High Speed UV Laser Beam Scanning by Polygon Mirror

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1. Introduction

Since the stereolithograpy system appeared on the market, various rapid prototyping machines based on the layer laminated manufacturing process have emerged one after the other, the range of applications of which is classified according to their features. Of these, stereolithogrraphy methods which make use of photocurable resin as material and laser beam as processing tools are gradually being established. They are currently the most widespread with a rich variety of models available. The scanning device used in stereolithography serves as the key technology for this method but consists basically of only the galvanometer mirror known for outstanding high speed ability and the XY plotter known for outstanding scanning position accuracy[1),2)]. Lately, many models are seen to use the galvanometer mirror due to improved accuracy, but still this scanning device is used only when the fabrication size allows, etc. From such reasons, the authors have developed a laser stereolithograpy system capable of high speed high accuracy position scanning by the high speed raster scanning method using a polygon mirror as the scanning device[3)]. The polygon mirror, which has a higher scanning speed than the galvanometer mirror, is moved along the NC servo shaft and the raster scanning spacing is made considerably smaller than the laser beam spot diameter.

This paper describes this system and the results of fabrication experiments with this system.

2. Outline and Features of System

This system is composed of a laser optical device system made up of a laser oscillator, EOM laser modulator as laser shutter synchronizes with X axis and Y axis, beam expander, and reflection mirror, optical scanning device system made up of the polygon mirror , and f θ lens , recoating device, liquid resin supply unit, resin tank, and system controller. Its main features include a high speed scanning speed by the polygon mirror of 138.2m/s and 69.2m/s, high position accuracy scanning of below $\pm$0.05mm at the resin surface, use of highly viscous liquid resin of approximately 2200cP with a unique recoating method, and highly accurate fabrication with a layer thickness of 0.05 to 0.2 mm. The system has a simple and stable mechanism; the resin is drawn from the resin tank by the bucket, poured over the fabricated part and the liquid level is controlled by an overflow method. The 3D CAD data slice data generation software used is SOUPware by NTT DATA CMET INC. The slice data edited on the software is transferred to the controller of the unit from EWS by Ethernet and converted to raster scanning data. The photocurable resins used are mainly the ASAHI DENKA KOGYO 's epoxy resin HS series and versions of these resins with high viscosity.

Table 1 shows the specifications of the system, Fig. 1 shows the configuration of the system, and Fig.2 shows the external view of the system and controller.

Table 1. Specifications of the system

Laser	He-Cd (325 nm, Multi-mode beam) ,100 mW
Laser penetration rate	65% (On liquid resin surface)
Laser beam spot diameter	ϕ 0.1mm (On liquid resin surface)
Laser shutter	EOM (Synchronizes with X axis and Y axis)
Laser scanning device	10 faces polygon mirror
Laser scanning speed (Y axis)	138.2 m/sec , 69.1 m/sec (Two steps)
Scanning position accuracy	±0.05 mm or less (On liquid resin surface.)
Recorter (X axis) speed (Simultaneous raster scan)	0.06 mm/sec ~ 6.67 mm/sec (Raster scanning line pitch 0.33~20 μ m)
Minimum layer thickness	About 0.05mm (Depends on the resin viscosity)
Work size	250 mm(X) x 250(Y) mm x 255(Z) mm
External dimensions	1950(W) mm x 1050(D) mm x 1400(H) mm

