Effective Mechanisms of Multiple LED Photographic Curing

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Abstract

Multiple LED Photographic Curing (MPC) has proven capable of drawing cross sections of three-dimensional objects like printing a sheet of paper. Using raster scanning, however, simultaneously exposing a photopolymer with 1,024 beams of light involves various unknown issues. The aim of this research work was to examine the formation of individual strings and the connecting mechanisms between strings and layers. At light power ranging from 19.0 to 30.3μW and at various scan speeds, string formation perpendicular to scan direction differs greatly from that in scan direction. Curing of plane layers happens by curing strings side-by-side with a constant spacing of 62.5μm.

1 Introduction

Multiple LED photographic curing (MPC) is based on the concept of exposing a liquid photopolymer through multiple beams of light simultaneously. Unlike Laser Stereolithography (SL), MPC uses light-emitting diodes (LED) as light sources (Loose et al., 1997). Exposure happens through an array of 1,024 beams of light which expose the surface of the liquid resin while using raster scanning. Similar concepts for multiple-spot exposure have been proposed by Ohtsubo et al. (1997) and Marutani et al. (1998). All concepts have successfully shown their practical applicability.

Nevertheless, very little is known about the effective mechanisms in multi-spot exposure. In spite of seemingly principal compatibility between MPC and SL—both processes are essentially an exposure of a liquid photosensitive resin leading to polymerisation, thus to solid objects—there is a number of challenges to be met considering the unique characteristics of the exposure pattern. It can be said that the research on MPC is at the developmental stage, and large number of measurements are required to improve the design. For example, the effective mechanisms when exposing the photopolymer resin surface are unknown. If they are understood to some extent, MPC can be improved to become applicable for rapid concept modelling.

This paper describes the results of the experimental examination of the curing process in MPC. Not only the curing of single strings but also the formation of layers and three-dimensional objects is studied. Consequently, the authors propose a means to generate an equal cure depth through multiple beams of light and investigate it theoretically and experimentally. In the following, experimental results are presented and the envisaged application explained. The results of this research indicate that MPC is a successful method for faithfully generating three-dimensional objects, and has the potential to aid design evaluation.

2 Background of the Examinations

Today, there is a growing demand for cheap and fast concept modelling. Research on MPC carried out at RIKEN aims at combining this application with the unique characteristics of Stereolithography parts, such as transparency. Using inexpensive technology, MPC is an attractive technique to process photopolymers into various shapes.

In the frame of the following examination, the decisive process-technological parameters of influence shall be investigated. **Figure 1** explains that the following examinations focus on the features which are characteristic of the MPC process. Together with an adjusted control software, the way how energy is absorbed in the resin surface is of utmost importance regarding the achievable accuracy to form and shape.

