In-process Layer Surface Inspection of SLA Products

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ABSTRACT

A sensor system for inspecting the layer surface quality in stereolithography process is proposed in this paper. Since stereolithography process builds 3-dimensional shape by forming layers repeatedly, it is very important to process each layer of stereolithography process products in some favored conditions: Every layer should be cured uniformly and hardly enough so that the adjacent two layers can stick together to each other. However, in many applications, two kind of defects are frequently found, i.e. void and delamination. Void is cavity inside the built part and delamination is detachment of the bond between two adjacent layers. To inspect such defects, we propose a sensor system which consists of a laser source, a galvanometer scanner, a photo-detector, a few lenses, and a beam splitter. In this sensor system, the laser beam and the field of view of the detector are co-axially positioned and scanned over the product surface by the galvanometer. The reflected light is then detected by the photo-detector. And from the photo-detector signal, the surface condition and quality of the layer being inspected can be estimated. Since stereolithography products are very transparent, the system needs very fine tuning of the system parameters that include the power of laser beam and the sensitivity of the detector, and etc. The experimental results are obtained for products of a variety of shapes and several cases are presented and discussed in detail.

Keywords: stereolithography, process monitoring, cross-sectional image, epoxy resin

1. INTRODUCTION

RPD (rapid product development) is an emerging concept for global marketing and manufacturing, which can be constructed through effective organization of RPD network consisting of solid modeling, CAE, CA reverse engineering, CA measurement and inspection, rapid machining, rapid prototyping, and so on. RP(Rapid Prototyping) is such technology that produces prototype parts in much shorter time than traditional machining processes. This technology includes SLA(stereolithography apparatus), LOM(laminated object modeling), BPM(ballistic particle manufacturing), SLS(selective laser sintering), TDP(three dimensional printing), FDM(fused deposition modeling), among which SLA shows the best accuracy of the shapes of parts, but hardly be used to produce functional parts. This is because stereolithography products are not tough enough to perform mechanical functions. Thus, it is natural to represent the quality of stereolithography products as their dimensional accuracy and surface quality, that is, how closely their dimensions are achieved and how fine their surfaces are.

As shown in Fig.1, a stereolithography process utilizes an ultraviolet (UV) laser and a scanning mechanism to selectively solidify liquid photo-curable resin and form a layer whose cross-sectional shape is previously prepared from CAD data of the product to be produced. Once forming process of a layer is finished, the elevator moves down a specified distance, called layer thickness. Through repeating to form layers in a specified direction, a desired 3-dimensional shape is constructed layer by layer. To achieve high quality of stereolithography products, it is therefore necessary to maintain high quality of each layer. In other words, the following four conditions should be satisfied for high product quality. First, each layer should be formed to have the desired cross-sectional shape. Secondly, each layer should be cured uniformly over the surface. Thirdly, each layer should be firmly bonded to the lower adjacent layer. And finally, all of former conditions should be kept during the building process, i.e. the uniformity of layer quality.

The main factors affecting the uniformity of layer quality are the degradation of resin quality and the changes in system parameters. The optical and chemical reactivity of resin can be changed by moisture, contamination, and long time

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exposure to the laser light as well as day light. If there happens any change in system parameters such as the laser power, focus size, and the positioning accuracy of laser beam path, etc., then, depth of curing and spacing of hatching are apt to get uncertain, which leads layer quality to some unfavorable condition.

The degradation of resin quality and the uncertainty in process parameters can cause such defects as void, delamination, waved surface, and overshrinking. Void is cavity in part, which is mainly due to local overshrinking and air bubble formed during sweeping operation or elevator movement. Delamination is the failure in bonding between two adjacent layers, which is due to lack of irradiance of laser beam. If stereolithography process keeps building process with some delamination formed, it may not guarantee the quality of subsequent layers. Thus, this may lead to waste of time and cost. Overshrinking is caused by excessive irradiance of laser beam, which can lead to serious dimensional error and shape distortion. Therefore, it needs to develop a means of monitoring such defects of layer quality in an on-line manner, through which we can interrupt building processes of defective layers.