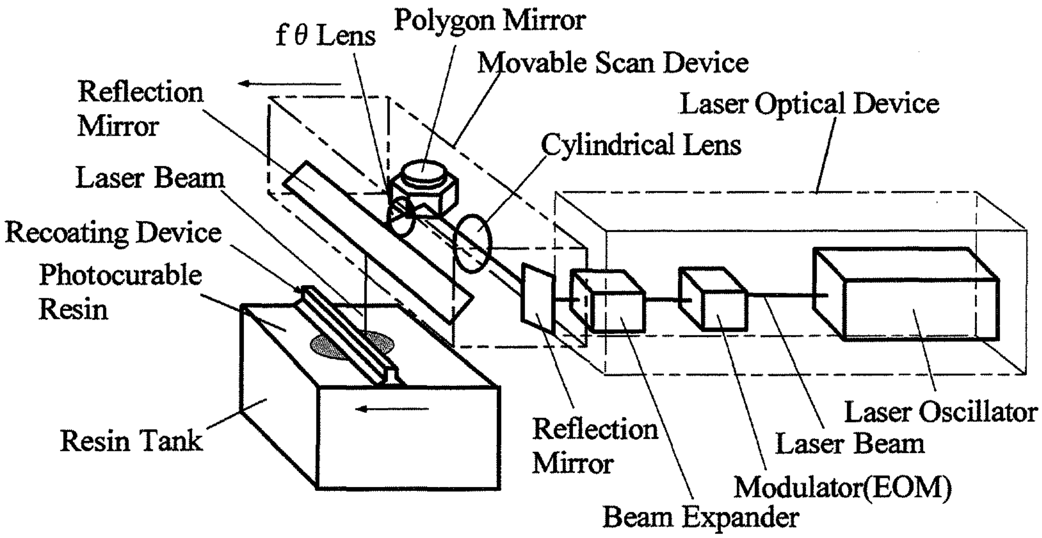

Figure 1. Configuration of the stereolithography system using by polygon mirror

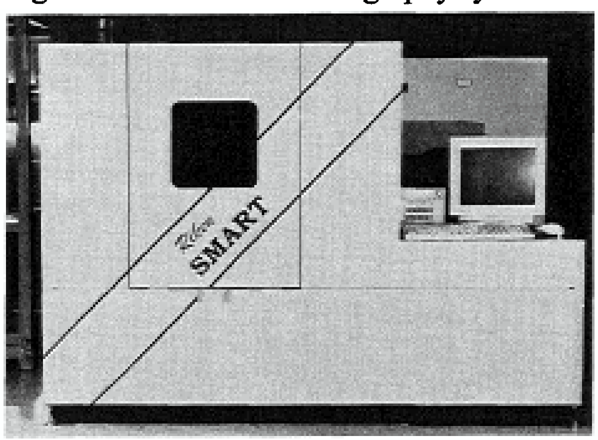

Figure 2. External view of the system and controller

3. Micro Spacing High Speed Raster Scanning

The polygon mirror is a laser beam deflection device currently used in scanning optical system such as the laser printer, etc. As shown in Fig.3 , a polyhedron mirror is rotated at a constant speed by a high speed motor to reflect the laser beam by each of its face so that scanning is performed linearly in one direction in one dimension[4]. Consequently, it is incapable of vector scanning which traces the contour of the slice data along one line during fabrication. Since the polygon mirror is rotated at an equiangular speed, the angular changes of the reflected laser beam are proportionate to time. A $f\theta$ lens is used to scan at a constant speed. For the polygon mirror to rotate stability, it cannot be rotated at low rotational speeds of less than about 1000 rpm. Scanning can therefore be performed only at high speeds, and the resin does not reach the critical exposure required for it to harden with only one scanning line at the resin surface. From such reasons, the scanning optical system incorporating the polygon mirror, etc. is moved by NC servo driving at very small spacing compared to the laser beam linewidth (spot diameter) as shown in Fig.4 while performing high speed raster scanning to form a consistent cured layer by drawing the desired photocurable liquid resin surface and average exposure.