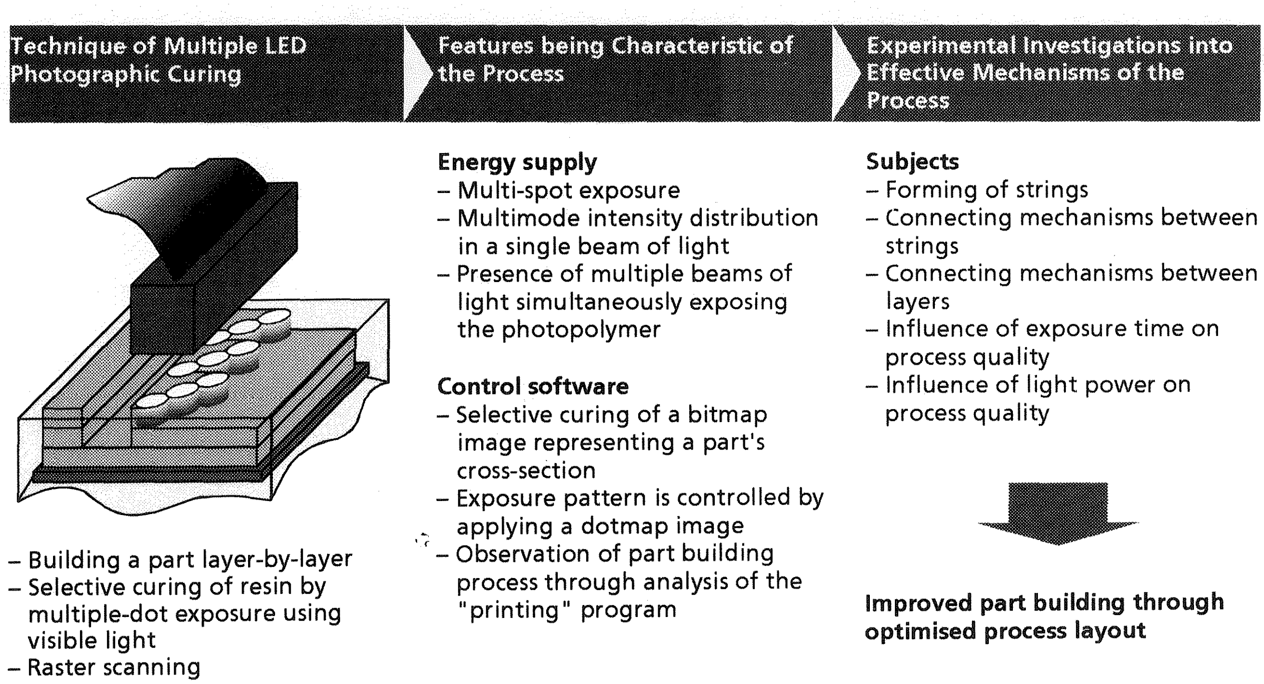

Figure 1: Concept of investigating the effective mechanisms of MPC

Besides process technological parameters of influence, the machine is of particular interest. Essentially, the kinematic accuracy of the linear guides and the temperature dependent behaviour of the entire machine must be given in particular. Here, only the motion of the projector scanning the resin surface has direct effect on the exposure quality. Therefore, the influence of the accuracy of the scanner guides is of great importance. The scanner, driven by a step motor, moves with an accuracy of 70μm per 90mm distance. In the direction perpendicular to the scan direction, the positioning accuracy is 20μm.

The influence of the material on accuracy to form and size, also regarding geometric long-term stability, is often underestimated. The two groups of photopolymers, acrylate- and epoxy-based resins, have some very different characteristics (Jacobs, 1992, Xu, 1997/1). In this context, the influence of the material is not further followed up. These aspects are not a particular characteristic of MPC but they are mentioned here because of their relevance for MPC.

3 Experiments into Effective Mechanisms of the Process

For the experiments, all test samples were built using a test facility which has been developed for *Multiple LED photographic curing* at RIKEN. The material is an experimental acrylate-based photopolymer resin, HSX-V-2 (by Asahi Denka). At a constant vat temperature of 30°C, the resin has a viscosity of $\eta = 3 \times 10^{-5} Ns/cm^2$. At the resin surface, the output power in each beam of light is $P_{L,V} = 29.2\mu W$. The experiments aid the investigation of the characteristic features when curing a photopolymer using multiple beams of light.

3.1 String Formation

The design of MPC necessitates simultaneous exposure of plane areas and thinnest strings with the same constant scan velocity and LED power. Therefore, in a computer-supported mathematical contemplation the exposure during curing using various numbers of beams of light for the exposure has been calculated. As a result, when exposing a plane area and a thinnest string at the same time, to ensure equal cure depth, the energy of at least five beams of light is necessary for exposing a single string. In this way, an equal level of exposure through superposition of single exposures in one layer is always guaranteed. Only under these conditions, a thin string can be created while a plane area is cured at the same time without overcuring.

For the initial experiments, single strings—exposed by five beam of light—have been chosen for investigating the curing phenomena. A single string is of particular interest because of both their well-known general importance when analysing the exposure process in Stereolithography in general, and investigating the characteristics of MPC in particular. At scan velocities ranging from 0.1 to 1.6mm/s, each string has been exposed by one (L1) to five (L5) beams of light at a fixed hatch distance of 62.5μm. The beam diameter is 0.5mm. Dimensions were measured using an optical microscope and a CCD (charge-coupled device) camera. A comparison of the line widths in scan direction and perpendicular to it at various scan velocities is shown in **Figure 2.** At constant light power at the vat, $P_{L,V} = 29.2\mu W$, it can be seen, that in general, the observed line widths decrease with increasing scan velocity. The graphs show, that in X-direction, the same line width can be achieved at higher scan speeds. Besides, perpendicular to scan direction line widths are slightly greater than they are in scan direction. The reason for that may be a not correctly adjusted timer for turning on and off the LEDs. A change in the software should solve this issue. The influence of the different number of beams of light used for exposure is considerable. At five beams of light, thinnest strings can be cured to up to 1.5mm/s and 1.3mm/s, respectively.