Many researchers have tried to improve the quality of stereolithography products through a variety of approaches such as hatching style development,[1, 2] resin development,[3~5] process parameter tuning,[6~8] SLI data generation,[9] and laser scanning and positioning systems. Lan et al.[10] and Otto et al.[11] have found the optimal building direction of stereolithography parts. Zhang et al.[12] have proposed the exposure based method for predicting curl distortion of stereolithography products. However, they all paid attention on the improvement of stereolithography system but not on detection of the defects which may degrade the quality of stereolithography products.

In this paper, we aim to detect such defects as void, delamination, and waves in layers of stereolithography products while building process is in progress. For this purpose, an optical imaging system is proposed which can acquire the images of cured part in stereolithography process. The principle of the imaging system is similar to that of laser scanning confocal microscopes. A laser beam is scannned over the top surface of liquid and solidified resin in vat. A photo-detector measures the intensity of reflected light at the point of laser focus. To discriminate solidified part from liquid resin, the optical properties of liquid and solidified resin are investigated. The following sections of this paper include the optical properties of liquid and solidified resin, sensing principle of the system, configuration of experimental system, and experimental results. In section 2, the optical properties of liquid and solidified resin are measured and discussed how to utilize them as a means of discriminating the solidified part from liquid resin. And also, the configuration of experimental system is presented. In section 3, a series of experiments for some basic geometry are performed, and the results are presented and discussed in some detail.

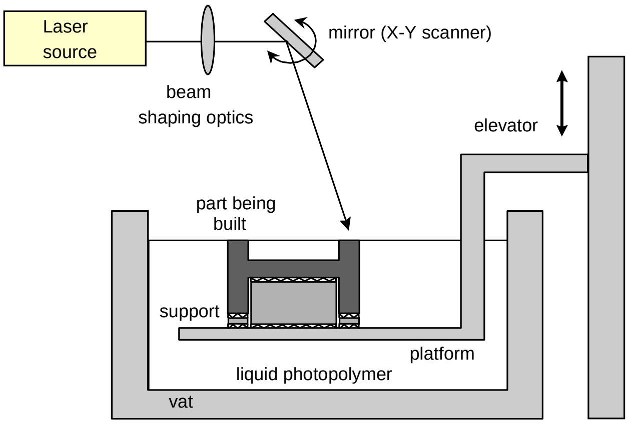
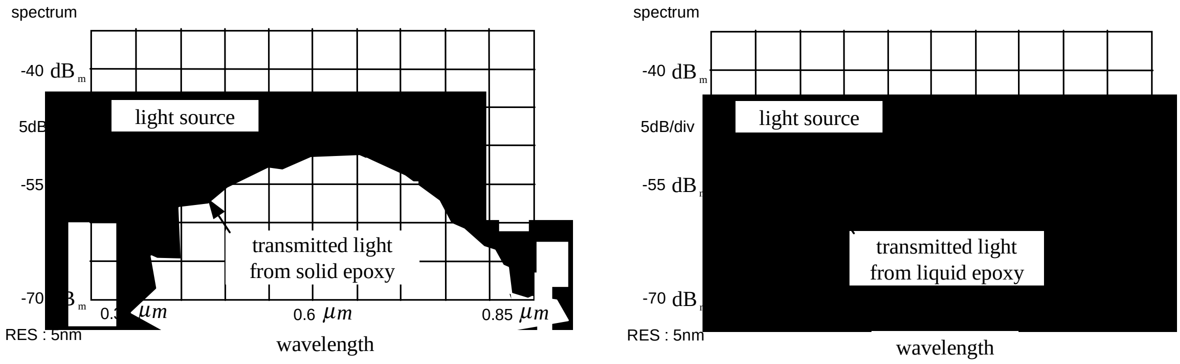


