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Microphotofabrication of Very Small Objects : Pushing the Limits of Stereophotolithography

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Stereophotolithography (SPL) allows to manufacture 3D polymer parts directly from Computer Aided Design data files. Its principle is the space resolved polymerization of a resin by a laser. We first discuss the possibilities to make parts with a very high resolution. A first approach was to push the classical SPL process to its limits to get a resolution of about 30 micrometres . A second really innovating one was to modulate the light flux by a liquid crystal display and we obtained a resolution of 5 micrometres. Since the use of these parts is limited by the nature of photopolymers, we also developed a new process to make complex polymer/metal parts directly. It consists in making the part layer by layer by using three techniques : SPL, electrodeposit of copper and laser silver plating.

Keywords: stereophotolithography; microfabrication; liquid crystal; resin; metal

INTRODUCTION

Stereophotolithography (SPL) has been developed since 1981 by different teams in the USA[1], Europe[2] and Japan[3] and is now widely used in the automotive and aerospace industries for the manufacturing of industrial prototypes. The idea

is to go directly and automatically from the CAD (Computer Aided Design) data files to the 3D physical model. With commercial machines, the parts dimensions range from 1 to 50 cm and the accuracy from 0.1 to 0.5 mm. So we cannot use them for microfabrication.

The basic principle of SPL is the following[4] : the part is manufactured layer by layer by selectively curing a photosensitive resin by a UV laser beam. The laser beam is deflected by two computer-controlled low inertia galvanometric mirrors on the open surface of the resin so as to draw the outline of every part slice. Due to the Beer-Lambert law, the thickness of the solid polymer obtained ranges from of 0.05 to 0.3 mm after curing, according to the resin chemistry, to the laser beam power and to its deflection speed. The part is built on a platform which is positioned below the resin surface and, to obtain the third dimension, the slices are accumulated by moving down the platform into the resin.

As it is a 2D drawing process, one advantage of SPL is that it allows to build very complex structures with intricate details and hollow parts. Unlike conventional machining techniques, the SPL process needs neither tools nor molds: it is independent of the part geometry and can be fully automated. As lithography in electronics, SPL uses light and photosensitive resins. So, as well as other teams[5], we expect to reach a very high resolution in the manufacturing of 3D parts and even to be able to make complex 3D microparts. In the first part of this article, we will review the state of the art of microstereophotolithography (μSPL) in our laboratory and give one detailed example.

One disadvantage of SPL is that it is limited to polymers which are usually acrylate or epoxy. Therefore we developed a new process to make complex polymer/metal parts directly. It consists in the manufacturing of the part layer by layer by combining three techniques : SPL, electrodeposit of metal and local laser silver plating on polymer. We shall describe this process in the second part of this article and discuss its potentialities for microfabrication.

MICROSTEREOPHOTOLITHOGRAPHY

We developed several approaches and built new machines so as to manufacture microparts.

Point by Point Microstereolithography

First we pushed the classical SPL process described above to its limits by improving the focusing of the laser as well as the chemical composition of the reactive medium and reached a typical resolution of about 30 μm[6,7]. Small objects were made with this type of device but the main limitation comes from the poor resolution due to the use of galvanometric mirrors.

A second approach[6,7] is a better focusing of the laser beam : we obtained a laser spot diameter of 10 μm and replaced the galvanometric mirrors by a x-y motorized positioning stage with a 0.1 μm resolution. The laser beam and all the optical parts remain fixed while the resin tank, the platform and the part are moved all together. The main problem with this technique is the very high light flux when the laser beam is so highly focused. This induces parasitic thermal polymerization. Microparts, and even active parts with shape memory alloy elements have been manufactured[7,8] by this technique.

Layer by Layer Microstereolithography

Figure 1 shows a new approach based on a different and really innovating principle[9] : as previously, the part is built layer by layer, but the difference is that a complete layer is cured by only one laser irradiation, using a liquid crystal display (LCD).