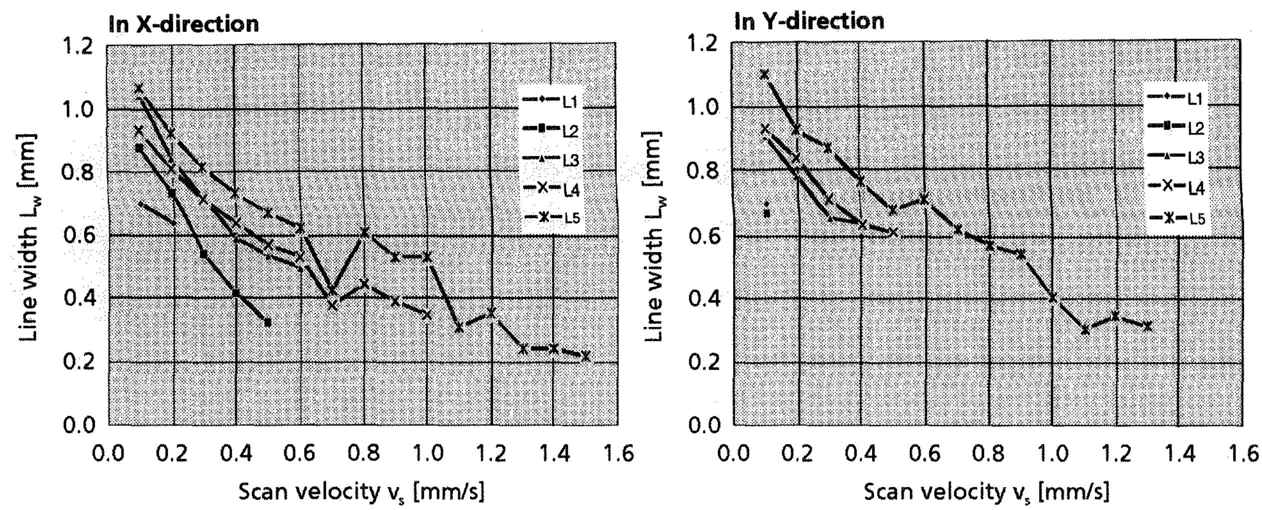

Figure 2: Line width in X- and Y- direction at light power $P_{L,V} = 29.20\mu W$

Perpendicular to the scan direction (Y-direction), at a scan speed of more than 1.3mm/s, no curing occurs. Compared to the exposure in scan direction, to start the polymerisation perpendicular to the scan direction, the scan velocity must be reduced, thus providing more exposure. The lower levels of curing found during exposure in Y-direction may be due to the exposure pattern. Across the scan direction, curing happens gradually and closely spaced. Initially, dots at a distance of 0.5mm are exposed. The energy, however, is not sufficient to connect these individual dots on the resin surface. The next row of beams of light are, therefore, not able to expose the resin anywhere near the previously cured dots. As a result, no strings can be formed at all.

