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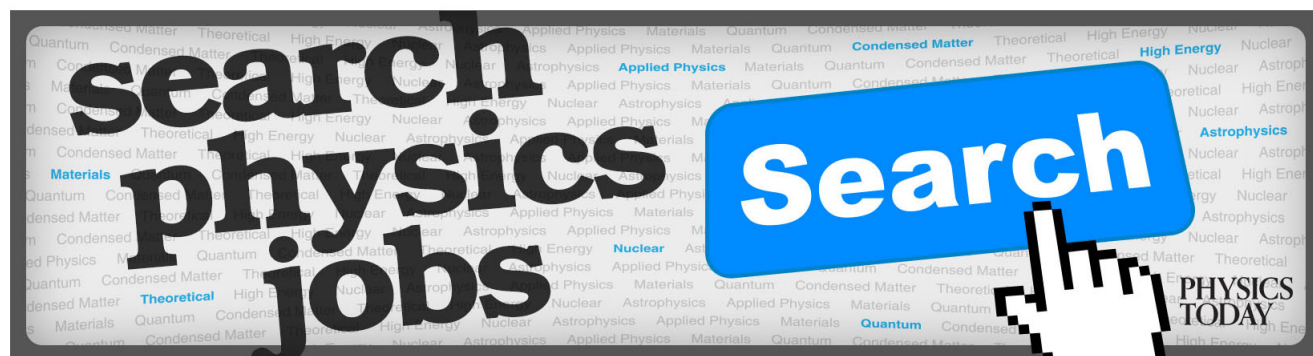Coupled Plasticity and Damage Modeling and Their Applications in a Three-Dimensional Eulerian Hydrocode
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Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer

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A new method for automatic fabrication of a three-dimensional plastic model is presented. A solid model is fabricated by exposing liquid photo-hardening polymer to ultraviolet rays, and stacking the cross-sectional solidified layers. Three types of equipment were constructed, their operational conditions were investigated, and some solid models were fabricated. A transparent plastic model whose internal structure was visible from the outside of the model was obtained. The operations are simple and can be easily automated. The present method is useful in displaying three-dimensional shapes.

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INTRODUCTION

To show three-dimensional shapes such as those stored in the memory of a computer or imaged in the mind, one must normally substitute two-dimensional displays (on paper or television), since no good method has been developed to show three dimensions easily. In spite of many improvements in two-dimensional displays, it is still difficult to obtain three-dimensional images from two-dimensional displays when a shape is complicated. Holographic techniques can give three-dimensional images, but many and complex calculations are needed to obtain the hologram for nonexisting shapes and there is insufficient accuracy and clearness. A solid model gives fine information about three-dimensional shapes and is useful in geometrical analysis of the figure. However, such models require long fabricating times, high cost, and excessive labor.

This paper presents a new method of fabricating a solid model by using liquid photo-hardening polymer in a short time, at low cost, and without excessive manual labor.

I. PRINCIPLE

In this method a solid model is fabricated by stacking the cross-sectional layers. The number of the layers should be determined by considering the complexity of the desired shapes and the accuracy needed in the model. The thickness of each layer is determined from the number of the layers and the model scale.

When a liquid photo-hardening polymer is exposed to ultraviolet rays (wave length, 300–400 nm), it is solidified from the surface. The thickness of the solidified layer is a function of the UV intensity and the exposure time. Therefore, a solidified layer of the desired shape and the thickness can be grown by controlling the exposure area, intensity, and time.

If the solidified layer is immersed into the liquid with top at a depth equal to the thickness of the layer to be solidified, its top surface is covered with un-solidified liquid polymer. At this stage, if the liquid surface is exposed again, a newly solidified layer of the desired thickness is stacked just on the previously solidified layer. The layers adhere tightly.

In such a procedure, if the exposure areas are controlled to correspond to the cross-sectional figures of the desired model and the exposure and immersion is repeated in turn, a solid model presenting the desired shape is grown in the liquid.