This device is used as a dynamic masks generator. The LCD (Infocus System 1600GS PC VIEWER® LCD Projection Panel) is made of 640x480 pixels separated by threads for electrical connections used for their control by computer. Every pixel is a small cell containing liquid crystal molecules which can be set to its transparent or opaque states by changing the orientation of the liquid crystal molecules. The LCD is inserted between four protecting glass plates and polarizing filters which absorb some UV. Therefore we used a 1 W Ar^+ laser (Coherent® INOVA 90) emitting at 514 nm and modified the reactive medium as described below.

To obtain a high resolution, it is necessary to illuminate the largest possible surface of the LCD. To do so, the beam is expanded so as to use its central part only. After passing through the LCD the laser beam is reduced and directed with

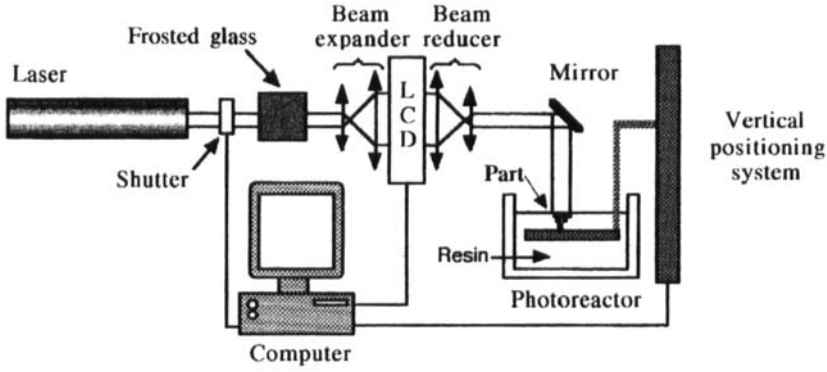

FIGURE 1 Layer by layer SPL with a LCD dynamic masks generator

a mirror onto the resin surface. The part is built on a platform which is moved down during the manufacturing process. Compared to the devices described above, this machine is very simple and the number of mobile active elements has been reduced to one : the motorized z positioning stage.

The main advantage of this method is that it allows a good control of the physico-chemical processes which occur during the polymerization steps. The light flux on the surface of the resin is weak compared to the one in the point by point processes and so the parasitic thermal initiations become neglectable. Furthermore, there is no double exposure or crossed polymer lines. The time required to manufacture a layer is independent of its pattern and this process can be used for collective fabrication processes.

The disadvantage of this method comes from the present low resolution of the LCDs and from their poor contrast. The pixels in their opaque state let still pass some 20% of the light through them. The electrical wires controlling the LCD make an opaque matrix and also generate diffraction phenomena. As a result, every polymerized layer surface has a bumpy aspect.

Many threshold systems with photoinitiators which can directly initiate the chain reaction[10] are suitable to obtain space resolved UV polymerization. But above 400 nm, very few chemicals can initiate the photoreaction by themselves. So, in order to work at 514 nm, we use a more complex reactive mixture[11] composed of eosin, methyl diethanolamine and pentaerytritol triacrylate which reactivity threshold also counterbalances the low LCD contrast. Nevertheless, the control of the vertical and transverse resolutions, essential to manufacture accurate small parts, is particularly difficult to obtain. This is due to the photobleaching of eosin in the polymer and to the fluorescence of the medium. This is studied in details elsewhere[12].

