

## GENERATION OF MICRO MECHANICAL DEVICES USING STEREO LITHOGRAPHY

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### Abstract

A high resolution machining setup for creating three-dimensional precision components from a UV-curable photo-resin has been developed. By using frequency-converted diode-pumped solid state lasers, functional micro-mechanical devices are directly fabricated in a successive layer-by-layer fashion. Within this paper, the direct generation of micro assemblies having moving components without further assembly of parts will be presented. The micro system design is based on user-defined 3D-CAD data and will completely be built up within the fabrication cycle. By using specially developed  $\mu$ SL materials with suitable properties for micro-mechanical parts, the development from Rapid Prototyping towards Rapid Production of small series is intended.

### Introduction

Nowadays, micro system technology is a rapidly expanding market with applications in both research and industrial sector in the field of automotive, medicine or biotechnology [1]. Surfaces of artificial lenses for the human eye made of a hydrophilic acrylate can be mechanically machined with a roughness in the micron range [2]. The trend of miniaturisation and integration of functional micro systems is becoming more important and requires the further development of new and existing production technologies. As consequence of scaling down the part size, the integration of micro components becomes more demanding. For the extensive handling of micron sized parts, a high degree of automisation is intended to meet the distinctive quality requirements in micro technology [3]. In order to increase the level of product innovation, the use of materials with specific properties in the optical or mechanical range is essential. The combination of both advanced material properties and innovative process technology can further lead to products with high complexity, leading to new functionality at lower costs. Within this paper, the authors present a free form micro fabrication technology for the production of three dimensional complex objects based on the stereo lithography (SL) principle.

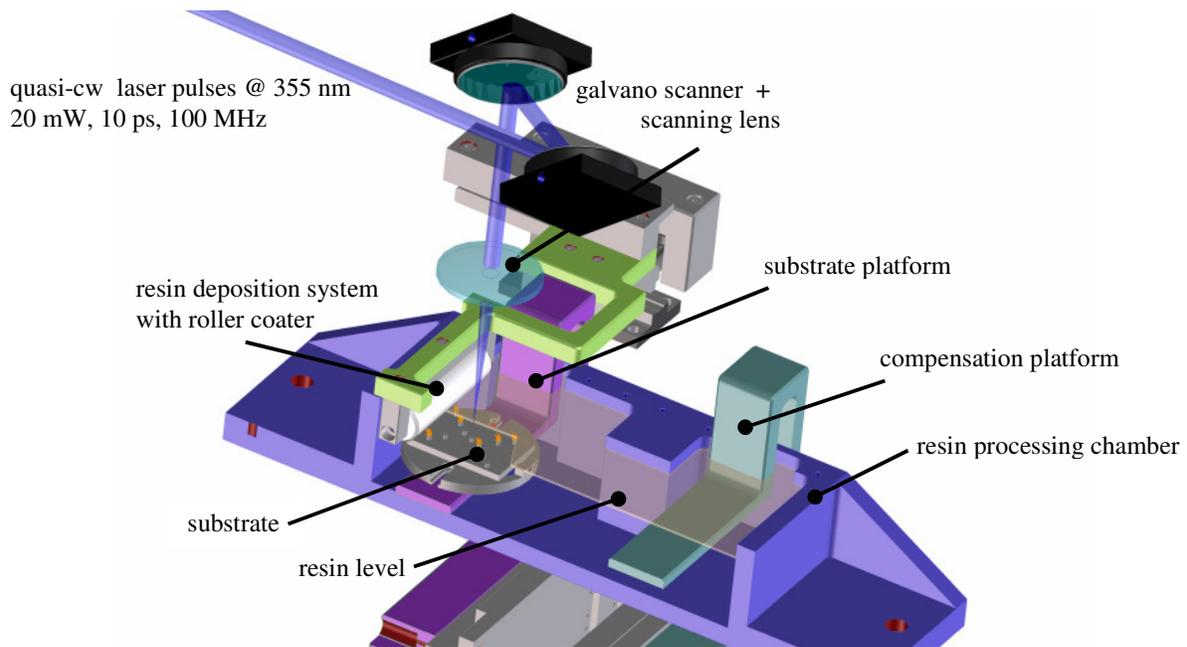
Basically, SL was used to generate prototypes to provide important visual and haptic data for parts that will be subsequently fabricated in mass production processes like injection molding or die casting (Rapid Prototyping). Recently, layer-based fabrication techniques are applied to directly build up functional parts with properties close to materials that are used in batch production (Rapid Manufacturing). The advantages of such fabrication processes are low production costs for small batch sizes, high flexibility in the product design and its change and the fast delivery of functional parts. The usability of this production technology for special applications in the micro technology will be demonstrated during this presented work. Main innovation of the developed technique is the direct production of mechanical assemblies with movable mechanical components without the necessity of conjoining individual parts. Since no additional assembly steps are required during the production cycle, the developed technology enables the cost-effective fabrication of a small number of high-complex systems. Innovative resin materials with material properties after curing close to some ceramics are used for production. The curing properties can be adjusted towards lateral and vertical dimensions for high resolution processing.

Recently, the suitability of custom made stereo lithography systems for the generation of micro mechanical parts has been shown for the fabrication of individual precision parts [4-6]. By using an Argon-Ion laser operating at 351.1 nm, gearwheels with diameters in the range of 500 – 700  $\mu\text{m}$  have been produced. The geometrical information was delivered by a spatial light modulator as a dynamic lithographic mask. The material which was used was the Ciba-Geigy Cibatool SL 5180 leading to a layer thickness in-process of around 50  $\mu\text{m}$ . The number of layers was up to 105. Micro gears with a diameter of 1500  $\mu\text{m}$  have been produced by applying a UV spot curing system which is equipped with a broadband high pressure mercury lamp (300 - 470 nm). The lateral resolution that has been achieved during the experiments was down to 20  $\mu\text{m}$ . In order to use resin materials with high viscosity, ultra-sonic vibration was applied to reduce the polymer settling time.