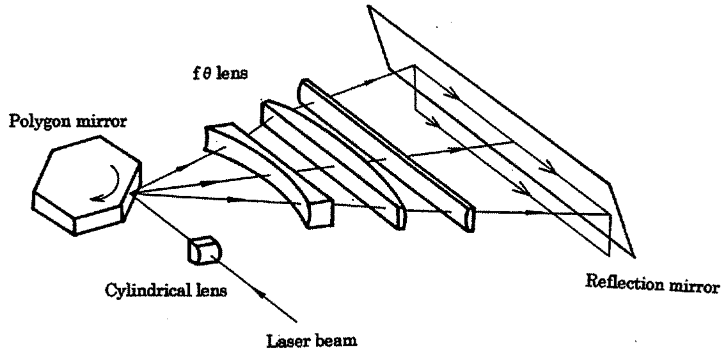

Figure 3. Optical scanning system

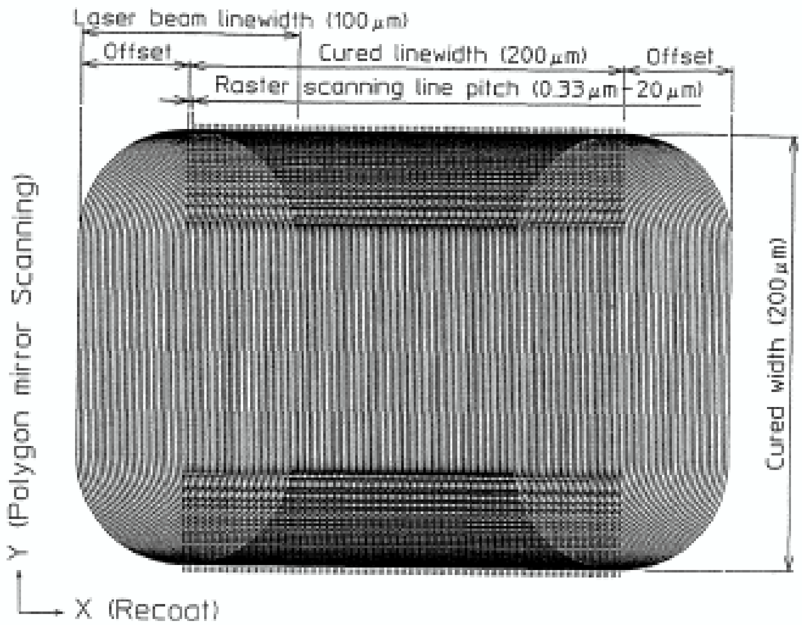

Figure 4. Drawing of micro spacing raster scanning locus

4. Recoating System

The scanning optical system comprised of the polygon mirror and the recoater which levels the unhardened resin liquid layer have been integrated and are moved together along the same axis to realize recoating of the liquid layer and raster scanning simultaneously. The liquid surface is controlled in a different way in this system. As shown in Fig.5 ,"the semi controlled liquid surface method" is used, in which laser beam is irradiated over the recoated layer, whose liquid surface has been semi controlled, immediately after the recoater blade passes through. This eliminates the need for waiting after recoating in order to remove the effects of the resin viscosity and trapped volumes of the fabricated product on the liquid level.

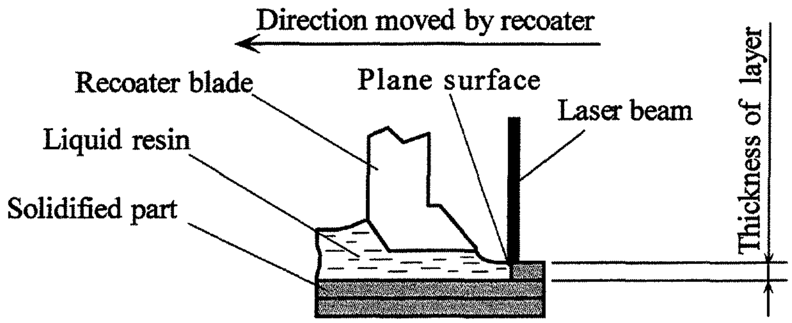

Figure 5. Semi controlled liquid surface method

5. Relation Between Laser Beam Raster Scanning Spacing (Raster Scanning Line Pitch), Recoating Speed, and Cure Depth

The cure depth required for the desired layer thickness can be calculated with the following equations from the laser beam scanning spacing, recoating speed, average exposure, and features of the resin used. The relation of these factors is shown in Fig. 6.

$$\text{Average exposure} \quad E_{av}\ [\mathrm{mJ/cm^2}] = P_L / (L_p \cdot V_s \cdot 10) \quad ^{5)}$$

where; P_L : Laser output on liquid resin surface[mW]

V_s : Laser scanning speed [m/s] (set according to the rotation speed of the polygon mirror)

L_p : Raster scanning line pitch [mm] (set according to the recoater speed V_r)

$$\text{Cure depth} \quad C_d\ [\mathrm{mm}] = D_p \cdot \ln(E_{av}/E_c) \quad ^{5)}$$

where; The critical exposure is $E_c = 7.9[\mathrm{mJ/cm^2}]$ and penetration depth is $D_p = 0.08[\mathrm{mm}]$ based on "the Working curve" of the photocurable resin.

In this system, the raster scanning line pitch is made large and the recoating speed is raised as shown in Fig.7 in order to shorten the time required to laminate one layer. This however results in a shallow cure depth. Consequently, to shorten the fabrication time, it is necessary to project the average exposure over the liquid resin surface in such a way that the required cure depth can be obtained in respect to the layer thickness set, which means that the required cured depth can be achieved by using a high laser output and raising the photosensitivity.