Example of a Bevel Microgearing With Helical Cogs

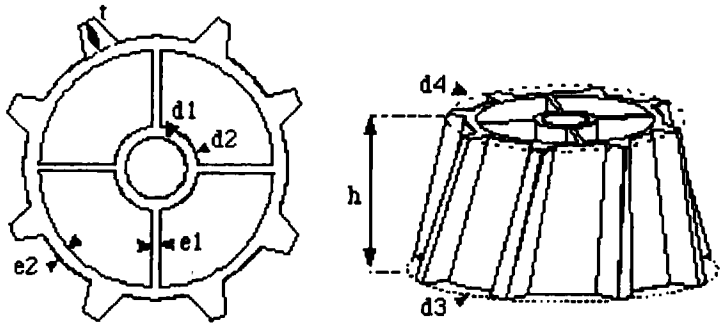

FIGURE 2 Scale drawing of a microgearing

The part shown in Figure 2 was built in different sizes with the device described in Figure 1 (cf. Table 1). It is made of 110 layers, every of them being about 3 μm thick. Its empty cylindrical axis is bounded to the outer truncated cone by four vertical walls. The building time was about 90 minutes. Figure 3 is a scanning electron microscope photograph of the smallest gear we manufactured and shows the high resolution of the part : it is better than 5 μm.

TABLE 1 Three scales of microgearing manufactured by μSPL

	Microgear n°1 (μm)	Microgear n°2 (μm)	Microgear n°3 (μm)
d1	210	150	90
d2	380	225	130
d3	1775	1100	690
d4	1375	900	510
e1	70	30	15
e2	85	37.5	15
t	175	112,5	60
h	1675	750	350

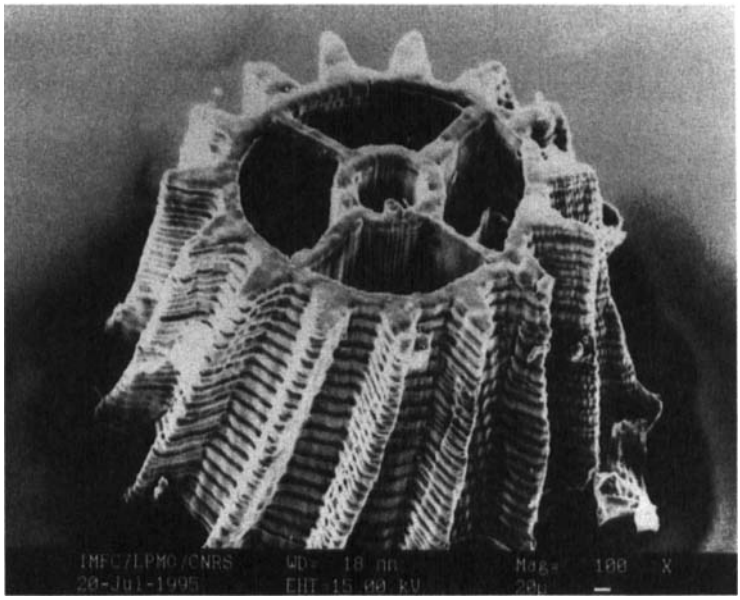

FIGURE 3 Microgearing n°3 manufactured by μSPL

MANUFACTURING OF COMPLEX METAL/POLYMER PARTS

Nowadays, SPL only allows the manufacturing of polymer parts, so we developed a new technique[13] to get composite metal/polymer objects which may be interesting in the future for microparts and micromotors. Its principle is to build, layer by layer, the 3D object so as to obtain the conducting and non-conductive parts together instead of manufacturing them separately and assembling them afterwards. For example, to build the cylindrical object described in Figure 4 which consists of a metallic element (Part 1) freely rotating inside a polymer housing (Part 2). We combined the following steps :

- electrodeposit (ECD) of copper to make Part 1;
- local laser silver plating on polymer to get the conducting base for ECD;
- SPL with an insoluble resin to make Part 2;
- SPL with a soluble resin to make a sacrificial structure between Part 1 and 2.