To further demonstrate the capability of micro SL for complex structuring, the fabrication of functional micro assemblies with moving parts will be in the following presented.

### Experimental set-up

The principle set up of the applied micro stereo lithography machine is depicted within figure 1.

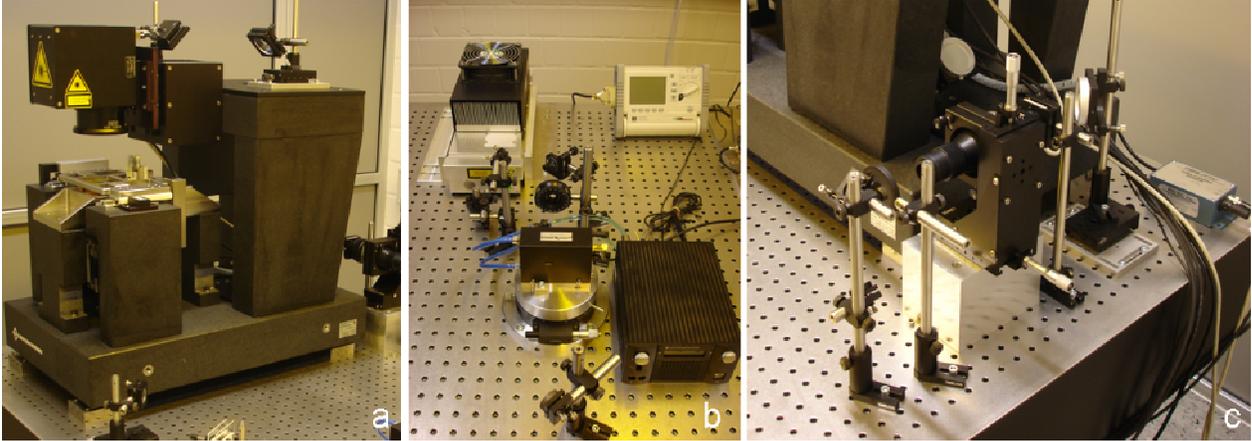


**Figure 1:** Principle setup of the processing chamber of the applied micro stereo lithography setup

The custom micro machining system is set up on an optical table that carries the optical setup (laser source with beam guidance) and a granite based frame with the resin processing chamber, positioning stages and laser scanning system (Figure 2). The system is equipped with in total four piezo controlled positioning stages offering a maximum encoder based resolution of 300 nm. The substrate displacement inside the resin processing chamber is done in negative z-direction below the resins surface. The substrate is mounted on a custom made stainless steel frame.

In order to keep the resin surface at a constant level during the positioning cycle, a frame identical in construction to the substrate frame can be moved in the opposite direction. The coating mechanism consists of a novel roller coater that is in constant contact with the resin. The

coater laminates the substrate with a resin layer of defined thickness. The focal position can be precisely adjusted by moving the scanner system in the vertical direction with a micro meter screw offering a 1  $\mu\text{m}$  resolution at a maximum travel of 50 mm. For illumination purpose, a frequency tripled diode pumped solid state Nd:YAG oscillator (355 nm) is used. Pulse trains of 10 pico seconds (ps) at a repetition rate of 100 MHz are provided. The calculated focal radius is around  $\omega_f = 7.5 \mu\text{m}$ . The focused laser beam is scanned on the photo resins surface with two perpendicular oriented galvanometric mirrors of a scanning system with a working field of  $A_w = 50 \times 50 \text{ mm}^2$ .



**Figure 2:** Picture of the custom made micro stereo lithography set-up consisting of granite based frame and the optical setup with AOM and laser source (b) and beam guidance (c)

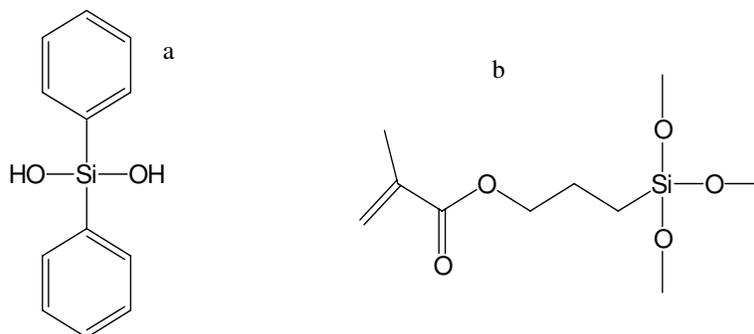
### Experimental procedure

For the fabrication of three dimensional precision parts for micro mechanical applications, a specially designed inorganic-organic UV-curable hybride polymer from the typeOrmocer<sup>®</sup> b59 has been used. In order to apply a suitable material for the micro stereo lithography process, the basic material has been chemically modified. Afterwards, a set of material samples has been prepared and characterised in a first step. Main aspect of investigation during the characterisation process has been both the lateral and vertical curing resolution and the viscosity of the resin. In the following, the chemical modification of the basic material with additives for the manipulation of both the curing properties and viscosity will be explained.