Figure 1 A schematic view of the stereolithography

2. SYSTEM CONFIGURATION

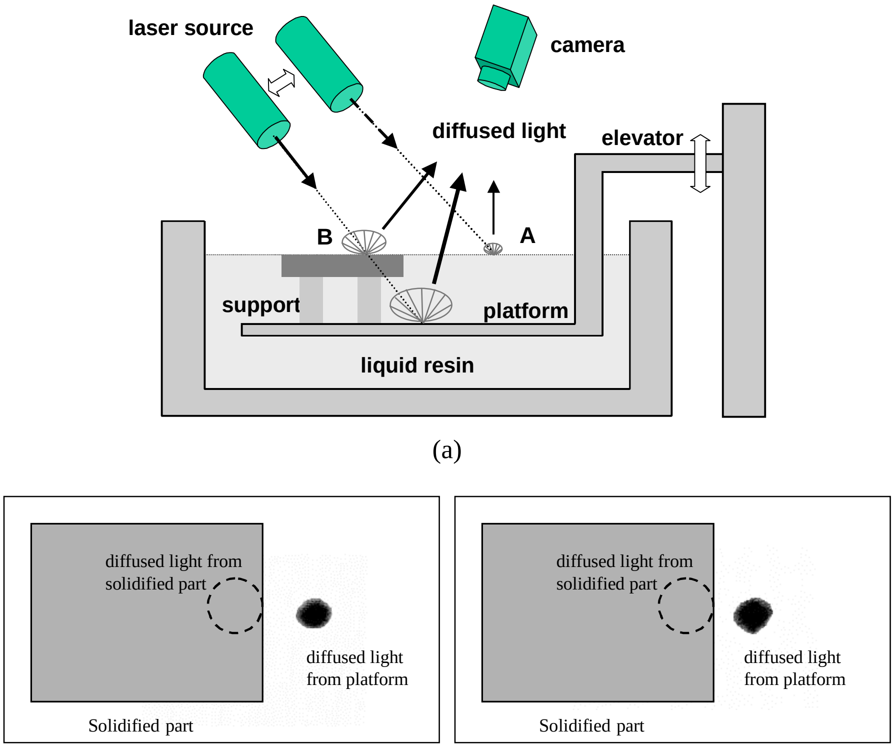
2.1 Optical properties of epoxy resin

To find characteristic features which can help us easily discriminate solidified part from liquid resin, the spectra of transmitted light from liquid and solidified resin are measured and compared as shown in Figs. 2 (a) and (b). The resin used in the experiment is SL 5170, the most popular resin, and the white light source is a halogen lamp. In the figures, the spectrum of the light source is also presented. We can see there is no useful characteristic feature for discriminating between liquid and solidified resin.



(a) (b)

Figure 2 Spectrum of transmitted light of epoxy resin : (a) liquid state; (b) solid state



(b) (c)

Figure 3 Difference between the diffused light of liquid resin and solid resin : (a) experimental setup; (b) in case that the laser beam illuminates liquid resin; (c) in case that the laser beam illuminates solid resin

Another property to be checked was the intensity of reflected light from the surfaces of liquid and solidified resin. We prepared an experimental system and observed the reflected light as shown in Fig. 3. A laser beam is incident onto the top surfaces of liquid resin (point A) and solidified part (point B) provided a camera looking over both surfaces. To observe the strengths of diffused component from points A and B, the camera is aligned so that it does not meet any specularly reflected component from point A and B. Figs. 3 (b) and (c) are the images acquired by the camera in cases that point C and A are illuminated by the laser beam, respectively. We can see the intensity of diffused light from solidified part is stronger than that of liquid resin. This property can be used to discern both states of resin. In the Figs. 3 (b) and (c), there are the diffused components from the plaform which look very strong. It is a kind of noise that can be rejected through an enlarging numerical aperture (NA) and through designing the platform of low reflectance. As for the specular component, the intensity of specular component of liquid resin is stronger than that of solidified part. This property can also be used for discriminating both states of resin, but expected difficult to practically utilize since the specular component is very sensitive to surface normal.