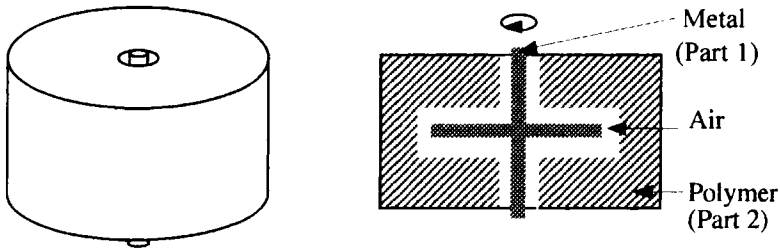

FIGURE 4 Example of a complex metal/polymer part

Figure 5 describes the different manufacturing steps. The object is built on an epoxy substrate coated with a thin copper layer Cu1. This copper is etched with nitric acid to define the starting base for the ECD of copper Cu2. Two resins SPL1 and SPL2 are successively used. SPL1 sets the limits for ECD and is soluble after curing while SPL2 remains insoluble to form Part 2.

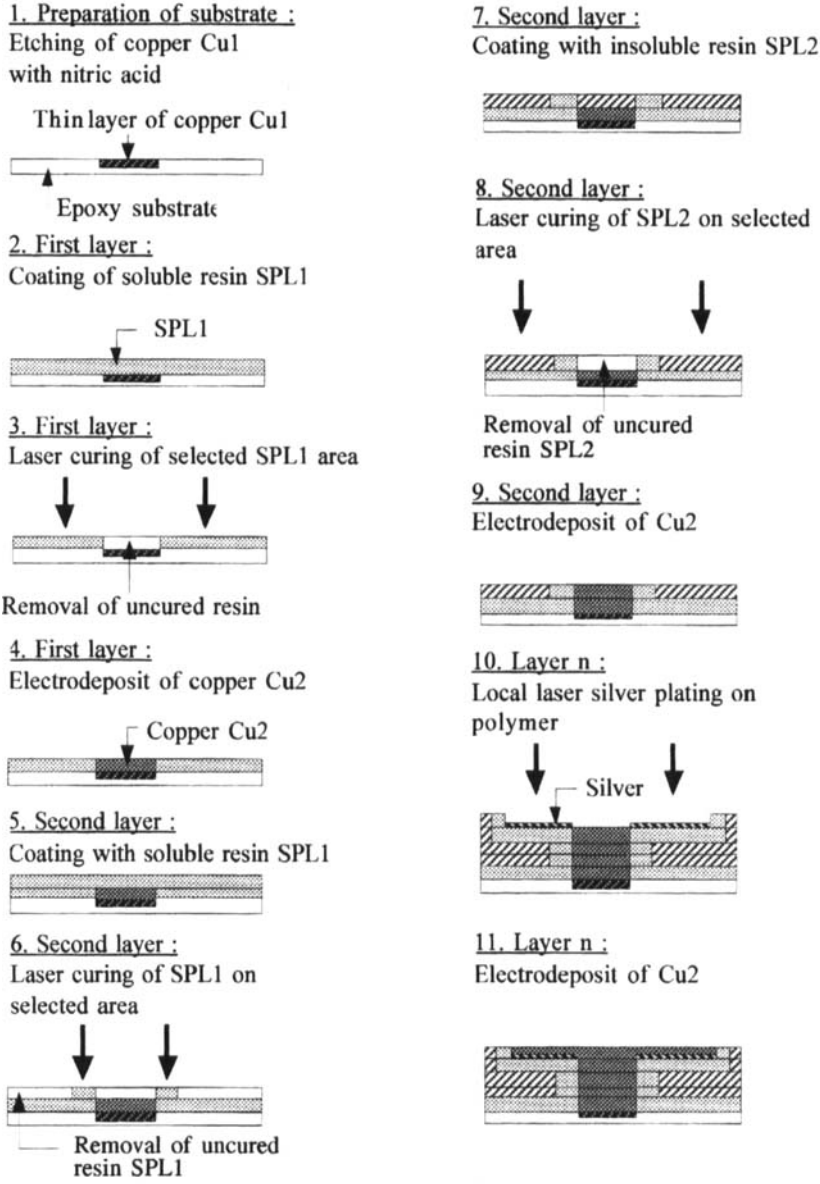

FIGURE 5 Layer by layer manufacturing of a complex metal/polymer part

Cu2 is electrodeposited layer by layer. A laser is used to plate SPL1 with silver when the diameter of Part 1 increases suddenly so as to continue the ECD. In the end, SPL1 is dissolved to separate Part 1 from Part 2.

