# Microscopic Flow Observation of Photopolymer by UV-Laser Beam Exposure

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## ABSTRACT

Microscopic flow of liquid photopolymer around the cured polymer was observed during laser exposure. The maximum velocity was about 4 mm/s. The temperature raised by reaction heat, causes the density of liquid photopolymer to vary, resulting in this flow. This flow causes the nearby cured strands to sway and it decreases the accuracy of SL model.

## 1 INTRODUCTION

Stereolithography (SL) is a technology which directly creates 3D objects from digital data. Because SL offers the advantage of enabling models with complicated geometry to be created easily, it has been applied in numerous fields. Recent developments of SL focus on the applications of rapid tooling. For example, the SL model is used as the master model to create the die and model for small lot production. SL can also be employed to make die and mould of filler-in composite. All of these set high demands on the accuracy of the SL process. However, there is obviously a distance between the present available accuracy and such demands. The phenomena such as curl distortion and steps of models are factors which decrease the accuracy. To solve these problems, especially curl distortion, it is necessary to have a better understanding of the curing process of photopolymer. Numerous research works have pointed out that cure shrinkage and temperature are the potential factors which have influence on curl distortion. The attempts to quantify these factors are being made so as to control the curl distortion. Polymerization is exactly the transition of monomer from liquid phase to solid phase. Since the cured polymer has to be immersed in liquid photopolymer for a relatively long period, the liquid photopolymer should have certain effects on the curing process. As one of the liquid photopolymer's influences, swelling is a phenomenon where the cured polymer absorbs the monomer. It is known that swelling decreases the strength of the cured polymer[1] and induces curl distortion[2]. In addition to this, the flow of photopolymer during part building may decrease the accuracy. The possible causes of flow include the movement of the recoating system, flow induced by the heating system in the vat used for increasing the sensitivity of UV light. However , there is strong possibility for the generated heat or cure shrinkage to cause photopolymer flow. The purpose of this research is to observe the flow behavior of liquid photopolymer during laser exposure and clarify its causes so as to provide a clear understanding of the curing process.

## 2 PARTIAL MICROSCOPIC FLOW OF PHOTOPOLYMER

2.1. Experimental Details

In this experiment, a He-Cd laser (Output is 20mw) was used to cure the epoxy-based photopolymer HS-660 ( Asahi Denka K.K).

In order to observe the photopolymer's flow, BN powder (average diameter is 1.5 μm ) was used as the tracer ( BN powder : photopolymer = 1 : 1400 in weight ). The photopolymer was placed in a glass box (100x30x30). During laser exposure, a video camera was used to recorde the behavior of photopolymer and nearby cured strands from the top and front(Fig.1). This observation was carried out in spot and scan exposures by laser.