2.2 Principle and configuration of the imaging system

Since epoxy resin is translucent, it is hard to take images of stereolithography products by a normal vision system. To take images of the products being built, it primarily needs to discriminate solidified part from liquid resin. For this purpose, we adopted the fact, which was introduced in section 2.1, that the diffused light of solidified part is stronger than that of liquid resin. Fig. 4 shows the configuration of the proposed imaging system with actual values of dimensions and system parameters used in experiments, of which the results will be presented in following section. The two optical axes of the laser beam and the field of view of photo-detector are co-axially aligned and swung by a galvanometer scanner. In this configuration, no matter which point the laser beam is steered to by the galvanometer scanner, the photo-detector can measure the brightness of the point. If the point of interest is on the surface of solidified part, the photo-detector reads high. If the point is on the surface of liquid resin, the photo-detector reads low. Through scanning over whole suface in which the two top surfaces of liquid resin and the part being built are equally leveled, we can make an intensity map of the reflected light with respect to the two mirror angles of the galvanometer scanner. From this intensity map, we can construct an appropriate intensity map with respect to two dimensional rectangular coordinates in metric scale. The conversion of intensity map is to be presented in following section.

In this imaging system, if the laser beam is perpendicular to the surface, the photo-detector reads very high even if the surface is of liquid resin. This is because liquid surface is more specularly reflective than solidified surface, from which the imaging system may get some noise. To prevent this, a polarizer is used in front of the lens of photo-detector as shown in Fig. 4. Diffused light from the platform of stereolithography apparatus can be another source of noise as shown in Fig. 3. It can be rejected by intentional defocusing of it. This can be achieved by enlarging both numerical apertures (NA) of the laser beam and the field of view of photo-detector, through which the platform gets out of focus.

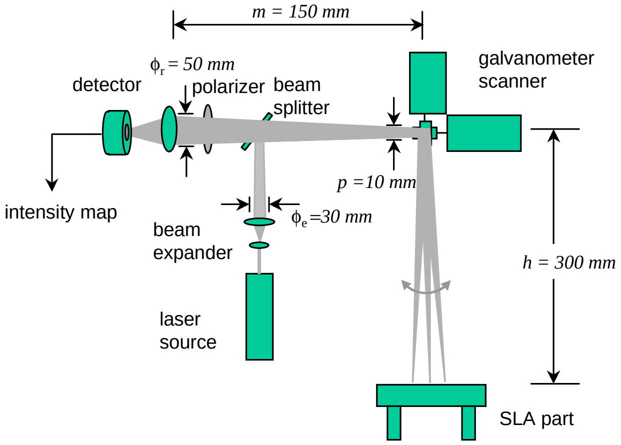


Figure 4 The proposed imaging system configuration

3. EXPERIMENTS

In order to verify the effectiveness of the proposed imaging system, we prepared an experimental system as shown in Fig. 5. In the system, a CCD camera is used for measuring the brightness of the laser focus. Since the two optical axes of the laser beam and the camera are scanned together by galvanometer scanner, only a bright spot appears in camera image. And the position of the bright spot in image does not vary during scanning process. To measure the brightness of the spot, we, therefore, need only to take the graylevel value of the representative pixel in the spot. As previously described, when the laser focus in on the top surface of solidified part, the spot looks very bright. On the contrary, when the laser focus is on the top surface of liquid resin, the spot looks relatively dark. Typically, the average graylevel value of the spot on solidified part is larger than 170 in 8-bit image, and that on liquid resin is smaller than 60.