6. Fabricating Process

As shown in Fig .8 , this unit completes the lamination of one layer by drawing the resin with the bucket, pouring it over the fabricated part, and performing recoating and laser scanning simultaneously. After this, the Z table moves to the position of the next layer, and the same process is repeated. After completing the lamination of all layers, the table is raised up and pulled towards the front to remove the part built.

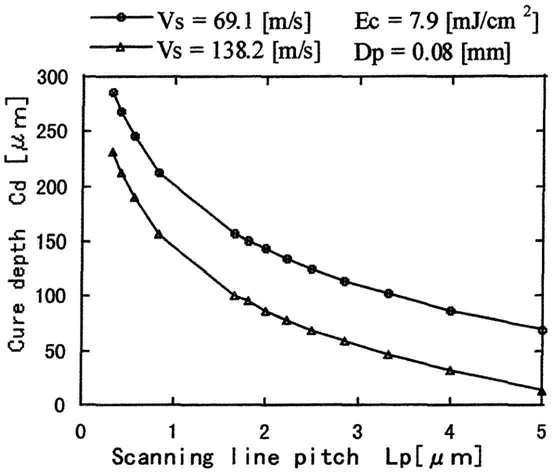

Figure 6 . Raster scanning line pitch versus cure depth for various raster scanning speed ($P_L = 65$ [mW])

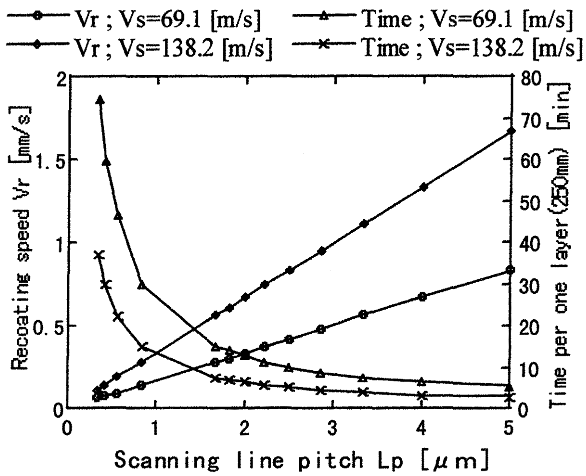

Figure 7 . Raster scanning line pitch versus recoating speed and time consumption par layer (X : 250[mm])