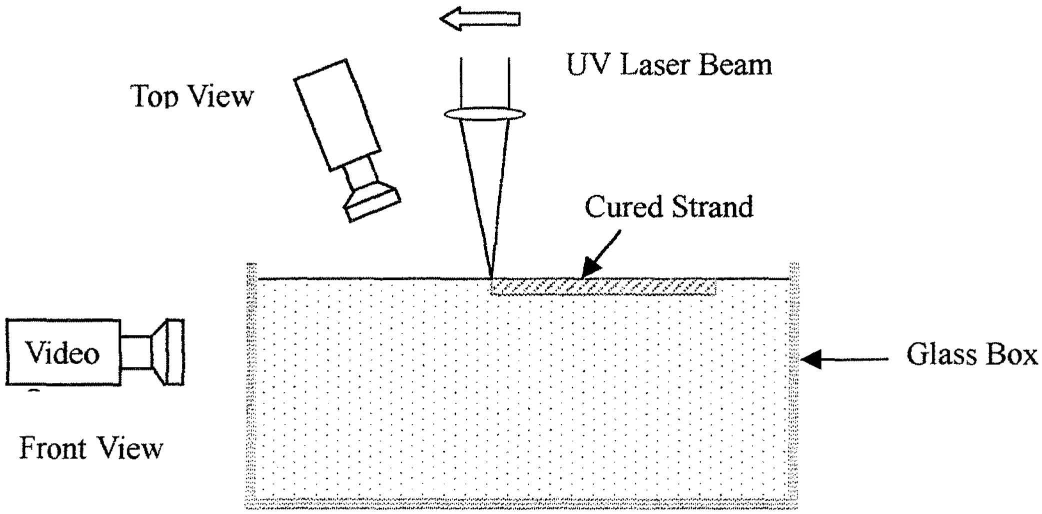


Figure 1 Observation of Flow during Laser Exposure

2.2 Behavior of Liquid Photopolymer Exposed by Laser Spot

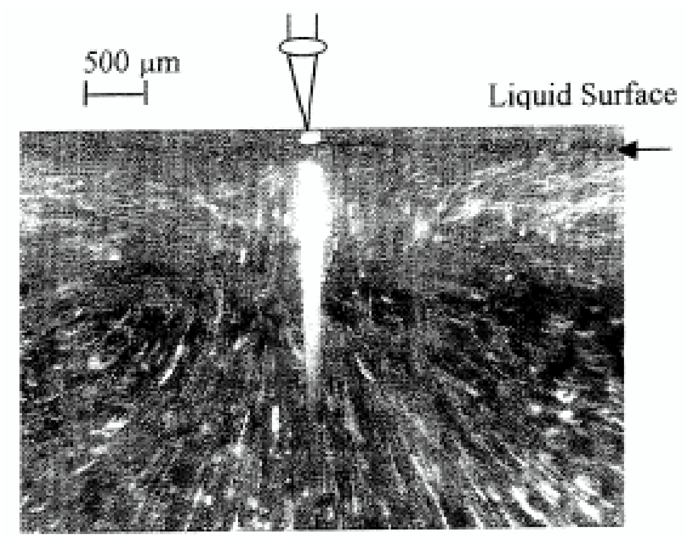


Figure 2 Partial Flow of Liquid Photopolymer During Laser Exposure

Fig. 2 shows the flow behavior of liquid photopolymer when spot exposed by UV laser spots to photopolymer, Once laser beam is projected onto the surface of the photopolymer, flow of the liquid photopolymer around the cured polymer results. At the beginning, the photopolymer under liquid surface moves away from the curing center. This is followed by movement along the solid boundary upward. Finally, circular movement of the photopolymer near the cured polymer results. When exposed by UV-laser, the curing area expands and the movement center of the flow moves away from the laser beam center.