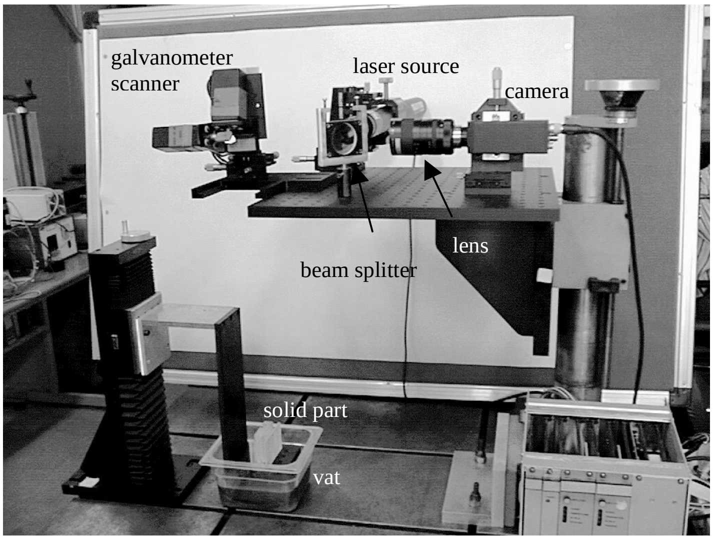
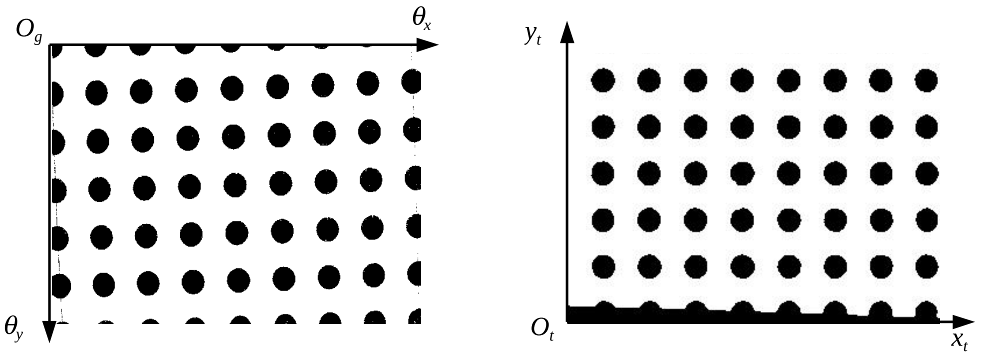


Figure 5 Photograph of the cross-sectional image acquisition system

In the proposed system, once a scanning process over an object is terminated, we get an intensity map with respect to two galvanometer mirror angles, say θ_x and θ_y. For quantitative evaluation of part quality, we need to convert the intensity map into metric scale. This can be achieved through galvanometer scanner calibration, which is an identification task for the functional relationship between the two galvanometer mirror angles and the two-dimensional rectangular coordinates as shown in Eq. (1).

$$\begin{bmatrix} x_t \\ y_t \end{bmatrix} = \vec{\mathbf{F}}\left(\begin{bmatrix} \theta_x \\ \theta_y \end{bmatrix}\right) \tag{1}$$