II. EQUIPMENT

Three types of equipment a, b, and c, constructed in the present study are schematically shown in Fig. 1 (a), (b), and (c), respectively. In a and b, the exposure area is controlled by a mask pattern. In a, UV is exposed from the top, and in b, from the bottom. A mercury lamp (200 W) or a xenon lamp (500 W) is used for the UV source. The liquid photo-hardening polymer used is "Tevista" (a commercial product from "Teijin Ltd."), which is a mixture of unsaturated polyester, cross linking agent such as acrylic ester and styrene monomer, polymerization initiator, and sensitizer. By UV illumination, the unsaturated polyester turns to a cross linked polymer and it is solidified. Of course other types of photo-hardening polymer are also available.

In a, a movable plate on which the solid model will be grown is set in the liquid polymer. This plate is immersed intermittently by a pulsed motor, and the solidified layers are also immersed with the plate.

In b, the movable plate is pulled up instead of being immersed. The other procedures are almost the same as in a.

In c, the liquid surface is exposed to UV through a scanning fiber transmitter. The fiber is mounted on a commercially produced XY plotter. The scanning speed, linewidth, and the area to be scanned are controlled by the machine. A xenon lamp (500 W) and an optical fiber of 3.2 mm in diameter are used. An optical lens is set before the end of the fiber to adjust the
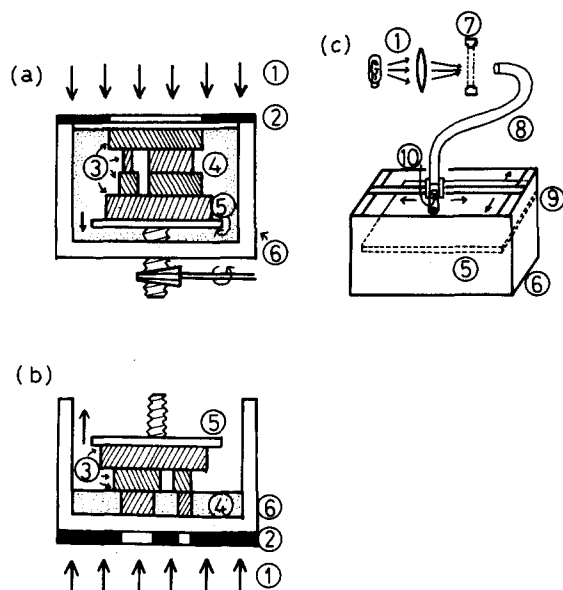
FIG. 1. Schematic sketches of three types of apparatus constructed in the present work. In this Fig. ① ultraviolet rays ② mask ③ solidified layers ④ liquid photo-hardening polymer ⑤ movable plate ⑥ receptacle ⑦ shutter ⑧ optical fiber ⑨ XY plotter and ⑩ optical lens. Exposure and shift of the movable plate is repeated in turn, and the solid model is grown on or under the plate.

diameter and dispersion angle of the beam. A shutter is set between the lamp and the fiber. This shutter is controlled to be open when the position of the scanning fiber is in the area to be exposed.

III. EXPERIMENTAL RESULT

The dependence of the solidified thickness upon the exposure, intensity, and time was examined. The results obtained by the equipment a are summarized in Fig. 2. In this examination the distance between the lamp and liquid surface was measured instead of measuring the UV intensity. The lamps used are not so small as to be regarded as a point source, then the UV intensity may not be inversely proportional to the square of the
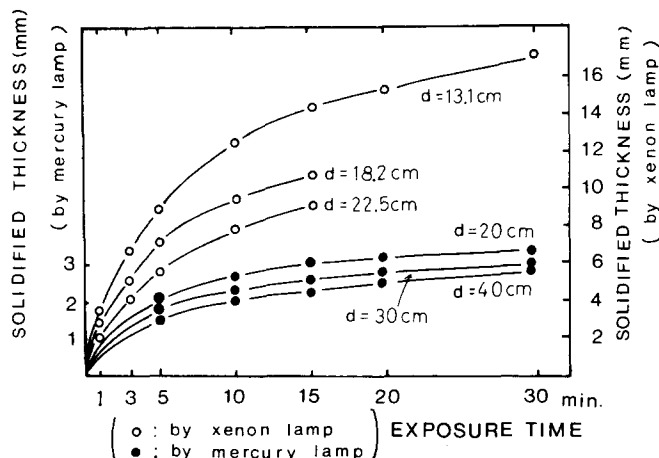