## 2.2 Behavior of Liquid Photopolymer Exposed by Laser Scan

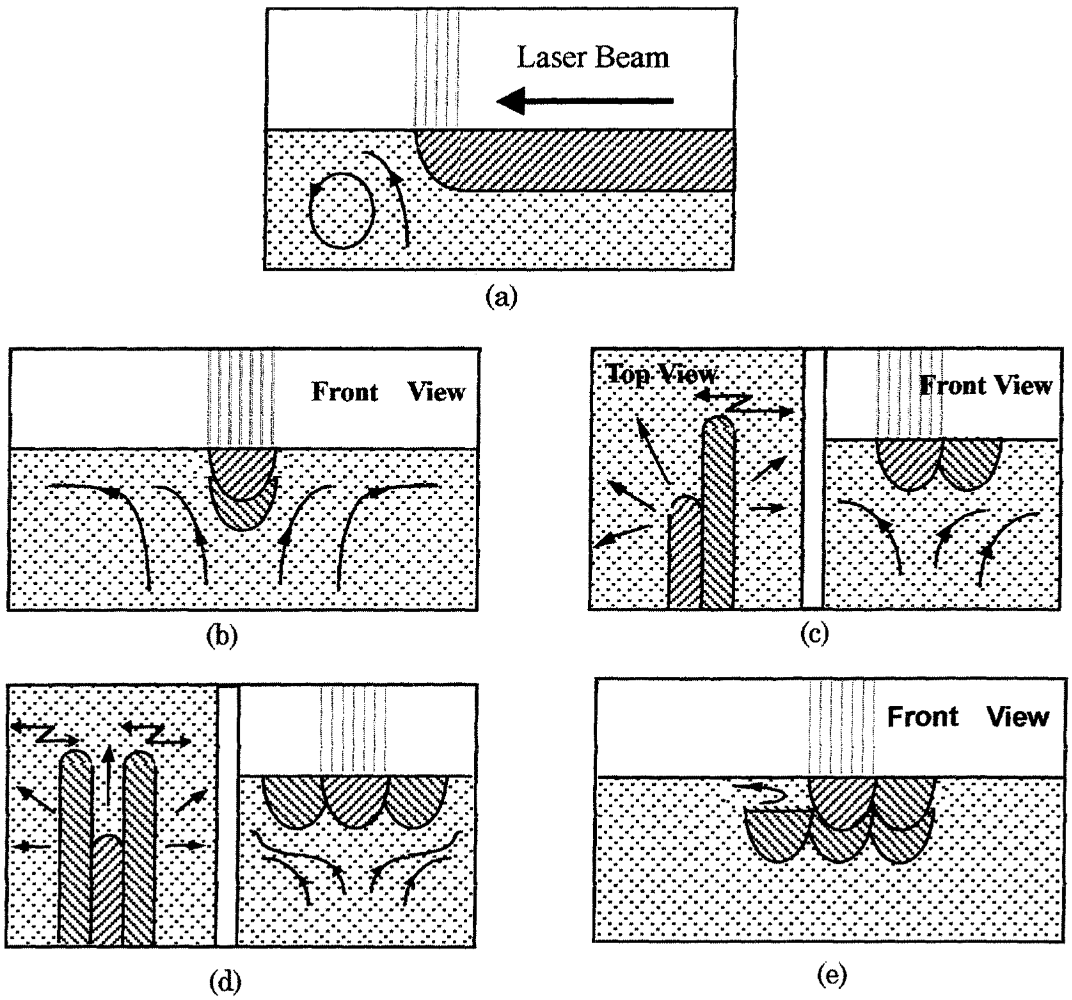


Figure 3 Flow Behavior of Photopolymer during Laser Scanning

When laser beam scans the surface of the photopolymer at a certain speed, a similar movement of photopolymer can be observed near the cured strand. The most active flow is in front of the laser beam center, and it moves with the laser beam. This movement is explained in Fig 3a.

When the laser beam scans the region where there are pre-cured strands nearby at two sides or at the lower level, the flow of photopolymer overruns these pre-cured strands

(Fig.3b,Fig3c,Fig3d). Even if the photopolymer is trapped by the pre-cured strands (Fig 3e), a slight flow is still observed.

2.3 Velocity of Flow

To express the flow precisely, it is necessary to know the velocity in any region of the liquid photopolymer as the functions of time and position. With this knowledge, it then becomes possible to know the impact applied on the nearby liquid photopolymer and cured polymer. To clarify the cause of this flow, it should be helpful to investigate the temperature distribution within this area. By using microcapsulized thermo sensing liquid crystal particles, the temperature and velocity can be measured[3]. In this experiment, the temperature was measured by an integrated thermocouple sensor[4.] Therefore, PTV (Particle Tracking Velocimetry) [5] was used to measure the velocity distribution of the liquid photopolymer. The principal of PTV is to directly track the tracers in the continuous images of video.

In this experiment, A laser beam with a speed of 10 mm/s was used to cure photopolymer. The movement of the tracer particles was consecutively recorded at a time interval of 1/30 s by a NTSC video format camera(Fig.4). A computer software modified from conventional image processor NEXUS 6400 was used to process the image and calculate the velocity of tracer particles.

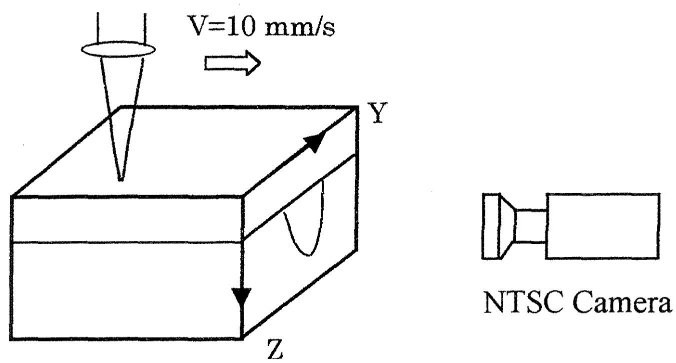


Figure 4 Measurement of Velocity of Flow

Fig.5 and Fig.6 show the velocity distribution of the flow of the photopolymer at the YOZ plane(Fig.4) at the initial moment of the flow induced by laser exposure.

When laser cures an individual strand, there is rapid flow around the strand. The maximum velocity reaches about 4 mm/s( Figure 5). The liquid photopolymer of the two sides of the cured strand flows rapidly ( greater than 2 mm/s), but the liquid photopolymer under the strand flows slowly (smaller than 2 mm/s). This shows that source of the flow may lie in the upper region of the two sides of the strand. In general, the velocity is very high.