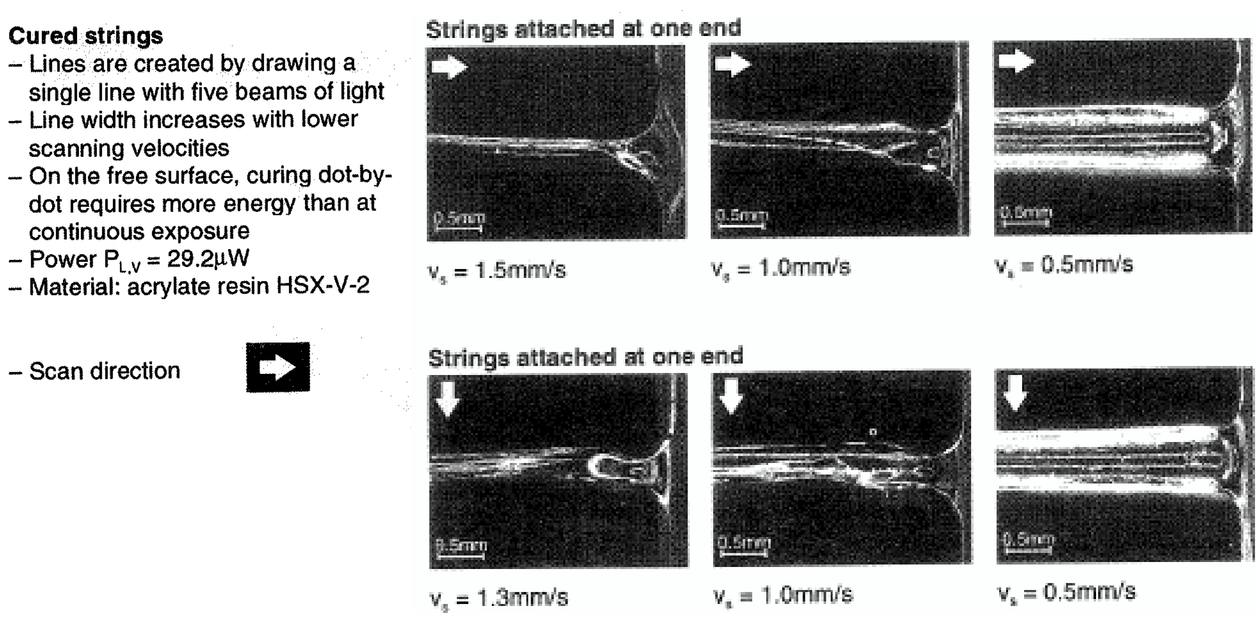

Figure 3: Formation of strings at various scan velocities v_s in scan direction and across to it

In scan (X-) direction, at scan velocities between 0.1 and 1.5mm/s, the shape of the strings differs greatly (**Figure 3**). As expected, the line width increases with decreasing scan velocity. At 1.5mm/s, a string has a width of about 0.11mm. Where the string is attached to a frame holding it in position in a right angle, the geometry is unclear. At low exposure, due to the low degree of polymerisation and its position free flowing on the resin surface, the string is rather soft and unstable. Xu et al. (1997/2) found that microscopic flow generated by the process heat could be observed. It is assumed that, during exposure, flow and probably shrinkage cause the string to move slightly on the resin surface. Width increases rapidly up to 0.68mm at 0.5mm/s. At 0.5mm/s, the string has been cured more and, therefore, is stronger and more stable. In Y-direction, at 1.3mm/s, the string is cured at a width of about 0.31mm. At 0.5mm/s, its width increases to about 0.7mm.

3.2 Connecting Mechanisms Between Strings

The connections between up to five adjacent lines formation a single string can be observed best at low scan velocities (**Figure 4**). The scan velocity is constant at 0.1mm/s. When exposing with just one beam of light, the shape of the cured string reminds a little bit on a string of pearls. With increasing number of beams, the string becomes smoother. At the same time, however, the line width increases only a little.

Cured strings
- Lines are created by drawing a single line with one to five beams of light
- Shape of the line becomes smoother with increasing number of beams of light
- Light power $P_{LV} = 29.2\mu W$
- Material: acrylate resin HSX-V-2
- When exposing one string with one beam of light, exposure happens in steps caused by the slightly jerky motion of the projector which is driven by a step motor
- With increasing number of beams of light, this effect disappears

- Scan direction

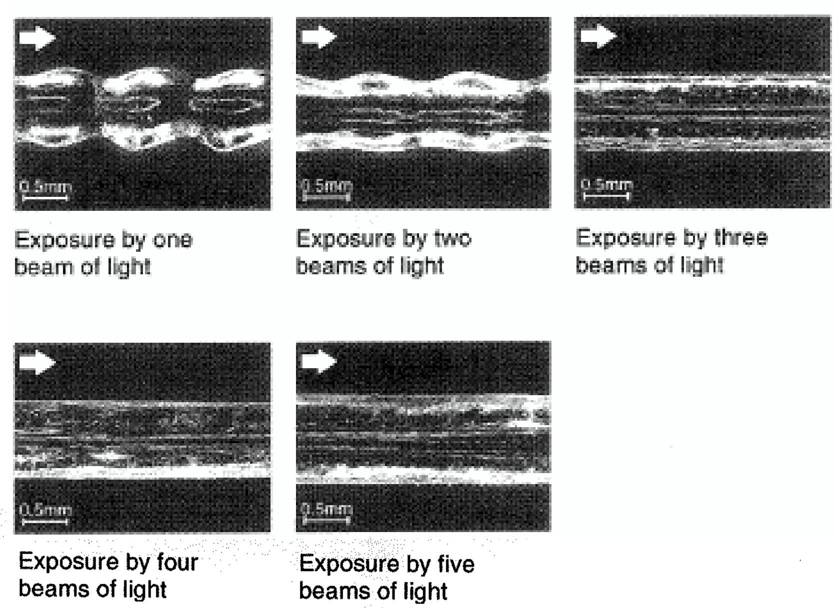

Figure 4: Simultaneous multi-beam exposure at a scan velocity $v_s = 0.1$mm/s in scan direction

Uneven curing when exposing at extreme low scan speeds is caused by the motion of the projector. In scan direction, the curing becomes sensitive to the slightest movements of the projector. The exposure happens in steps caused by the slightly jerky motion of the projector, which is driven by a step motor. This effect disappears with increasing number of beams of light exposing the string. Each additional beam of light exposes the same string at a slightly shifted time according to the arrangement of the beam array in the projector. Another observation is, at least three beams of light are necessary for curing one single string. Then, the contour of the string is similar to that of a straight line.