#### *Material properties, preparation and modification:*

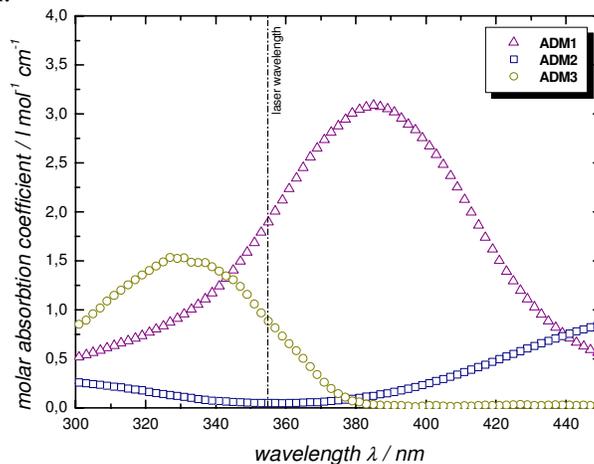
The hybrid polymer was synthesised in a water free sol gel process where Diphenylsilandiol reacts with Methacryloxypropyltrimethoxysilane (MEMO) (see Fig. 3) in alkaline conditions. During the sol-gel reaction an inorganic Si-O-Si network is formed [7]. Diphenylsilanediol acts as a network modifier, whether MEMO provides the organic cross-linking functionalities [8]. The size of the formed oligomers with an inorganic core and an organic shell is typically between 2 and 10 nm [9], but the detailed structure has not been shown yet. After the synthesis and removal of solvents, 1% of a radical initiator (Irgacure 369 from Ciba, used as received) was added. When the initiator is illuminated with UV-radiation it decomposes to radicals, which can start a

radical crosslinking reaction between the oligomers. Those will form a three dimensional network with a high mechanical stability.



**Figure 3:** Chemical structure of Diphenylsilanediol (a) and Methacryloxypropyltrimethoxysilane (MEMO) (b)

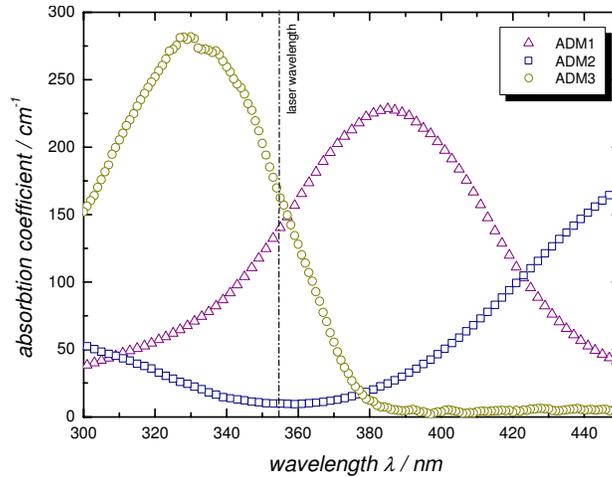
In order to reduce the optical penetration depth of the laser radiation, experiments with several absorbing dye materials (ADM) were carried out. The dyes are supposed to absorb at the wavelength of the laser (355 nm). In Figure 4, the molar absorption coefficient of three potential dye materials can be seen over the wavelength. ADM 1 shows the highest absorption coefficient at the laser wavelength.



**Figure 4:** Absorption coefficient of the dyes over the wavelength.

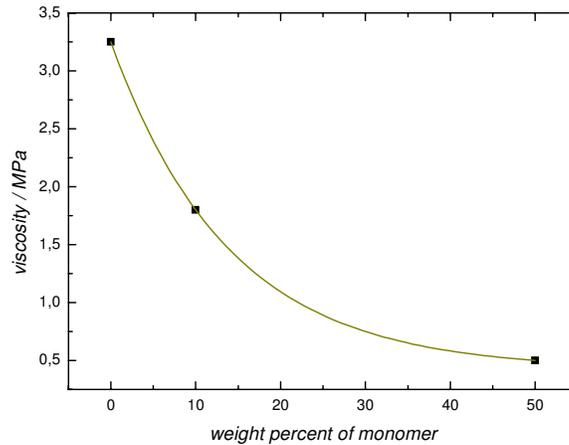
However, the total quantity of the selected dyes that can be mixed into the basic material had to be taken in account. With 0.2 % of ADM1, 0.3 % of ADM2 and 0.5 % of ADM3, the maximum amount of the dyes that could be solved, have been introduced into the inorganic-organic hybrid material. As a result of the variation in solubility of the three absorbing dyes, the effective resulting absorbance differs from the absorbance of individual dyes. Figure 5 shows the resulting absorbance of the dyes in combination with the hybrid material.

As ADM3 shows the highest resulting absorbance at the selected laser wavelength, the further investigations were carried out with mixtures of the hybrid material and ADM3.



**Figure 5:** Resulting absorbance of the dyes in the hybrid material

Further chemical modifications of the hybrid material have been made to reduce the viscosity since it was known from recent investigations that the high viscosity of the hybrid material leads to long settling periods after the coating procedure. Several samples with a low viscosity multifunctional acrylate monomer (MAM) were prepared. The influence of the monomer concentration on the viscosity of the resulting material is shown in Fig. 6.