When the second strand is cured beside the first strand. The velocity shows a different trend (Figure 6). At the side of second strand, the velocity is as high as that shown in Figure 4. However, the velocity at the (right) side of the first strand is far lower than that at the left side.

It proves that the flow at the right side is induced by that one of the left side

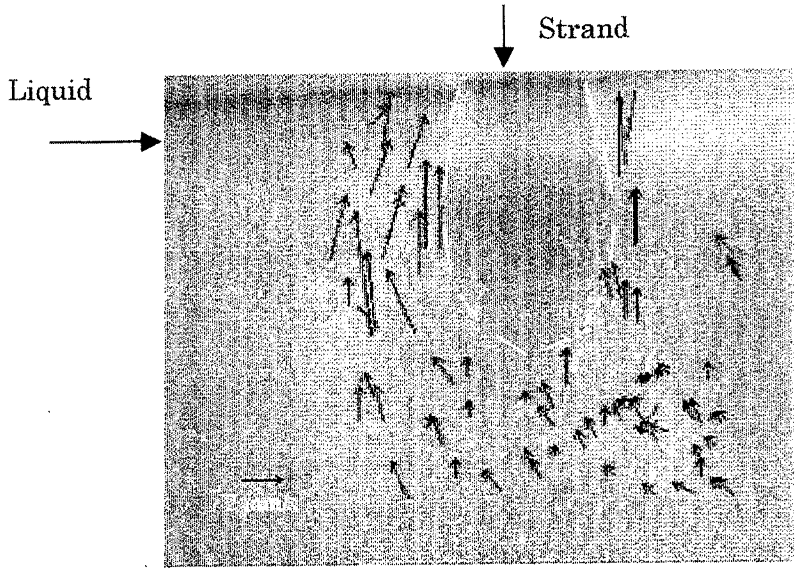


Figure 5 Velocity Distribution around Cured Strand

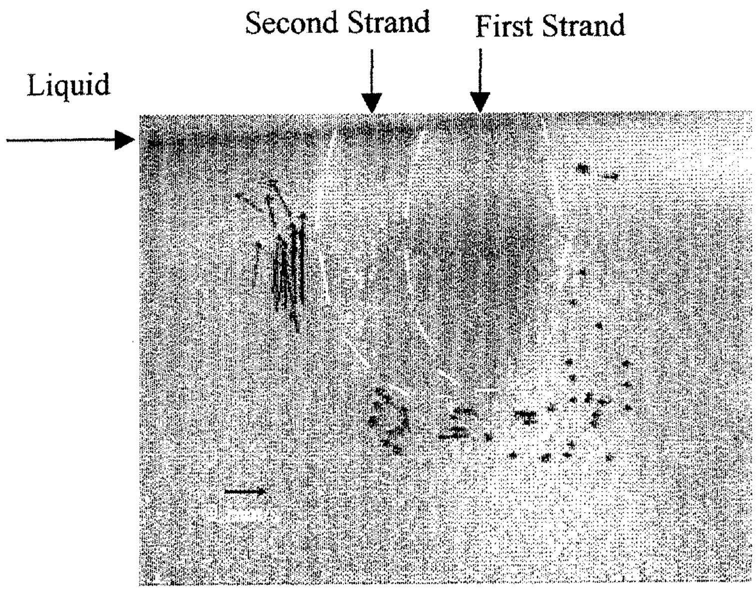


Figure 6 Velocity Distribution of Flow Influenced by Neighbor Cured Strand

2.4 Behavior of Cured Strands during Laser Scanning

The above measurement results show that the maximum velocity of the flow is as big as about 4 mm/s. It should have a very big impact on the nearby cured strands. From video observation, it was seen that the free ends of the cured strands sway if the laser beam scans near them. For investigating the impact from the flow, a sample was created as shown in Fig.7. This is a twin-cantilever sample with only one layer. The distance between the strands is twice the cured width. It means that the strands should disconnect each other completely. However, the free ends of the cantilever-strands have been connected together. When laser draws the strands, the free ends sway due to the liquid photopolymer flow. Because the interval for laser to draw the next path is very short. The swaying free ends of the cured strands happen to be in the laser path. Finally, these free ends are connected. After several strands have been connected, there is a enough strength to resist the impact of flow. The connected free ends do not sway again. Then the group of connected free ends are formed by laser drawing. This is the reason why there are three groups of connected free ends.