Electrodeposit of copper

The ECD of copper is guided by the soluble SPL1 polymer. So, by changing, layer by layer, the 2D polymer shapes, it is possible to obtain a 3D complex metal part. We used 0.7 Mol/L copper sulfate mixed with 1 Mol/L sulfuric acid as electrolyte. The cathode was the part itself and the anode was made of copper. Tests[13] showed that a current of 40 mA/cm^2 was a good compromise to get an acceptable surface quality : the copper layers were 100 μm thick growing at a rate of 50 μm/s. Figure 6 shows a part built in copper by this technique.

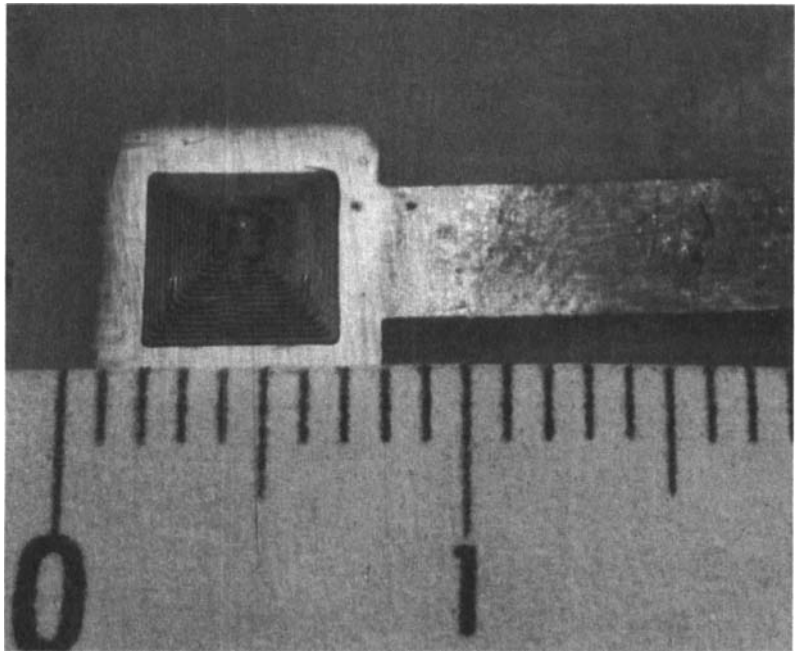

FIGURE 6 16 layers copper pyramid (5x5x1.3 mm) (See Color Plate III).

Local Laser Silver Plating on Polymer

As ECD can only occur on an already conducting substrate, we use a process to control the silver plating on polymer substrate thermally by a laser. This process[13] is based on the reduction of silver nitrate ions and the oxidization of glucose and is used to manufacture mirrors and reflective coatings for the Christmas tree balls in the industry. The reaction is :

$$H0\text{-}CH_2\text{-}(CH\text{-}0H)_4\text{-}CH0 + 2\ Ag(NH_3)_2^+ + 3\ OH^- \longrightarrow H0\text{-}CH_2\text{-}(CH\text{-}0H)_4\text{-}COO^- + 2\ Ag + 4\ NH_3 + 2\ H_2O$$

and is highly temperature dependent[13]. The reactive medium is a transparent liquid made of a volume V of glucose in water (175 g/L) mixed with an equal volume V of silver nitrate of ammonia (45 g/L) and a volume 2V of sodium dodecyl sulfate (25 g/L) acting as surfactant. The principle of the process is to coat the SPL1 substrate with a continuous film of liquid, 1 mm thick, and to irradiate it by a laser. The absorption of light by SPL1 causes a local elevation of the temperature substrate which induces the reaction and consequently the local deposit of silver. To increase the absorption of the laser, Crystal Violet dye is added to SPL1 and a 514 nm Ar^+ laser (INOVA 90 Coherent Inc.) is used for this plating step. This allows to adjust the UV curing of SPL1 and SPL2 independently from the temperature elevation of SPL1. Silver conductive micropatterns with widths thinner than 20 μm have thus been obtained.