**Figure 6:** Influence of the multi functional acrylate monomer (MAM) concentration on the viscosity of the resulting material

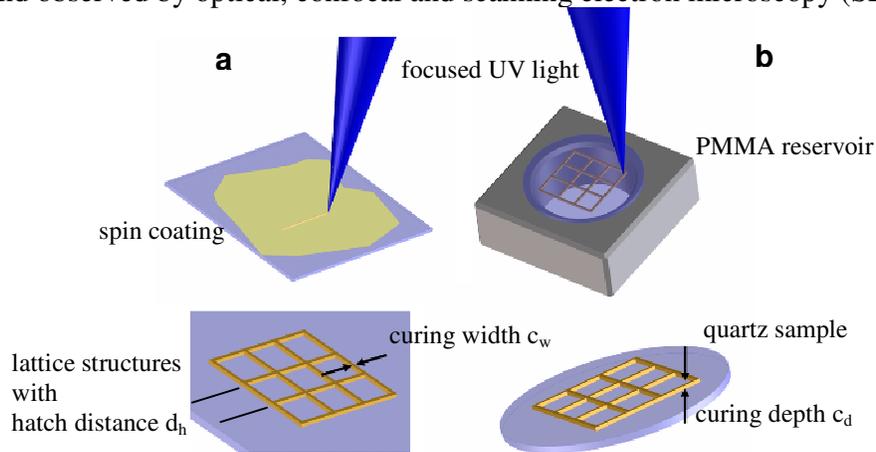
The modified materials have been filtered down to 0.8  $\mu\text{m}$  before the curing investigations.

*Basic investigations:*

The curing properties of the developed material samples have been studied in 2D (irradiation of spin coated samples) and 2 1/2 D (irradiation of small resin reservoirs) tests.

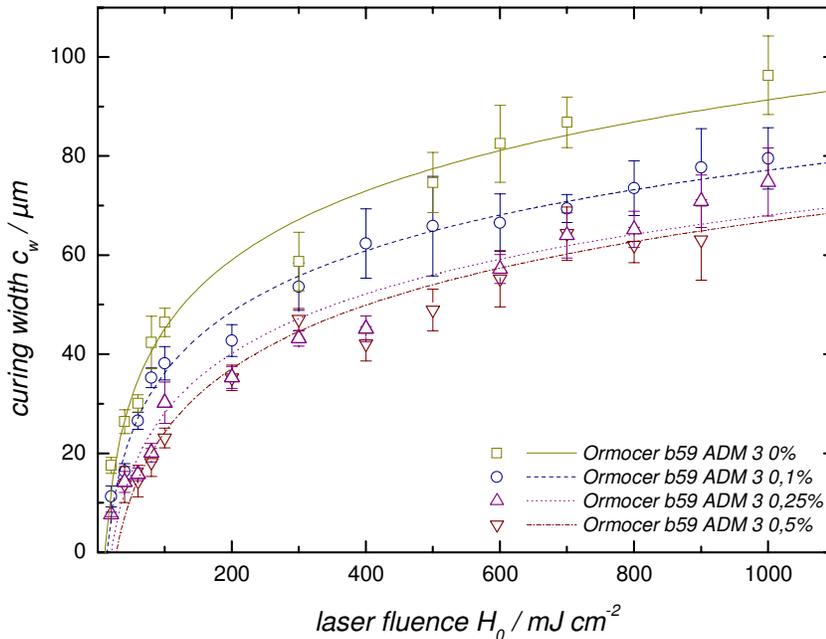
For the determination of the lateral resolution  $c_w$ , rectangular glass samples have been spin coated with a constant layer thickness of 10  $\mu\text{m}$  and subsequently irradiated with lattice structures under the influence of varying laser scanning speed  $v_s$  at a constant laser power of  $P_L = 300 \mu\text{W}$ . (Figure 7). The calculated laser fluence was in the range from  $H_0 = 10 \text{ mJ/cm}^2$  to  $1000 \text{ mJ/cm}^2$

and the distance between individual lines of the lattice structure has been  $250\ \mu\text{m}$ . The prepared samples have been cleaned after illumination with a solvent of 2-Propanole and 4-Methyle 2-Pentanone and observed by optical, confocal and scanning electron microscopy (SEM).



**Figure 7:** Experimental technique for the determination of the curing width  $c_w$  (a) and curing depth  $c_d$  (b)

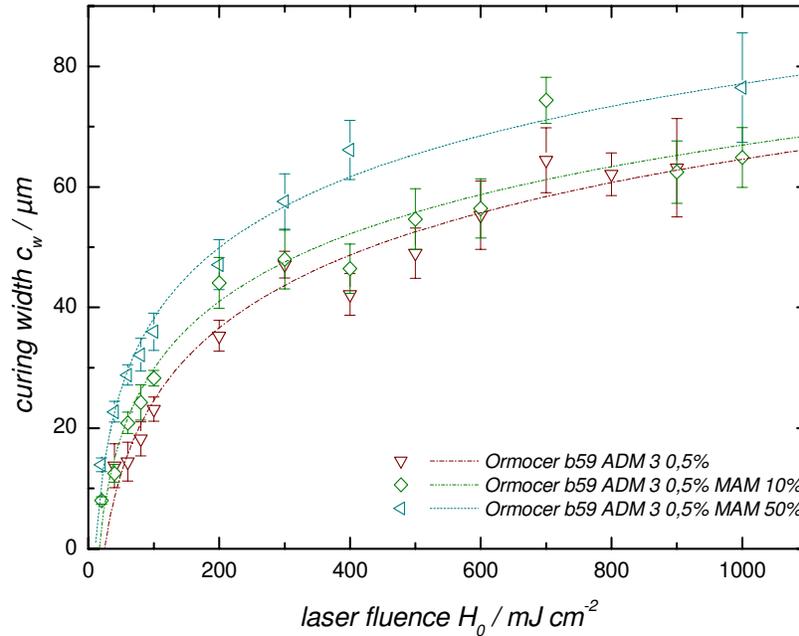
The curing width  $c_w$  for Ormocer b59 with varying parts of ADM3 (0%-0.5%) is depicted within figure 8. According to the graph, the lateral curing width  $c_w$  strongly depends on the part of the absorbing dye that has been introduced in the basic material. By applying a laser fluence of  $500\ \text{mJ}/\text{cm}^2$ , a curing width of  $70\ \mu\text{m}$  is achieved without the use of an absorbing medium. With 0.5 % of ADM3, the curing width is reduced by a factor 1.4 towards  $50\ \mu\text{m}$ . Generally, a higher process resolution can be achieved by increasing the part of the absorbing dye. However, it has to be taken in account that the usage of a laser fluence  $H_0 < 100\ \text{mJ}/\text{cm}^2$  might result in an unstable process due to the high gradient.



