages compared to Scanning micro-SLA. The light flux density incident on resin surface while projecting the image pattern of a complete layer is low, compared to accurately focused light beam at a single point. Unwanted curing due to thermal effect will not take place in projection-SLA. Projection-SLA is fast because the irradiation and solidification of a complete layer are done in a single step, irrespective of pattern complexity.

2.2.1. Liquid Crystal Display (LCD) as a dynamic mask.

Projection micro-SLA with LCD as a dynamic mask was first demonstrated in 1995 by Bertsch et al. The LCD used in first micro-SLA was archaic, could only be used with visible light and not with UV light [12]. Photopolymer resin sensitive with visible light wavelengths had to be developed. Argon ion laser with 515nm wavelength was used as a light source. A complex optical system was added to eliminate speckle effect to get the light with a uniform intensity and to redistribute laser light irradiation from a Gaussian to a top-flat profile. Specific resins sensitive to green light wavelength were formulated. Such resins undergo photo bleaching at the time of photo polymerization, controlling thickness of the polymerized layers is difficult in such cases.
A Polysilicon thin-film twisted Nematic LCD was irradiated with 351.1nm argon ion laser by Farsari et al.Gaussian irradiance distribution was reshaped to rectangular irradiance using diffractive optical elements. Epoxy-based commercial SLA resins were used as the machine operated in UV[13].

2.2.2. Digital Micromirror Device (DMD) as a dynamic mask.

DMD technology is owned by Texas Instruments. DMD is a Micro-electromechanical system which works as a light switch. It consists of several hundred thousand microscopic mirrors arranged in a rectangular array which are actuated by electrostatic forces. The number of mirrors corresponds to the resolution of the screen. Mirrors reflect the light towards the absorbing area. Black and white pixels are sufficient micro-SLA applications for manufacturing objects layer by layer. The maximum available resolution of the image using DMD is 2560x1600.The major advantage of using DMD is development of high resolution projection micro stereo lithography [11]. DMD has higher contrast compared to LCDs and can be used to get wider range of wavelengths.

The first micro-SLA machine with DMD as a pattern generator is developed by in 1998 Bertsch et al.A metal halide lamp with adequate optical filters was used to irradiate UV light on the resin. Different acryl ate-based resins sensitive to 515nm or 410nm were used. Later, the machine was modified to work with 365nm UV light.

Zheng et al. developed projection micro-SLA machine which works on 'step and repeat' method. Polymerization of each layer is achieved through multiple exposures, resulting to larger polymerized layers. The system allowed to build bigger objects with same resolution. Emami et al. developed a new SLA process to build large objects with good resolution. DMD is moved continuously in *X* and *Y* and the images are projected continuously. This Scanning-projection SLA method eliminates the limitation of projection-SLA systems in which size of object is limited by size of dynamic pattern [14].

2.3.Sub micrometer micro-SLA

Instead of manufacturing layer by layer at the surface, the object is manufactured directly inside the reactive medium. resin. It eliminates the need to spread the layer of fresh resin over the object under construction, which potentially speeds up the fabrication. There is no need for support structures [16]. Freely movable components and assembled objects can be made easily. Sub micrometer micro-SLA processes were developed in two manners, either on two-photon photo polymerization or one photon under the surface to build objects with a sub micrometer resolution.

2.3.1. Two-photon micro-SLA.

Two photon absorption occurs when combined energy of two photons exceeds the transition energy between the ground and excited state. It is an optical nonlinear phenomenon which takes place at sufficiently high level of irradiance. Two-photon absorption rate is proportional to the square of the intensity of incident light. The quadratic dependence on the intensity of the light confines the absorption to an area at the focal point. The power of light source should be extremely high as the rate of two-photon transition is very high.

The first machine based on two-photon photo polymerization was presented by Maruo et al. in 1996 [15].Mode-locked Ti:sapphire laser emitting at 770 nm light source was used. A photopolymer, transparent to 770nm light, based on urethane acrylate oligomers and monomers was used. This photopolymer did not attenuate the light beam and the incident light can be focused inside the photopolymer without polymerization at the surface of the resin. The object was manufactured by moving the photo reactor in vertical direction. Kato et al. presented collective manufacturing using two-photon micro-SLA. Simultaneous fabrication of almost 200 microstructures was achieved using microlens array for multifocal photo polymerization [16].

2.3.2. Single photon micro-SLA.

Single photon micro-SLA was used in similar manner as two-photon micro-SLA to execute local photo polymerization of resin under the surface. Tightly focused irradiation is weakly absorbed in photopolymer. Intensity of light is sufficiently low and polymerization will take place only at the focal point. Oxygen is dissolved in the resin to inhibit the polymerization in the out-of-focus region where intensity of light us adequately low. The resin with nonlinear behavior in response to light intensity is used. The first machine working on single photon polymerization was developed by Maruo and Ikuta [16].

CONCLUSION

Micro-SLA technologies are versatile with respect to the scale at which object can be built and freedom of design of the structure. Micro-SLA processes can be effectively used to fabricate real 3D complex objects which are difficult to manufacture by conventional machines. Different research teams have contributed to explore different ways to modify the micro-SLA processes using a distinct range of components: optical elements, irradiation configuration, different light sources etc. Different resins were formulated dedicated to these technologies. Though Scanning micro-SLA is widely used, Projection micro-SLA is gaining significant amount of interest of researchers. Some of the micro-SLA techniques are combined to collectively fabricate objects with good resolution.

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