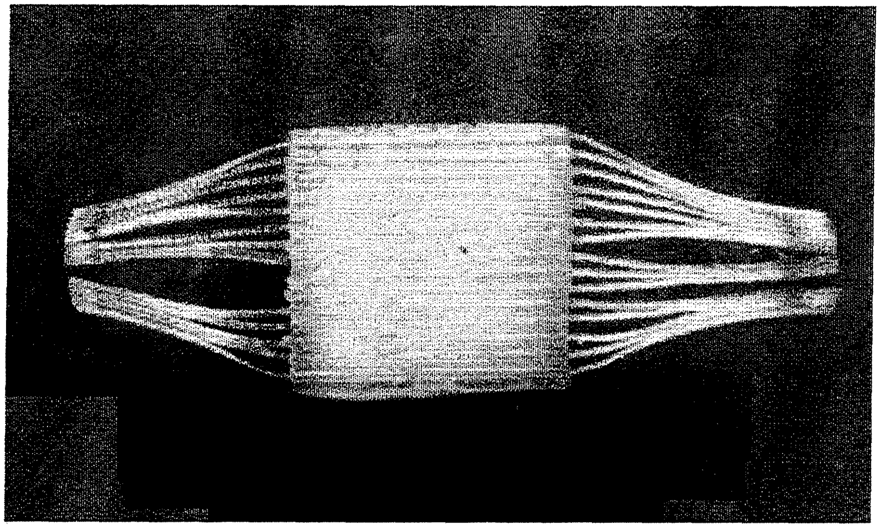

Figure 7 Connected Free Ends of Continuous Cured Strands

**3 Cause of Photopolymer Flow**

There are two potential factors which cause the flow of liquid photopolymer. One is the cure shrinkage and the other is temperature variation.

The maximum linear cure shrinkage of the photopolymer HS-660 used in this experiment is about 2.2%. If the profile of cross-section of the cured strand is assumed as a circle and its radius is 0.5 mm, the maximum linear shrinkage is about 0.01 mm. The velocity should be less than 0.01 mm/s because it takes about 100 seconds for cure shrinkage to reach its maximum. It is far less than the velocity in above measurement. In addition to this, the velocity should be in the radius direction if this flow caused by cure shrinkage which was obviously not the case with the observation result. Therefore, it can be concluded that cure shrinkage is a potential factor to cause flow but not the main one.

The inhomogeneous pressure and density distribution cause flow of the fluid[6]. For liquid photopolymer, heat is generated during laser exposure. Figure 8 shows the temperature distribution in the cured polymer and nearby liquid photopolymer. There is a temperature slope within the nearby liquid photopolymer. The high temperature leads to low density as shown in Fig.9 and there is a possibility for this inhomogeneous temperature to cause photopolymer flow.