**Figure 8:** The curing width  $c_w$  versus the laser fluence  $H_0$  of modified Ormocer b59 with varying parts of ADM3

The smallest line structures that adhere at the quartz material after chemical cleaning have been around  $7.5 \mu\text{m}$  at a laser fluence of  $H_0 = 20 \text{ mJ/cm}^2$ . Nevertheless, structures could be produced with  $H_0 < 20 \text{ mJ/cm}^2$ , but not measured.

The curing width  $c_w$  for Ormocer b59 with a constant content of 0.5 % of ADM3 and varying parts of MAM (0 %-50 %) is depicted within figure 9.



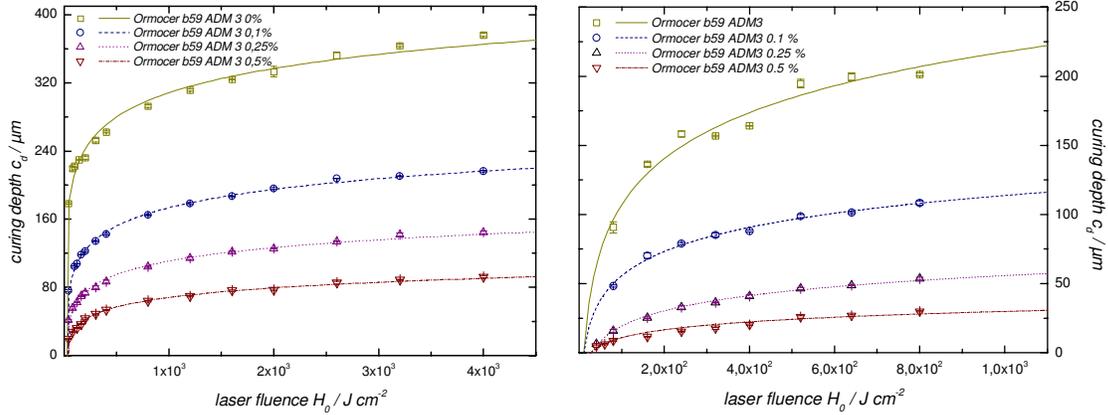
**Figure 9:** The curing width  $c_w$  versus the laser fluence  $H_0$  of modified Ormocer b59 with 0.5 % of ADM3 and varying parts of MAM.

According to the graph, the lateral curing behaviour also depends on the part of the introduced MAM. With increased content of MAM, the curing width increases.

The lateral process resolution can be adjusted within the range  $7 \mu\text{m} < c_w < 80 \mu\text{m}$  by modifying the basic material with varying contents of ADM3 and MAM. Here, the highest process resolution is achieved with Ormocer ADM3 (0.5 %) and MAM (50 %). Useful processing dimensions for  $\mu\text{SL}$  are achieved in the range  $H_0 < 100 \text{ mJ/cm}^2$ .

For the determination of the vertical resolution (curing depth  $c_d$ ) a small test cell according to figure 7b has been set up. By using a rectangular solid of PMMA ( $5 \times 5 \times 1 \text{ cm}^3$ ) with a blind hole, a resin reservoir has been constructed. The hole has been filled with the resin material and covered with a circular quartz substrate that was in direct contact to the resin material. By aligning the laser focus on the polymer quartz contact plane, structures that adhere at the bottom side of the quartz substrate have been fabricated. In contrast to 2D testing, lattice structures with varying lattice constants have been produced for the determination of the vertical process resolution. The lattice constant (= hatch distance  $d_h$ ) has been reduced until it was below the order of the previously determined curing width  $c_w$ . The aim of the investigation was to find out, to what extent the curing depth  $c_d$  changes, in the condition that individually cured lines of the generated lattice structure overlap. Curing depth measurements have been performed from  $H_0 = 10 \text{ mJ/cm}^2$  to  $200 \text{ mJ/cm}^2$ . To ensure a homogenous overlap, lattice structures with gap distances of 0.001 mm and 0.005 mm have been produced for curing depth measurement.

The vertical process resolution for Ormocer b59 with varying parts of ADM3 (0%-0.5%) is depicted for two hatch distances  $d_h$  within figure 10 (a) and (b).

