Manufacturing High Resolution Parts with Stereolithography Method

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1 Abstract

Due to the rapid development of micro techniques, there is a growing market need for appropriate RP methods in the micrometer range. Stereolithography in our experience has found to be the best approach for producing small and accurate parts. Our research project is focussed on the enhancement, development and test of RP systems based on stereolithography. An improved optical system gives us a today's part accuracy of 50 micrometers with the aim of 10 micrometers. A special focus is laid on optic and process. Prototypes produced by a stereolithography apparatus can be shown.

2 Introduction

International studies like the Wohlers Report 1998 [WOH98] show that the RP is a worldwide growing market. While RP in the beginning was mainly dominated by automotive and aircraft industries in the future we will see a change to precise parts for the consumer market, R&D and medical applications. Together with our partners, we found that there is a growing need for precise small and mid-sized prototypes that cannot be manufactured by conventional RP techniques. So, for example, the resolution and accuracy achieved by a conventional stereolithography apparatus like EOS' STEREOS Desktop, is in the range of 0.2 mm (0.008").

Our research project is aimed for improving the accuracy of the stereolithography method leading to application for micro techniques. Beside the new requirements for the hardware, we are on the way to an improved stereolithography process for this new field of application. The way to micro-RP can be obtained by two steps:

A visible progress is possible by upgrading conventional stereolithography apparatuses. Critical components are the laser, optical elements as well as the recoating system. The limit of structural resolution due to the design of those systems is in the range of an accuracy of 50..60 µm.

3 The unit: laser - scanner - optic

Curing of the photopolymer is usually realized by a focussed UV laser beam. The spot of the laser beam can be moved across the resin surface by a galvanometric scanner. This allows a selective curing of the UV-sensitive polymer. The cured area of the resin and hence the lateral resolution of the part is mainly determined by the diameter of the laser spot on the surface of the resin.

In a first step we want to increase the lateral resolution, i.e. by reducing the beam diameter in the build plane for a conventional stereolithography apparatus (e.g. for STEREOS Desktop) using the following demands:

- spot diameter 50 µm with
- build range 250 x250 mm.

3.1 Small spot for conventional stereolithography apparatus

Knowing the limitations of our project partner's stereolithography apparatuses, there are three components mainly effecting the lateral accuracy of a part:

- UV light source (laser),
- scanning system,
- focussing lenses.

The STEREOS Desktop stereolithography apparatus used for our tests showed a typical laser spot diameter of 250 µm. An analyses of the weak points of all optical components was done at a separate experimental setup.

3.1.1 Laser and Optic

The main cause for the large spot diameter is the beam quality of the HeCd laser. A typical value for the mode factor M^2 reported by the manufacturer is about 5. Therefore the focussing of the beam by a given focal length was limited to $d_S = 250$ µm. By simply replacing the UV light source by a HeCd laser with TEM_{00} beam quality ($M^2 = 1{,}05$) a first step is done. The spot diameter in the middle of the build area could be reduced to approx. $d_S = 70$ µm.

Due to the function principle of the scanning system an other error can be found at the focus plane: By deflecting the scanner mirrors towards the edge of the build plane the spot size will increase because of the short Raleigh range z_R of the focussed beam:

$$zR := \frac{\pi \cdot \omega s^2}{\lambda} \qquad zR = 5.754 \cdot mm$$

z_R - Raleigh range, λ - wave length, w_S – ideal spot radius

One solution for this problem is the use of a flat-field lens, or even better, f-theta lens. This lens can focus a parallel laser beam on a flat image plane almost independent of the deflection of the scanner mirrors. In the case of an f-theta lens, the lens must satisfy the f-theta equation:

$$s = f' \cdot \Theta$$

s – image height, f′ focal length, Θ - deflection angle,

to achieve a constant scanning speed of the laser spot across the scanning area with constant angular velocity of the mirrors.

First tests with a simple f-theta lens showed that a decrease in the spot diameter leads to a smaller build area, i.e. the spot diameter is in an acceptable tolerance range. To use the whole build area of the stereolithography apparatus (250 x 250 mm for the STEREOS Desktop) a new design of the beam expander and the f-theta lens was necessary.

The requirements for this optic can be described as:

• Beam diameter	50 µm
• Build area by ± 10° scanner defection	250 x 250 mm
• Acceptable tolerance of the beam diameter across the build area	±5%
• Adjustable beam diameter	50 µm .. 150 µm.