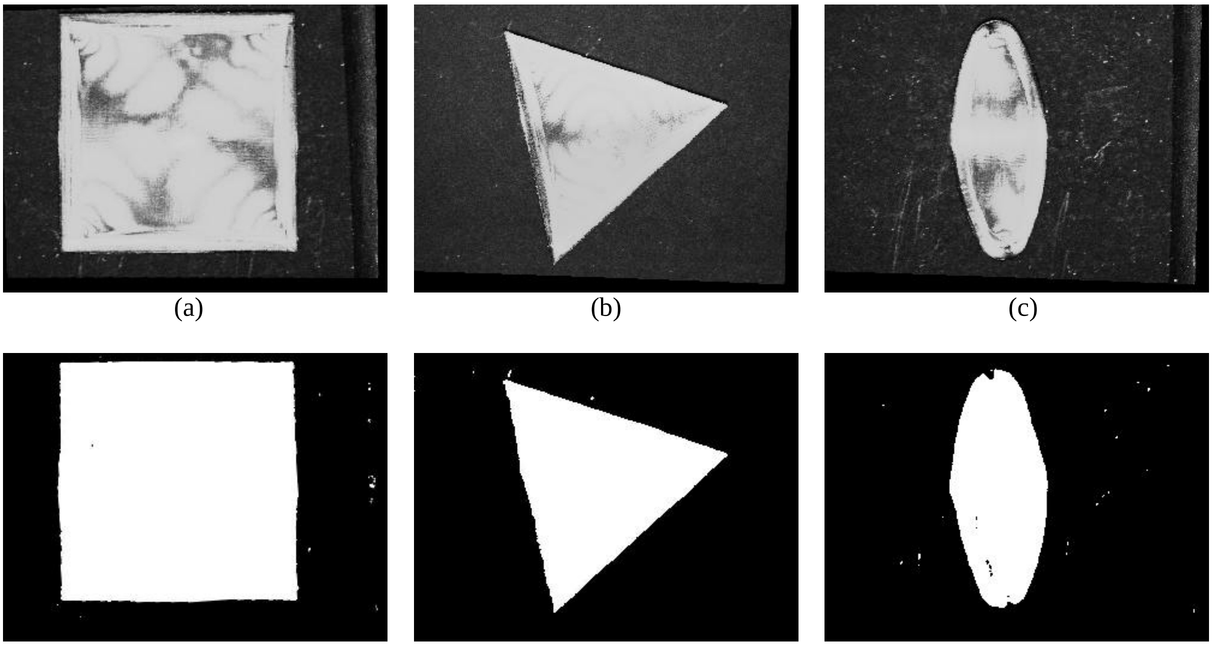
where x_t and y_t are the rectangular coordinates positioned on the surface of curing process. Fig. 6 shows the calibration target used in the calibration task. The target has a pattern of circular blobs with an equal spacing of 10 mm vertically and horizontally. Fig. 6 (a) is the image of calibration target in θ_x and θ_y coordinates and Fig. 6 (b) is in x_t and y_t. We can see the array of circular blobs forms straight lines in both x_t and y_t direction, but slightly bent and sloped in θ_x and θ_y coordinate system. The dark bands along the lower border in Fig. 6 (b) are the areas that do not correspond to any point of θ_x and θ_y coordinates in Fig. 6 (a).



(a) (b)

Figure 6 Image of calibration target: (a) scanned image; (b) calibrated image

Prior to detection of surface defects, a series of basic experiments for rectangular, triangular, and elliptical surfaces have been performed. The parts are made from SL 5170 resin by SLA 500 machine and they have no defect but plain surfaces on their top. Fig. 7 shows scanned raw images and binarized images of them. As shown in the figures, the parts look brighter than background. We can see the cross-sectional shapes of the part while it is hard to see them in vat with naked eyes or normal vision system.



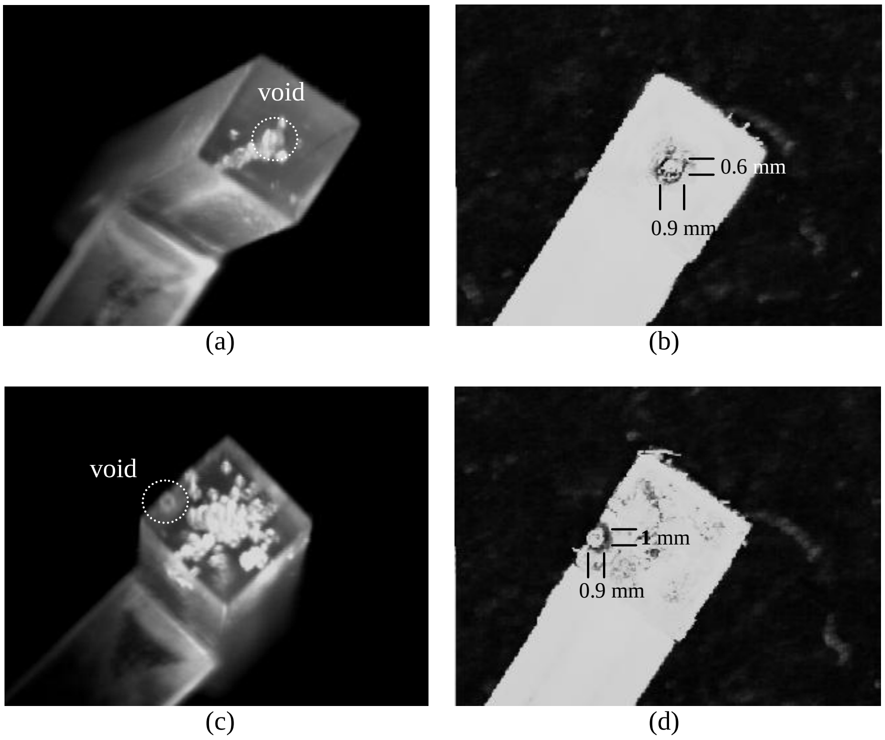
(a) (b) (c)