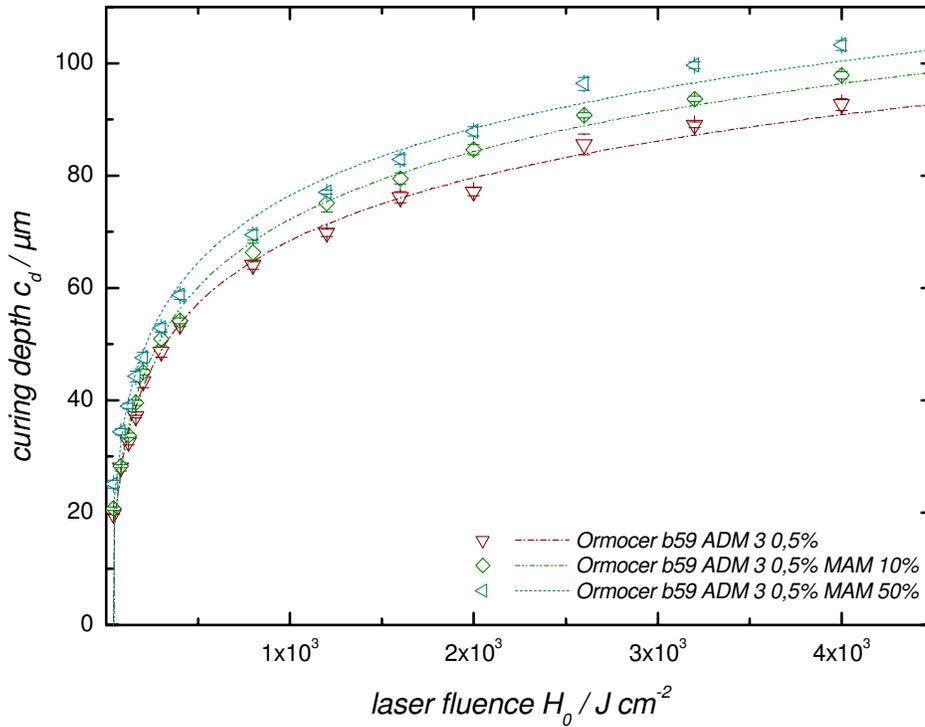


**Figure 10:** The curing depth  $c_d$  versus the laser fluence  $H_0$  of modified Ormocer b59 with varying parts of ADM3 at a hatch distance of  $d_h = 0.001$  (a) and  $d_h = 0.005$  (b)

The curing depth strongly depends on the laser fluence  $H_0$ , the hatch distance  $d_h$  and the part of the absorbing dye. Without parts of ADM3, the curing depth  $c_d$  of Ormocer b59 is the range  $230 \mu\text{m} < c_w < 375 \mu\text{m}$  for  $d_h = 0.001$  mm and shows no suitability for the  $\mu\text{SL}$  process. The introduction of ADM3 (0.5 %) leads to the effective increase of the achieved vertical process resolution down to  $18 \mu\text{m}$  at  $d_h = 0.001$  mm,  $H_0 = 20 \text{ J}/\text{cm}^2$  and  $8 \mu\text{m}$  ( $d_h = 0.005$  mm,  $H_0 = 40 \text{ J}/\text{cm}^2$ ). Suitable fabrication parameters for layer sizes around  $10 \mu\text{m}$  are in the area of  $20 \text{ J}/\text{cm}^2 < H_0 < 200 \text{ J}/\text{cm}^2$  at a hatch distance of  $d_h = 0.005$  mm.

The hatch distance  $d_h$  is a degree for the theoretical overlap  $\delta$  of individual fabricated lines of the lattice structure and can directly be calculated from the focal radius  $\omega_f$  and the hatch distance  $d_h$  according to  $\delta = (2\omega_f - d_h) / 2\omega_f$ . For  $d_h = 0.001$  mm, the overlap is calculated to  $\delta = 93 \%$ , for  $d_h = 0.005$  mm the overlap is equal to  $\delta = 66 \%$ . It has been found, that a higher overlap factor leads to increased curing depth  $c_d$  at identical laser fluence. At a laser fluence of  $H_0 = 1 \text{ kJ}/\text{cm}^2$ , the curing depth  $c_d = 220 \mu\text{m}$  for a hatch distance of  $d_h = 0.005$  mm. In contrast to this result, a curing depth of  $c_d = 300 \mu\text{m}$  has been achieved at hatch distance of  $d_h = 0.001$  mm. A strong correlation between the overlap of the individual scanned lines and the curing depth at identical laser fluence has been observed. Since the dynamics of the polymerisation are supposed to be the reason for this, further studies are planned to this issue.

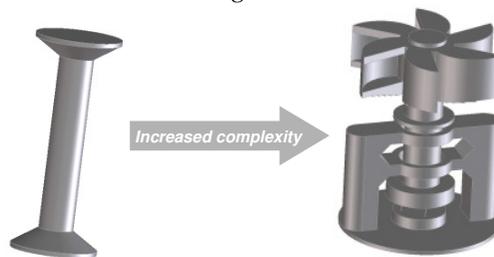
The curing depth  $c_d$  for Ormocer b59 with 0.5% of ADM 3 and varying parts of MAM (0%-50%) has been measured at a hatch distance of  $d_h = 0.001$  mm. The result is depicted within figure 11. The graph illustrates that the curing depth slightly increases with increasing part of MAM. The highest process resolution was achieved without MAM ( $18 \mu\text{m}$ ) in contrast to  $20 \mu\text{m}$  when using 50 % of MAM at a laser fluence of  $H_0 = 20 \text{ J}/\text{cm}^2$ .



**Figure 11:** The curing depth  $c_d$  versus the laser fluence  $H_0$  of modified Ormocer b59 ADM3 0.5% with varying parts of MAM (0-50%) at a hatch distance of  $d_h = 0.001$

It has been further found, that the chemical cleaning of the produced structures is more effective, the more parts of MAM are introduced in the basic material.