Together with a given aperture diameter of the scanner and the focal distance of $f'_{f\text{-theta}} = 500$ mm one can find the theoretical spot diameter $d_S = 2 \cdot w_0$ at the build plane:

$$w0 := \frac{2 \cdot \lambda \cdot M^2 \cdot f}{\pi \cdot D} \qquad 2 \cdot w0 = 33 \cdot \mu m$$

D – maximum beam diameter at scanner (2/3 of aperture radius)

Figure 3-1 A shows the new beam expander and f-theta optic in the design phase.

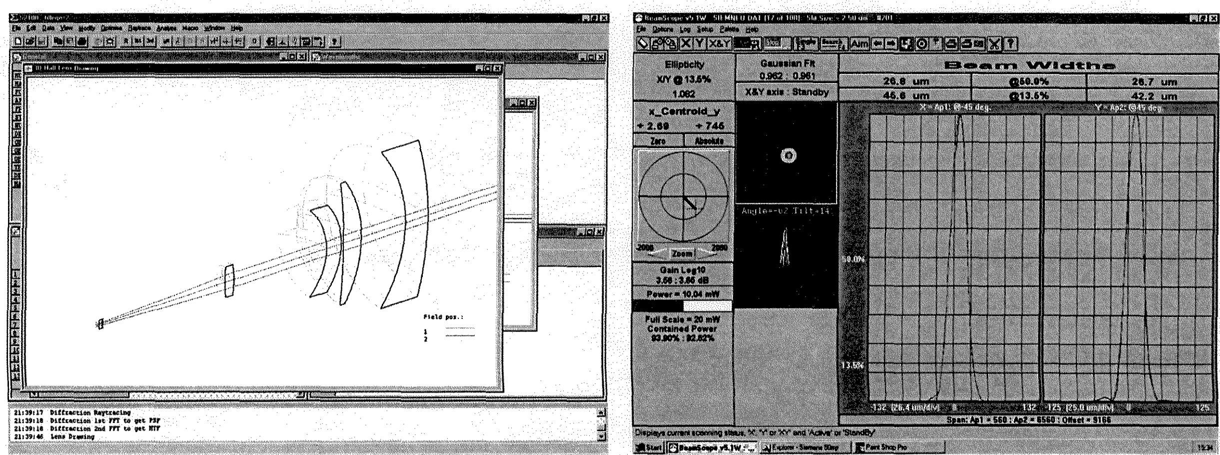

Fig. 3-1: A – Beam expander and f-theta lens of the 50-µm optic
B – Measured beam profile after installation of new components (Siemens)

The new optic was tested at TU München and installed in our partner's STEREOS Desktop. The measurements showed that all specification could be met, Fig. 3-1 B. The beam diameter d_S = 42 µm ± 3 µm is relatively close to the diffraction limit across the whole build plane.

Fig. 3-2 displays the components at the experimental platform at TU München's laboratory.

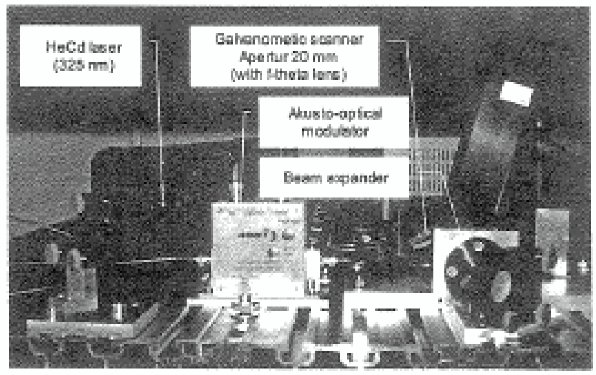

Fig. 3-2: Optical unit with 50-µm spot diameter (experimental setup)

3.1.2 Accuracy of the scanner unit

The third optical component responsible for the lateral part accuracy is the galvanometric scanner. The accuracy of the Scanlab SK1010 scan head used in STEREOS Desktop was evaluated with a beam profiler that has a position resolution of less than 1 µm. Long term position drift, position repeatability and short-term stability were measured. Fig. 3-3 shows the position of the laser spot for a short jump over a distance of 170 µm. The enlargement shows the stability at a stop point.