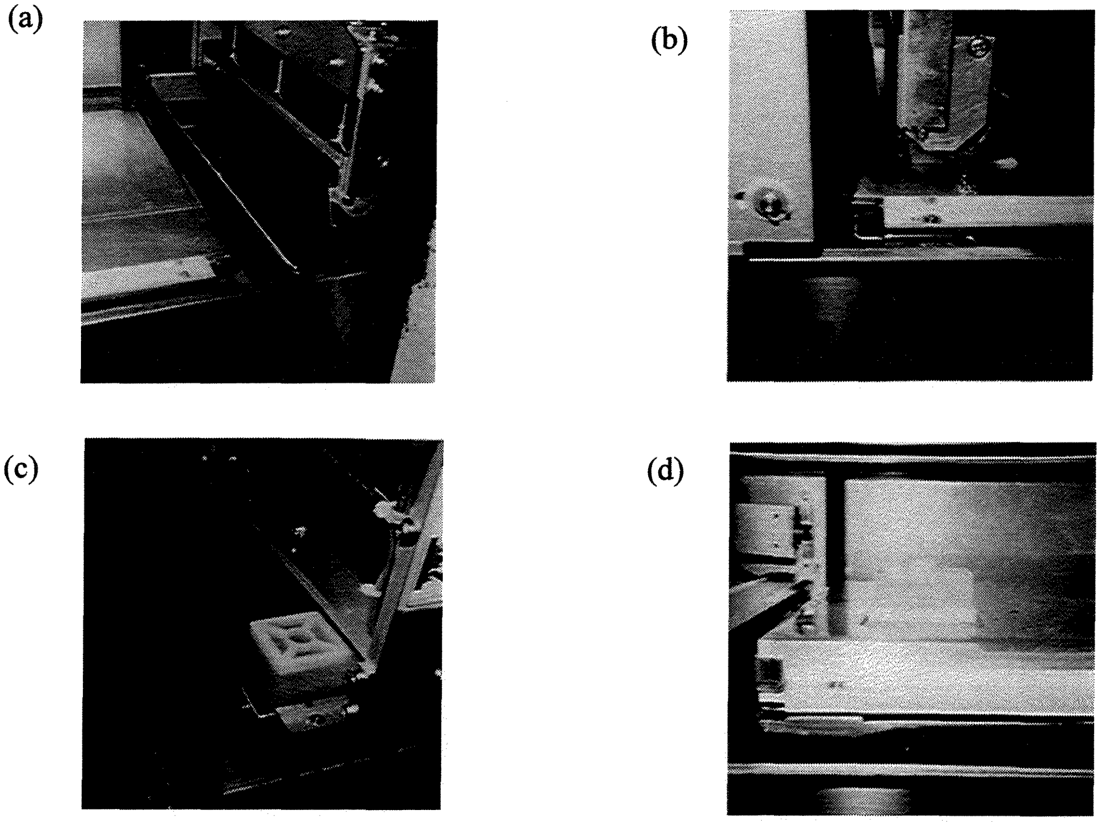

Figure 8 . Laminating process is shown as follows : (a) drawing of resin, (b) supply of resin over part built, (c) recoating and raster scanning, and (d) completion of lamination.

7. Results

Fabrication was carried out based on the conditions shown in Table 2 using the ASAHI DENKA KOGYO's epoxy photocurable resin. Fig. 9,10 and Table 3 show the fabricated sample part, the design contour of the fabricated product, and the position accuracy measurement results (height is the dimensions of the product). As seen in Fig. 11, the surface of the part fabricated by the micro spacing high speed raster scanning method and properties of the contour are good, indicating no need for contour scanning such as vector scanning. The minimum cured linewidth can be set on the control data up to 0.02 mm. As shown in Fig. 12, the linewidth could be calculated to the minimum of 0.1mm. This linewidth is the same as or smaller than that obtained by vector scanning using a galvanometer mirror. The cross-section of the part shown in Fig. 13 indicate that the part can be fabricated according to the thickness set. Lamination was also found to be good with the high viscosity resin (approx. 2200cP) and no effects of the change in the resin viscosity on the fabrication process were seen in particular. When the thickness of the uncured liquid is greater than the layer thickness set (cure depth), peeling occurs between the layers during fabrication. This requires the position of the recoater blade bottom to be set at an accuracy of ±0.1mm in respect to the liquid resin level.

Table 2 . Example of laminating condition

Layer thickness	0.1 mm
Viscosity of resin	80～2200 cP
Beam scanning velocity	138.2 m/s
Raster scanning line pitch	0.83 μ m
Recoating velocity	0.28 mm/s
Average exposure	56.44 mJ/cm^2
Critical exposure	7.9 mJ/ cm^2
Penetration depth	0.08 mm
Cure depth	0.16 mm

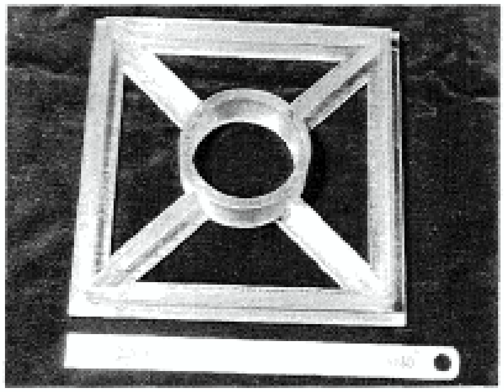

Figure 9. Photograph of the fabricated sample part

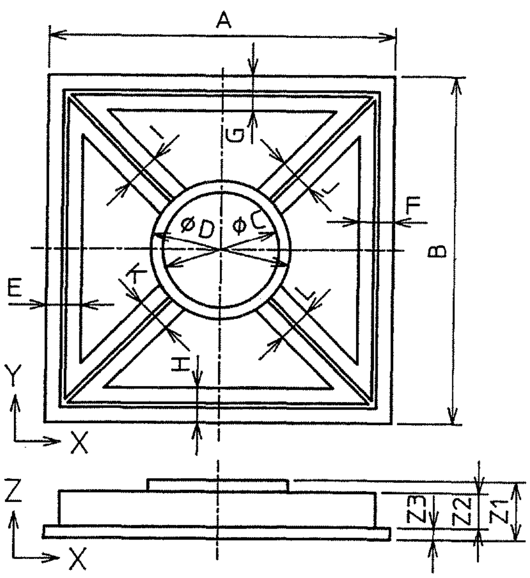

Figure 10. Drawing of sample part

Table 3. Accuracy (Average of 10 samples : [mm])