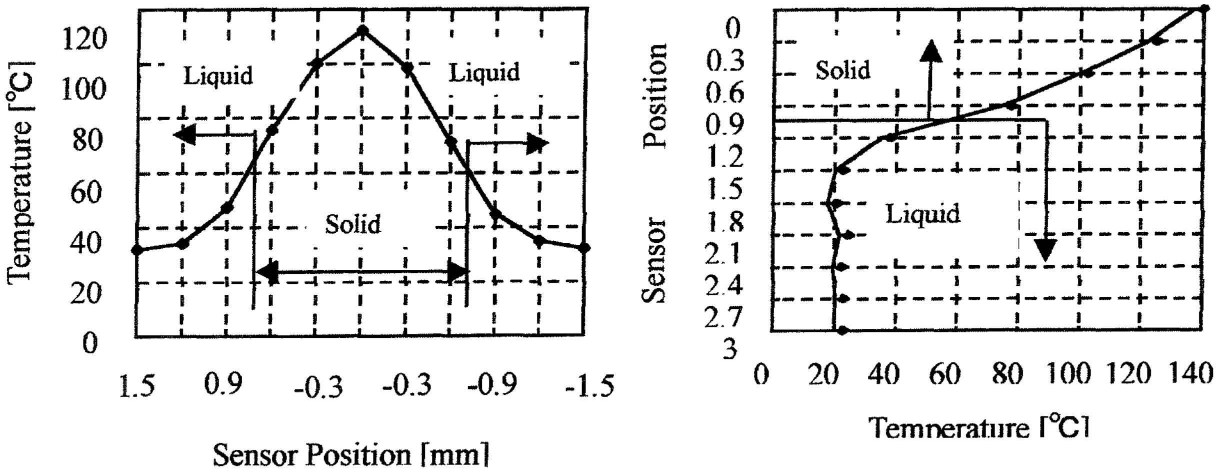


Fig. 8 Temperature Variation in Solid and Liquid Phases

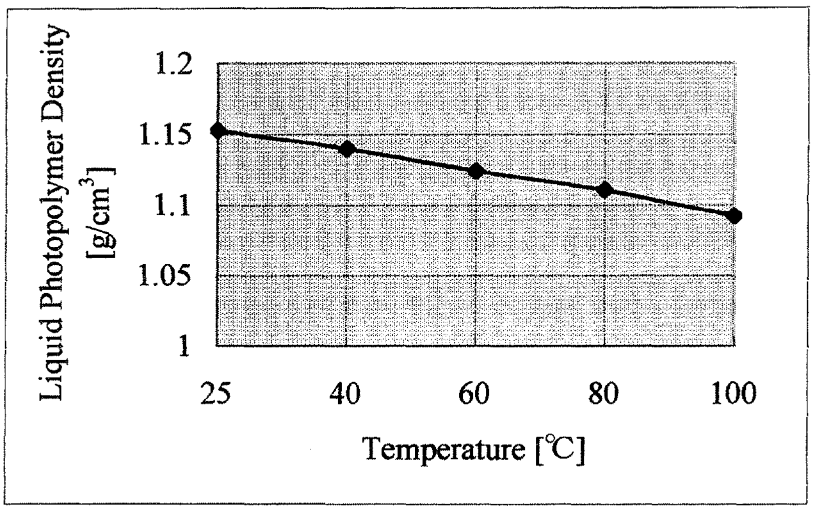


Figure 9 Relation of Density and Temperature of Photopolymer HS-660

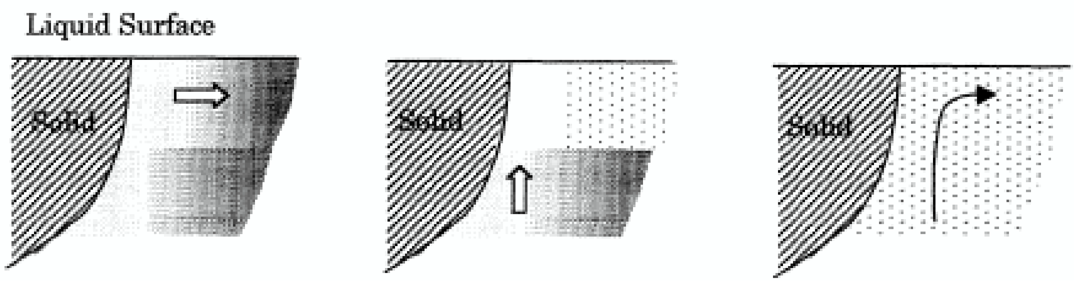


Figure 10 Enlarged Schematic Side View of Partial Microscopic Flow of Photopolymer during Laser Exposure

Under the liquid surface, there is a tendency for photopolymer to move to the right side because temperature is high near the solid boundary and the density is low. The photopolymer under this region trends also to occupy the space left by this right movement. These two tendencies causes the photopolymer to flow upward in the low region and to the right under the surface.

## 4.CONCLUSION

To investigate the influence of liquid photopolymer on cured polymer during laser exposure, experimental observation was carried out by means of a video camera. Partial microscopic flow of photopolymer was observed near the curing area. As soon as the laser spot projects on the surface of the liquid photopolymer, flow occurs. The velocity of the flow is very great. Measurements show that the maximum velocity reaches about 4 mm/s. Even though the neighbor cured polymer resists this flow, observations show that the flows overcomes this cured polymer and this flow causes the nearby pre-cured strands sway. This can been considered one of the sources of curl distortion. There is also a temperature variation near the curing area which varies the density of the photopolymer. This inhomogeneous density is the cause of photopolymer flow during laser exposure.

**Acknowledgements**

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