*Investigations on three dimensional structuring:*



**Figure 12:** Investigation strategy during the fabrication of micro mechanical systems: CAD models of basic modules with high aspect ratio towards movable micro mechanical systems

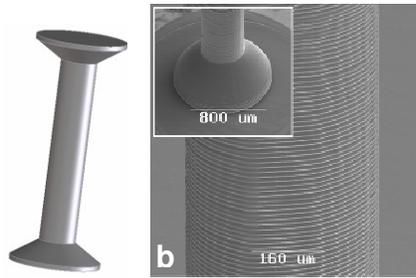
The investigations which are in the following presented have been made with Ormocer b59 and 0.5% of ADM3 at a viscosity of 3.2 MPa. (0% MAM). The main challenge during the investigations was the transfer of the process parameters which have been found during 2D and 2 1/2 D test towards the 3D patterning of micro mechanical systems and, if necessary, their additional fine adjustment. In order to apprehend systematically the parameter effects on the process, CAD models with varying level of complexity (figure 12) have been developed. In a first instance, basic modules have been planned to demonstrate the capability of the selected material and the custom made machining setup for the layer-based production of three-dimensional structures. In the following, basic investigations for the direct production of micro mechanical

systems having moving parts without the necessity of assembly steps have been done. Based on these results, the fabrication of functional parts with increased complexity for micro mechanical applications will be studied.

### Results

During the investigations on three dimensional structuring, it has been shown, that the results of the curing measurements are only conditionally useful. In fact, for achieving a high contour accuracy, a careful adjustment of the fabrication parameters has to be done, mainly depending on the complexity and design of the structure to be built.

In the first instance, basic cylindrical structures with a high aspect ratio up to 10 (Figure 13 (a)) have been successfully fabricated to show both the machining capability and the suitability of the developed material for micro structuring. In order to ensure a reliable adhesion between individual layers, the first experiments have been carried out with a laser fluence  $H_0 > 400 \text{ J/cm}^2$  at a hatch distance of  $d_h = 0.01 \mu\text{m}$ .

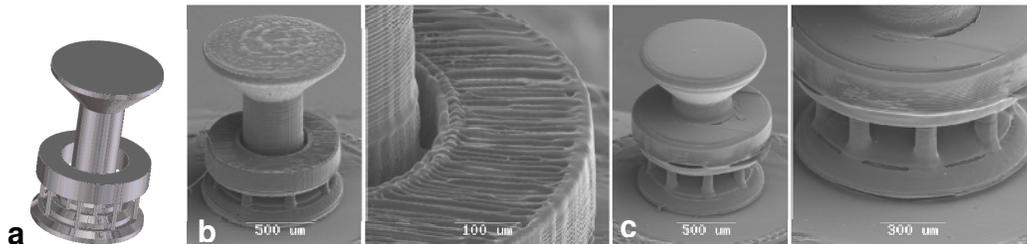


**Figure 13:** High aspect ratio (HAR) structure developed with the custom made stereo lithography setup

The structure displayed in figure 13 (b) has been fabricated with a laser fluence of  $H_0 = 560 \text{ J/cm}^2$  and consists of 250 individual layers at a thickness of  $10 \mu\text{m}$ . The outer diameter of the pillar was  $400 \mu\text{m}$ .

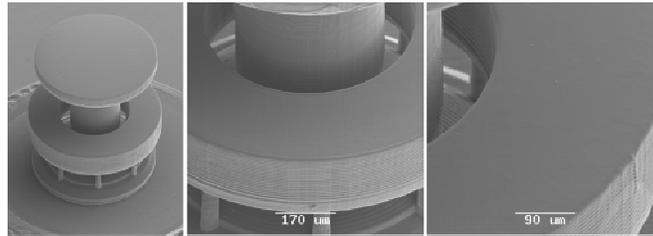
In the following, the direct production of complex structures with movable parts has been investigated. For this, the CAD model depicted within figure 14 (a) has been developed.

Basic approach was the fabrication of one basic structure that adheres at the building substrate. The components that will be movable after the finished fabrication will be carried by cylindrical support structures to prevent their displacement during the production cycle. Subsequently, the dissolution of the support structures is planned to be done automatically during the chemical cleaning process since other removal techniques are not reasonable in the micro meter scale.



**Figure 14:** Achieved results when fabricating micro parts with  $H_0 = 560 \text{ mJ/cm}^2$ ,  $d_h = 0.01 \text{ mm}$  (b), and  $H_0 = 4 \times 10^3 \text{ J/cm}^2$ ,  $d_h = 0.001 \text{ mm}$  (c)

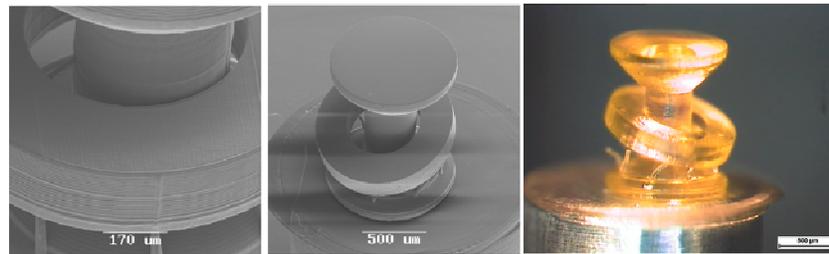
With varying process parameters (laser fluence  $H_0$ , hatch distance  $d_h$ ) the optimum fabrication parameters have been distinguished. It can be generally mentioned, that decreased laser fluence  $H_0$  enhances the process resolution, but minimizes the surface quality at a constant hatch distance  $d_h$ . Figure 14 (b) shows clear lateral gaps, but the surface has a periodic structure. The structure depicted in figure 14 (c) shows only minor contour accuracy, but simultaneously high surface quality. Further process optimisation lead to the result depicted within figure 15.