3.3 Parameters of Influence "Energy Absorption"

The course of the line widths and cure depths at various scan velocities and light power are shown in **Figure 5**. The data were obtained after curing several strings with three beams of light. In X-direction, line width and cure depth increase with increasing light power. The same result can be found in Y-direction. However, the line width is in average slightly greater than in X-direction. At scan velocities of 0.3 and 0.4mm/s, the increase in cure depth in Y-direction is slightly steeper than that in X-direction. The reason for that may be the initially very low degree of curing at a low exposure dot-by-dot. At higher exposure, the cure depths in X- and in Y-direction are the same.

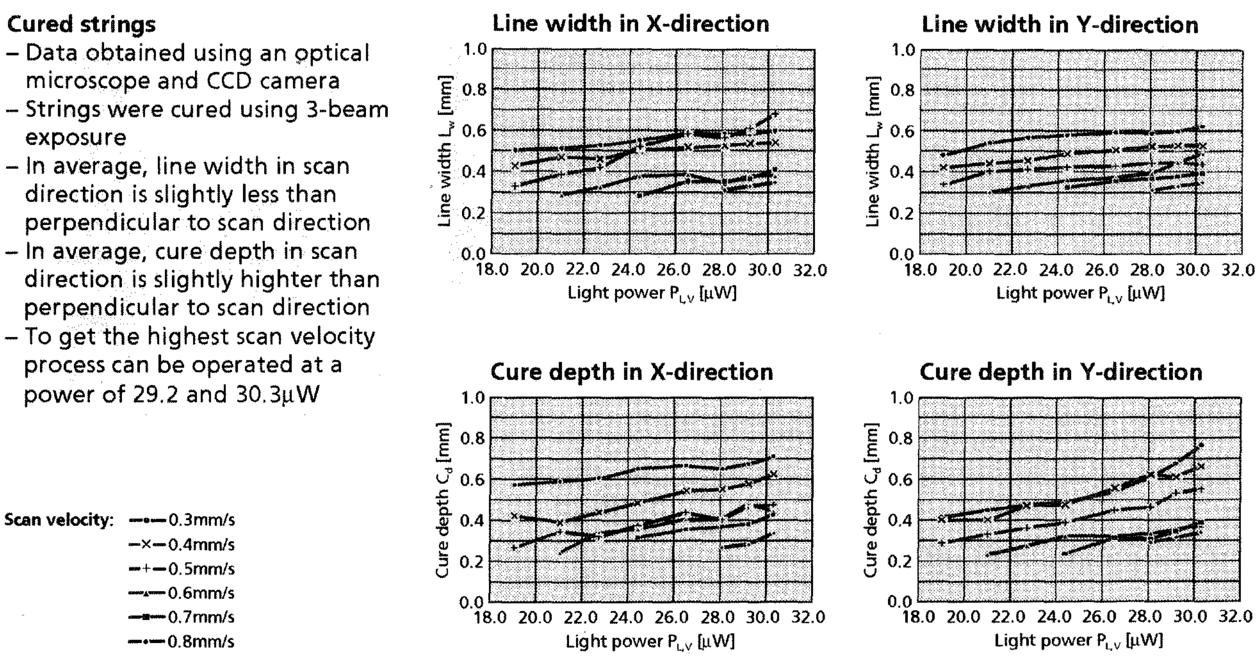

Figure 5: Parameters and their influence on curing

3.4 Parameter of Influence "Part Geometry"

The process parameters were varied over a wide range to find the optimum combination yielding good surface quality, fine detail, and sharp contours. The tests were carried out using the experimental resin HSX-V-2. The explanations in **Figure 6** focus on the results achieved when building simple geometric objects. A mesh can be build with walls as thin as 0.2mm and in good accuracy in X- and Y-direction as well as at various angles. The effect of multi-spot exposure is clearly visible in the vertical and the sloping elements. Part quality depends in the part orientation in the X-Y-plane. The vertical surfaces are smooth. It is one characteristic of MPC that strings which form layers lie exactly one above the other. This can not be changed since the arrangement of the lenses in the projector is fixed. MPC is successful for the process parameters for LED power and scan speed which were found above. A top view of the test part's surface shows that the lines from the exposure are clearly visible, even with the naked eye.