Position	Dimension	Measurement	Error
A	150.00	150.01	+0.01
B	150.00	149.96	-0.04
C	50.00	49.96	-0.04
D	60.00	60.00	0
E	15.00	15.01	+0.01
F	15.00	15.04	+0.04
G	15.00	15.05	+0.05
H	15.00	15.05	+0.05
I	15.00	15.05	+0.05
J	15.00	15.03	+0.03
K	15.00	15.03	+0.03
L	15.00	15.05	+0.05
Z1	25.50	25.50	0
Z2	15.00	15.08	+0.08
Z3	5.00	5.04	+0.04

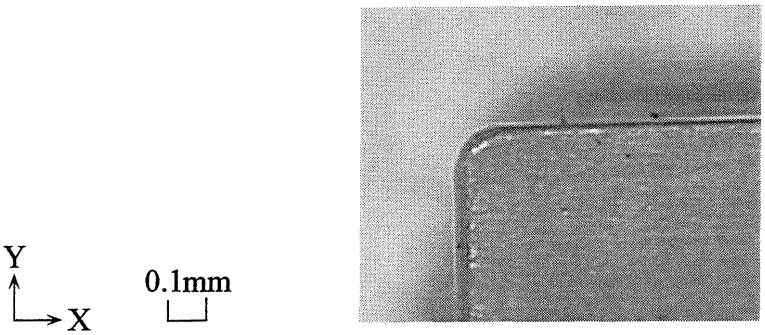

Figure 11. Photograph of surface and outline of part (Viscosity of resin 2200cP)

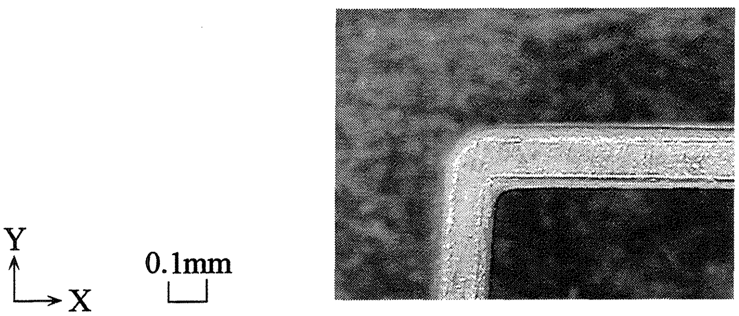

Figure 12 . Photograph of minimum cured linewidth of part (Viscosity of resin 2200cP)

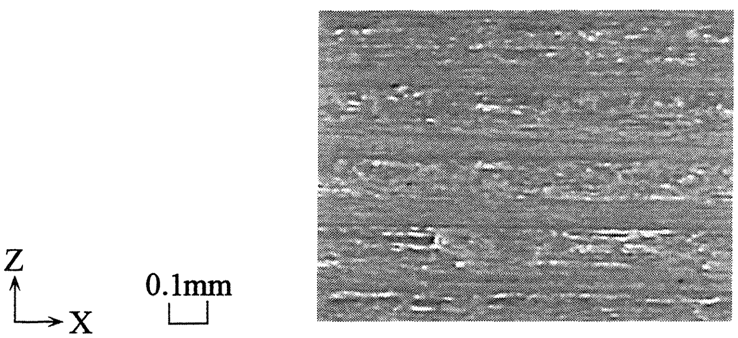

Figure 13 . Photograph of cross section of part (Viscosity of resin 2200cP)

8. Summary and Future Tasks

A new stereolithograpy system which employs a polygon mirror laser scanner and performs recoating and scanning simultaneously has been developed. The fabrication results show that layer manufacturing can be carried out for a broad range of resin viscosities using this high speed high accuracy scanning method. The fabrication process is also useful for reducing the waiting time after recoating in stereolithography process. In the future, efforts will be made to quantify the optimum fabrication parameters such a layer thickness, coefficient of resin viscosity, recoating speed, laser irradiation position, and cure shrinkage to raise the accuracy of the part built and put the method to practical application. Efforts will also be made to realize more accurate lamination of below 50 μ m.

Finally, the use of such laser beam deflecting devices capable of high speed scanning like the polygon mirror for stereolithography may shorten the fabrication time remarkably, given that lasers with higher outputs than current laser are available or photosensitivity of the photocurable resin is raised. Considered a promising stereolithography method, efforts will thus be made to further optimize the system as a productive and practical unit.

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