Use of Soluble Polymer to Manufacture a Sacrificial Structure

This resin[13,14] is made of photosensitive acrylic resin containing 50% silica and is modified by adding Crystal Violet as described above. The resin is cured by an Ar^+ laser beam at 360 nm and is dissolved with 2 Mol/L caustic soda at 80°C. This resin is not sensitive to the acid used for ECD and is not swollen by water.

Use of Insoluble Polymer

It is a resin[13] classically used in SPL, also cured by a 360 nm Ar^+ laser.

Example of manufacturing

Figure 7 shows the part that we manufactured. Its manufacturing lasted 8 days because the changes of techniques and lasers were done by hand. The dissolution of the soluble SPL1 polymer lasted 5 hours and, in the end, the metallic element was freely rotating in its polymer housing. The main problem identified is that SPL1 is too brittle and cannot stand a high laser flux during the silver plating. As a consequence, this induced deformations of SPL2 which were accumulated during the manufacturing. It was also difficult to obtain a good copper homogeneity for such a large part. Furthermore, the caustic soda damaged the copper. Nevertheless the manufacturing of this part proves the validity of the concept and our opinion is that most problems will become less critical at a smaller scale.

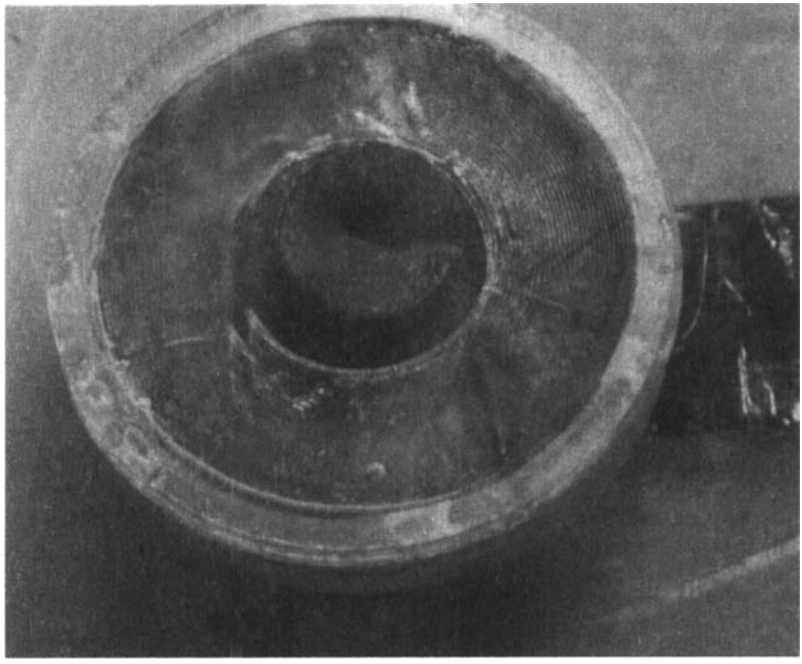

FIGURE 7 Complex metal/polymer part (diameter 10 mm - height 15 mm) (See Color Plate IV).

CONCLUSION : SPL AND MICROFABRICATION

In a first part, this paper describes several devices to manufacture microparts by SPL, mainly a really innovating new process using a LCD as dynamic masks generator. Even if it still has some limitations, it already allowed us to manufacture complex microparts and could easily be adapted to collective fabrication. Improvements are possible when LCDs resolution and contrast are increased.

In a second part, we introduce a very challenging new SPL process to manufacture complex polymer/metal parts with no assembling step. We think that this process can be improved and used in microfabrication. The main problem which is still remaining for the time being is the brittle properties of the soluble polymer. The process also needs to be simplified and completely automated so as to work with one laser only.

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