Material
- Acrylate resin HSX-V-2
- Resin viscosity $\eta = 3 \times 10^{-5}$Ns/cm²

Process parameters
- LED power $P_{LV} = 29.20\mu W$
- Wavelength $\lambda = 470nm$
- Scan velocity $v_s = 0.75mm/s$

Test part
- Size 45 x 45 x 9mm³
- Build time $t_B = 81min$

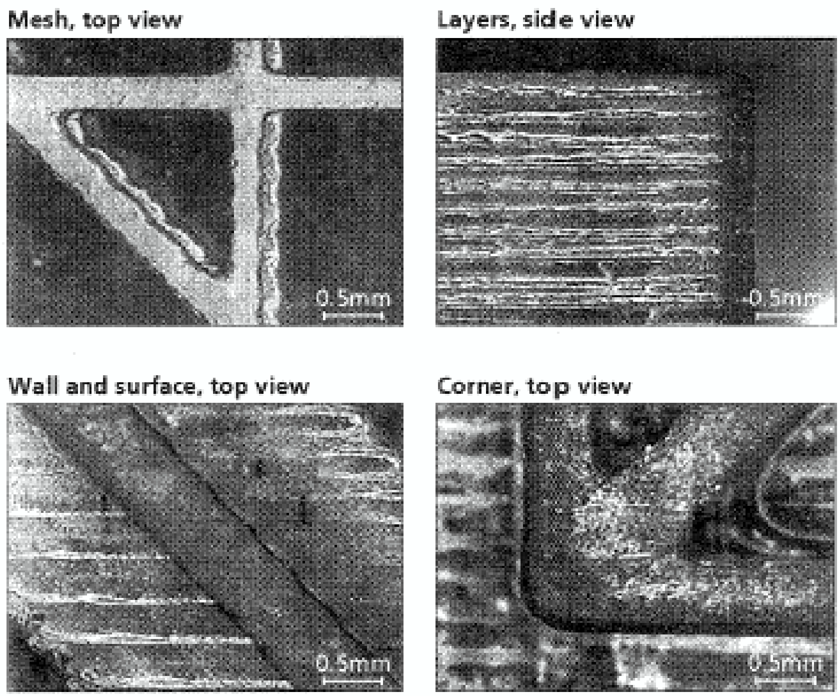

Figure 6: Influence of part geometry on surface texture and part quality

4 Discussion

The curing process in *Multiple LED photographic curing* (MPC) was experimentally examined. The effects of the parameters of influence on curing of single strings an formation of layers and three-dimensional objects were studied. Previously, theoretical investigations have shown that for the generation of equal cure depths in thin strings and plane areas, the exposure of at least five beams of light is necessary.

The data reported in this paper show that strings can be accurately cured at low light power. Line widths increase at lower scan speeds. In scan direction, strings could be polymerised at a velocity of up to 1.5mm/s. At high scan velocities, the strings are unstable and the geometry is sometimes unclear. One reason could be that microscopic flow causes the strings to move on the free resin surface. Besides, shrinkage may cause the strings to move. Across the scan direction, only up to 1.3mm/s strings could be created. These results can be explained by assuming that gradually and closely spaced exposure is not sufficient for polymerisation. At lower speeds, however, the exposed dots stick together and start formation strings. At extremely low scan velocity, the process becomes sensitive to slightest jerky movements of the projector when exposing with one beam of light. A jerky motion of the projector creates a line which looks like a string of pearls rather than a continuous line. Adding at least two beams leads to a smoother shape of the string. At high velocities, this effect disappears completely.

Due to the general characteristic of these investigations—strings were examined on a free resin surface—this study is limited to the basic curing process in MPC. It is the basis for further studies on the generation of three-dimensional objects, such as thin walls and other geometric shapes. The heat generation as the assumed reason for moves of the strings on the resin surface has not been examined and is subject of future examinations. The results of this study have implications on further developments of the process and the design of the machine itself.

This study could lead to new important findings about the MPC process. The results of this research indicate that MPC is a successful method for faithfully generating three-dimensional objects, and has the potential to aid design evaluation. Clearly, this technique has promise as a tool to fabricate three-dimensional objects in design evaluation. Future steps will thus include improvements in the light sources to increase process speed and accuracy of Multiple LED photographic curing.

5 References

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