**Figure 15:** Achieved results when fabricating micro parts with  $H_0 = 500 \text{ J/cm}^2$ ,  $d_h = 0.001 \text{ mm}$

Clean gaps and very smooth surfaces are visible when using  $H_0 = 500 \text{ J/cm}^2$  and  $d_h = 0.001 \text{ mm}$ . The support structures are well-defined with a diameter  $< 40 \mu\text{m}$ .

The further challenge was the separation of both ring and basic structure as key assumption for the production of movable parts. It has been shown, that the stability of  $10 \mu\text{m}$  supports for carrying ring-structures was sufficient during the process to withstand the mechanical stresses of the coating procedure on the structure. Preliminary tests of dissolving the support structures have shown success. The ring-structure has been individually separated from the basic structure (figure 16)

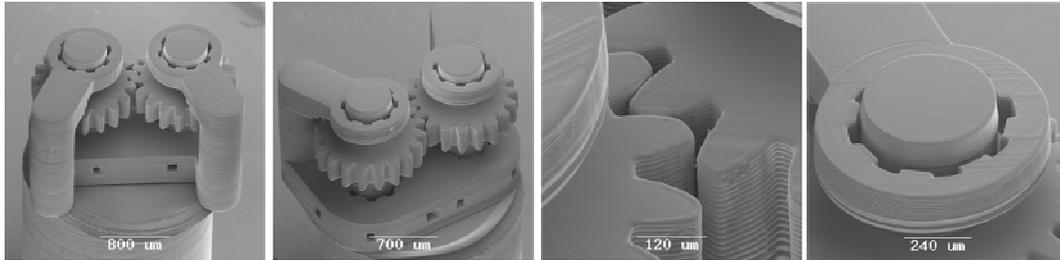


**Figure 16:** SEM and microscope images of two separated structures that have been fabricated in direct production without any assembly steps. The support structures are chemically dissolved during the cleaning process.

In the following the focus was on the production of structures for micro mechanical applications. Micro systems with evolvent gearwheels have been produced (Figure 17). The fabrication parameters have been using  $H_0 = 400 \text{ J/cm}^2$ , and  $d_h = 0.001 \text{ mm}$ . The gearwheels have been conjoined with axes that were on the other hand only conjoined with the bottom of the basic structure by supporting cylinders. The axes were specially embedded at their bottom and top inside precursors of bearings. Inside the base of the structure, drainage openings have been constructed to allow the chemical cleaning of the lower bearing. It has been shown, that the transmission of rotations is possible.

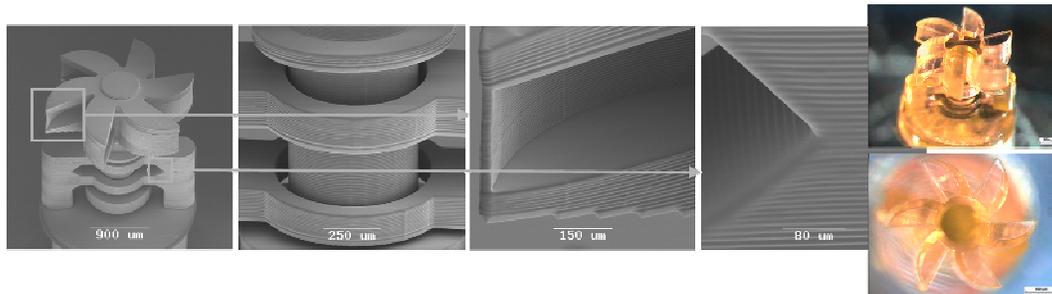
Especially the meshing of the gearwheels has been fabricated with distinctive quality. The distance between individual teeth is in the order below  $10\ \mu\text{m}$ .

The fabrication of basic drive units has been investigated to drive the micro systems with an air or water flow for micro fluidic applications.



**Figure: 17** Micro mechanical systems with technical gearing system

Figure 18 shows the first results when fabricating water wheels. Water shovels with a lateral size of  $680\ \mu\text{m}$  have been produced. Lateral gap distances between axle and bearing were successfully built below  $50\ \mu\text{m}$ . Drive tests have been successfully accomplished with a slightly modified structure that has been built up symmetrically by arranging the wheel between lower and upper bearing.



**Figure 18:** Functional micro mechanical assembly with water wheel for fluidic applications

### Conclusion and outlook

Within this paper, the authors have presented the development of a custom made stereo lithography setup. In combination with new materials suitable for rapid manufacturing, functional micro parts have been built up. By using the classical Rapid Prototyping approach, parts have been directly built in a layer based production process.

Polymer micro systems have been fabricated with both lateral and vertical resolutions below  $10\ \mu\text{m}$ . The developed One Step Production technique (OSP) enables the production of micro mechanical assemblies with included moving parts. Here, the in-process assembly without the necessity of further conjoining steps of the functional parts is one of the main innovations. Besides resolutions in the micron range with high surface qualities, one key approach towards Rapid Manufacturing is the use of functional polymer materials with mechanical properties suitable for functional parts.

During the fabrication of three dimensional structures, the high-viscosity resin has been successfully applied. However, a long settling time has lead to long process durations. We have shown the possibility of the chemical modification of the basic material to reduce effectively the viscosity. The application of the low-viscosity material and its suitability for the three dimensional patterning will be part of the upcoming period.

### Acknowledgement

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