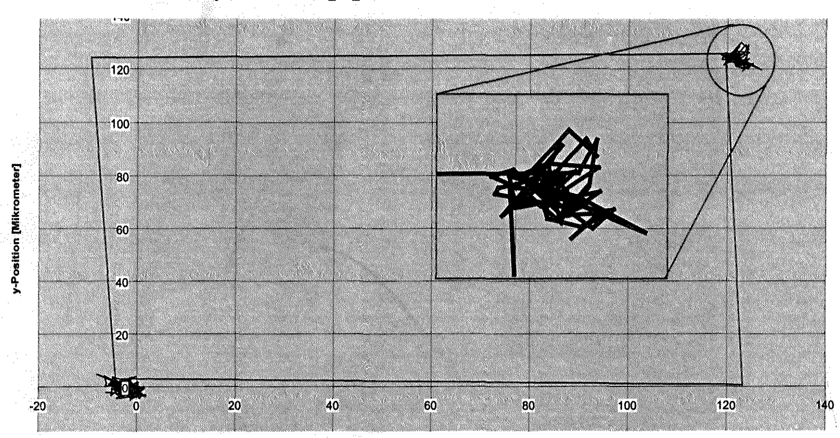

Fig. 3-3: Position repeatability of the laser spot

The positioning repeatability of the Scanlab SK1010 scanners could be determined to

- short-jump error ± 1..2 µm and
- long-jump error ± 2..5 µm.

The standard deviation of the

- long-term position stability is ± 2 μm for t = 30 min.

For the dynamic measurements of the spot position, we used a high-resolution UV sensitive photo plate. Limiting the maximum acceptable error to half of the beam width for SK1010 scan head a

- maximum scan speed of <1000 mm/sec

is recommended.

As a conclusion, one can say that the minimal lateral part resolution for conventional stereolithography apparatuses like STEREOS Desktop is the range of 50 μm.

3.2 High resolution optical unit

For higher resolution, great store is to set by the f-theta lens and scan head.

With our experimental setup, we are currently working on an optical system for a 10-μm spot diameter. The build area has a size of 100 x 100 mm.

4 Exposure and part building

4.1 Limitations for part building

For the calculation of the process parameters, one must for the cure depth. As described before the scan speed is limited by the dynamic positioning accuracy of the scan mirrors. To illustrate the problem some basic calculations can show that there is a contradiction between the minimization of the laser spot diameter and the use of maximum laser power. We assume a desired cure depth of $C_d = 100$ μm and the use of an optical unit with a 50-μm laser spot diameter.

Knowing from [JAC92] the cure depth C_d and the line with L_w are functions of laser power, scan speed and spot diameter:

Cure depth funktion:

$$Cd(P,vs,wo) := Dp \cdot \ln\left(\sqrt{\frac{2}{\pi}} \cdot \frac{P}{vs \cdot wo \cdot Ec}\right)$$

Line width function:

$$Lw(P,vs,wo) := 2 \cdot wo \cdot \sqrt{\frac{Cd(P,vs,wo)}{2 \cdot Dp}}$$

P - laser power; vs - scan speed; w0 - spot radius

Due to the optical unit (see section 3) the laser power and maximum scan speed is defined by

Max. laser power: $Pmax := 30 \cdot mW$

Max. Scan Speed: $vs\_max := 1000 \cdot \frac{mm}{sec}$

This gives us the following values for:

Cure depth: $Cd(Pmax, vs\_max, wo) = 316 \cdot \mu m$ Line width: $Lw(Pmax, vs\_max, wo) = 53 \cdot \mu m$

It clearly can be seen that the cure depth is very large (over-curing). The solution for this dilemma is to reduce the laser power that passes into the resin. This can be done by an optical filter or an analog acousto-optical modulator. By reducing the laser power to

$Pmin := 21.3\% \cdot Pmax \quad Pmin = 6.4 \cdot mW$,

we now get the desired cure depth combined with a very thin line width:

Cure depth: $Cd(Pmin, vs\_max, wo) = 100 \cdot \mu m$ Line width: $Lw(Pmin, vs\_max, wo) = 30 \cdot \mu m$

Fig. 3-4 illustrates the relation between the maximum laser power and minimum spot size diameter for a given cure depth of $C_d = 100$ µm.