(d) (e) (f)

Figure 7 Scanned images for plain surfaces : (a) and (d) graylevel and binary image of a rectangular surface; (b) and (e) graylevel and binary image of a triangular surface; (c) and (f) graylevel and binary image of an elliptical surface

Voids on top layer

Figs. 8 (a) and (c) show the camera images of a part having voids, and Figs. 8 (b) and (d) show the acquired images of voids by the proposed imaging system. The part used in the experiments is “letter-H” part,[7,8] which is one of standard parts for benchmarking stereolithography processes. In Fig. 8 (a), the part has many voids in a single file, among which only one is located on the top surface. Similarly in Fig. 8 (b), though there are many voids in the part, only one of them is on the top surface. We can see the only void on the top surface of each case in Figs. 8 (b) and (d), respectively.



(a) (b)

(c) (d)

Figure 8 Void detection : (a) and (c) Appearance of voids; (c) and (d) Image of voids on top surface

In Figs. 8 (b) and (d), each void on the top surfaces looks like a black ring of some radius. The black ring is the dark field in image, which is the area with less brightness than surroundings. The principle of image formation of bright and dark field is briefly shown in Fig. 9. One the laser beam is focused on a surface with voids, brightness of this area is high as shown in Fig. 7. But the laser beam is focused on a point having a slope, α, the detected power of the light reflected from the point is less than that of horizontal surface. This is because the majority of the reflected light goes out of the way to the photo-detector. Thus, the inclined areas of voids appear dark in image. While, the areas of void perpendicular to the incident laser beam are bright in image since their surfaces are horizontal or nearly horizontal. We can estimate the size of voids by measuring the dimensions of dark fields. The measured dimensions of the voids are shown in Figs. 8 (b) and (d).

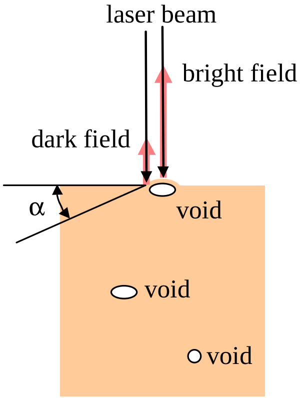


Figure 9 Measured brightness of of void

Delamination and dislocation of top layer

As described previously, delamination is a fatal defect affecting the product quality. Once delamination occurs the top layer floats on the liquid resin and may be dislocated during the sweeping process. Since delamination is the failure in bonding between top layer and its lower adjacent layer, it is hard to observe by surface scanning of top surface. Thus, it needs some dislocation of top surface to monitor delamination. In other words, we can regard a scanned cross-sectional shape as delamination if there is large difference between desired shape and measured shape. Fig. 10 shows the scanned raw image and binarized image of the rectangular part having a dislocated layer. The desired shape of the product is the same as the one shown in Fig. 7 (a). In the figure, we can see that the top layer, the dislocated one, looks clearer than the body. The top layer is dislocated 4.5 mm vertically and 4.3 mm horizontally.