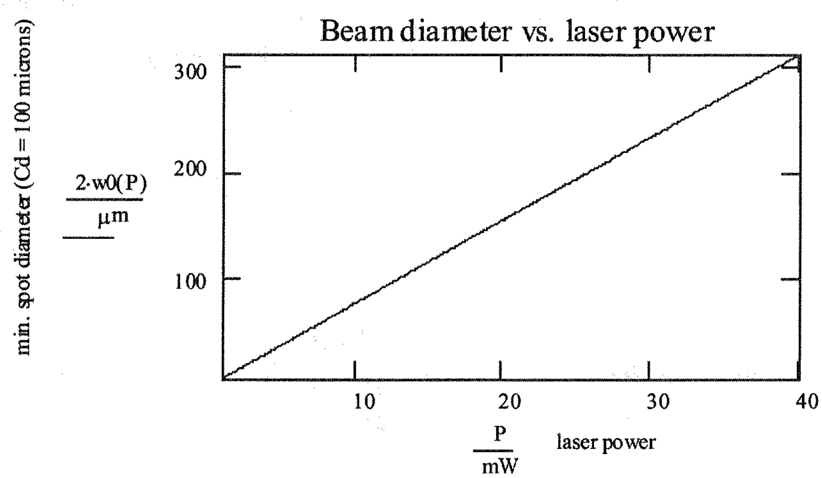

Fig. 3-4: Minimum beam diameter for curing 100-µm layer

Because of the reduction of the laser power one must take into account the extended build time for high resolution parts.

4.2 First applications

After successful optical tests, first structures were build with a STEREOS Desktop with enhanced resolution using a 42-µm spot diameter.

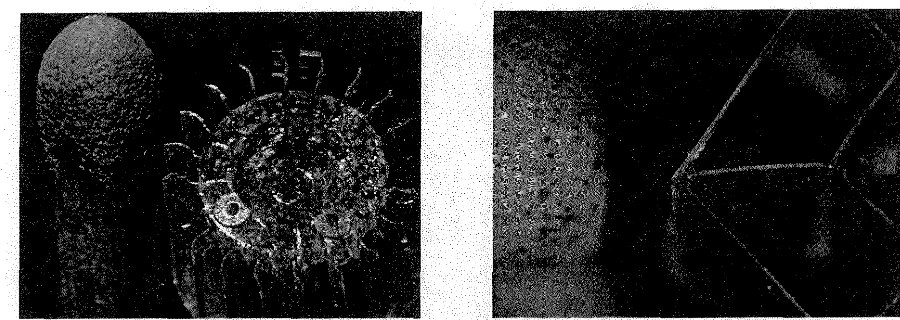

Fig. 4-1: A – turbine, B – honeycomb structure (wall thickness approx. 40 µm)

Following process parameters were chosen:

- laser power — P = 8 mW,
- scan speed — v_S = 1000 mm/sec with,
- layer thickness — t_L = 100 µm.
- material used for all parts — SOMOS 7100 series.

After the building process a conventional cleaning procedure was performed. One must take special care of handling the small structures.

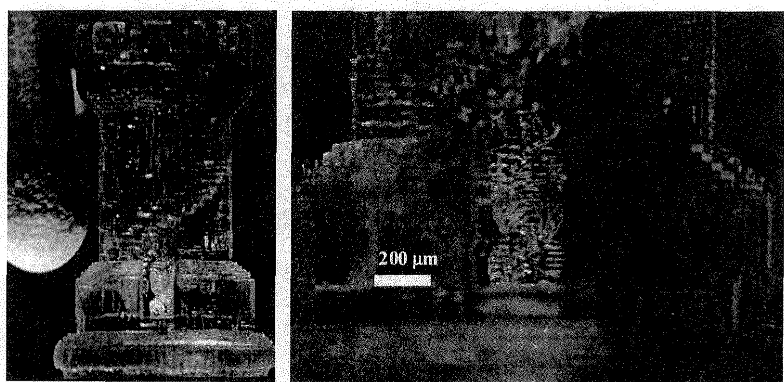

Fig. 4-2 A and B: Chess tower with inner spiral staircase, enlargement.

5 Conclusions

Knowing the limitations of today's stereolithography apparatuses one can considerably increase the lateral resolution of manufactured stereolithographic parts. For further reduction of the part's structural resolution to the range of less than 50 µm, the system design of the stereolithography apparatus must be reconsidered. For further progress in resolution a new recoating system and modifications of RP materials are necessary. Compared to other approaches to micro RP this way combines a full build area with a relatively high structural resolution.

6 Acknowledgement

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7 References

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