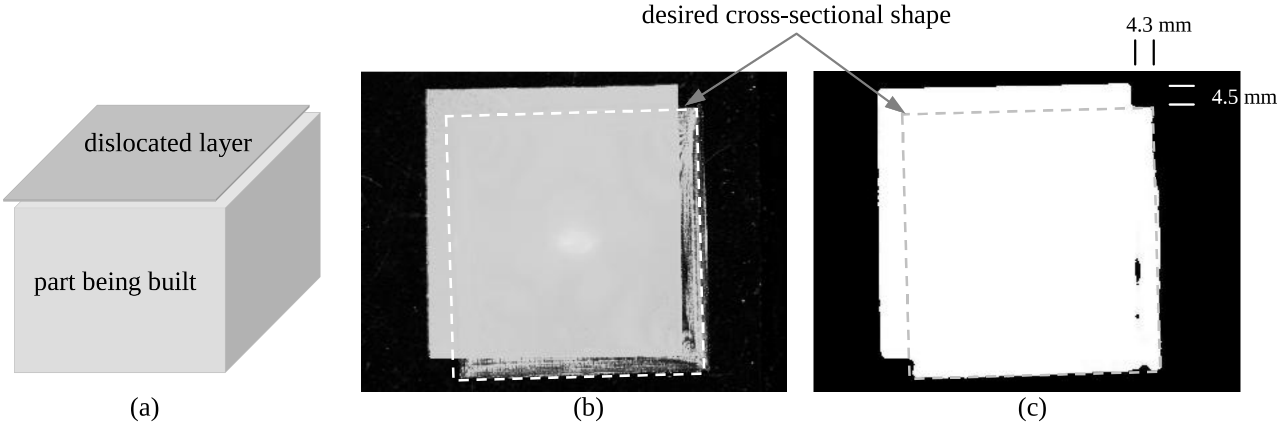


Figure 10 Dislocation of the top layer : (a) Appearance of a part having dislocated layer; (b) graylevel image; (c) binary image

Waved surface

Stereolithography products often have their top surface which are largely waved. This is because of either lack of laser beam power applied for curing or improper operation of sweeper. Fig. 11 shows a part having waved surface and its scanned raw image by the proposed imaging system. As shown in Fig. 11 (a), the waves of the surface are not seen by human eyes and normal vision system. However, in Fig. 11 (b), the proposed scanning system provides us with wave-intensified image. The dark fields in the figure are such areas having some slope from which a relatively small power of reflected light is detected by photo-detector.

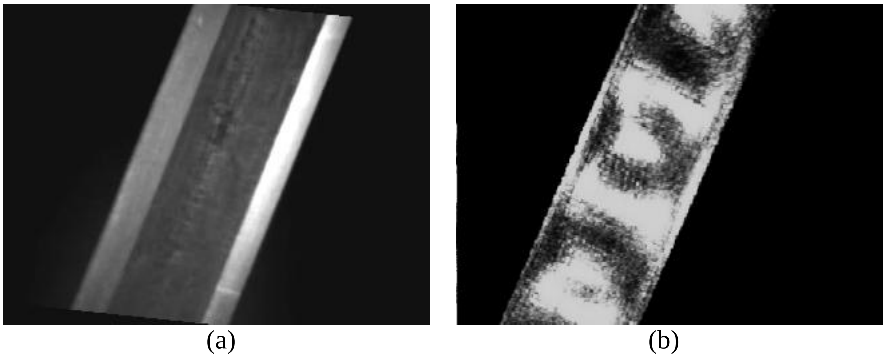


Figure 11 Waved surface : (a) apperance of waved surface; (b) scanned raw image of waved surface

4. CONCLUSION

In this paper, a surface scanning system to inspect stereolithography products is proposed for real time process monitoring. It scans over the top layer of a part being built in vat to make an image clearly discriminating solidified part from liquid resin. If there is any defect such as void, delamination, and waves, it also makes some pattern in image. The principle of the system is similar to that of laser scanning confocal microscope while modified to have wider field of view and faster scanning speed with some loss of resolution in the x, y, and z coordinates.

In order to verify the principle of this proposed system, a series of experiments have been performed for some basic objects and for some defects. From the experiments, the experimental results show that the proposed monitoring system can be an effective means of in-process monitoring of the quality of stereolithography products.

The scanned images acquired by the proposed system can help us see the quality of stereolithography products being built with our naked eyes and help us decide if the product quality is acceptable or not. For automated inspection, it needs some intelligent algorithms for defect detection and classification as well as some image processing algorithms for image enhancement, feature extraction, etc. The automatic inspection for the defects such as voids, delamination, and waved surface using the above algorithms is to be performed through further work.

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