FIG. 2. Plotted curves for the relation between the solidified thickness and the exposure time. The UV intensity is changed by changing the distance between the lamp and the liquid surface. The intensity may not be inversely proportional to the square of the distance.
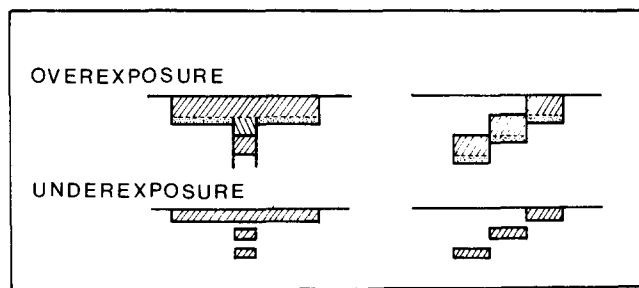

FIG. 3. Schematic sketches of solidification caused by overexposure or underexposure. Dotted area means excess solidification.

distance. Overexposure causes excess solidification as shown in Fig. 3. Conversely in the case of under-exposure adjoining layers do not contact each other as shown in Fig. 3, too. The optimum condition for the exposure intensity and the time to obtain the desired thickness of the solidified layer can be determined from the curves in Fig. 2.

In c, the solidified thickness should be a function of the beam diameter, scanning speed, and the linewidth. When a narrow area whose width is the same as the beam diameter is needed to be solidified, the scanning line is only single. While when an area whose width is bigger than the diameter is needed to be exposed, the scanning lines must be plural. Then if the linewidth is much less than the beam diameter and the solidified thickness at repeatedly exposed area is much bigger than the solidified thickness exposed by single scanning line, it is not possible to obtain a solidified layer of almost uniform thickness. Therefore, the dependence of the maximum thickness of the solidified layer upon the ratio of linewidth to the beam diameter was examined for the condition that the beam diameter and the scanning speed was 2.4 and 2.5 mm/min, respectively. This experimental result is shown in Fig. 4. When the ratio was 1, the solidified lines were separately formed and a continuous layer was not obtained. Figure 4 shows that the optimum line width is three quarters of the beam diameter. In this condition, the solidified thickness is not affected by the overlapped exposure caused by plural scanning lines.

The dependence of the solidified thickness upon the beam diameter and the scanning speed was also ex-amined for the condition that the fiber moved along a single line. This result is summarized in Fig. 5. The
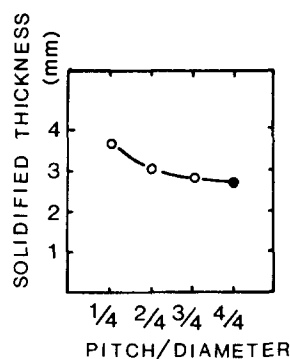

FIG. 4. Plotted curve for the relation between the solidified thickness and the ratio of the line width to the beam diameter. The mark ● shown at 4/4 ratio means that the solidified lines were separately formed and a continuous layer was not obtained.
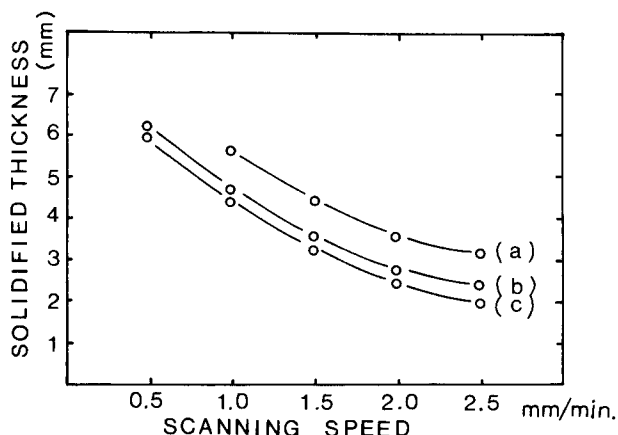
FIG. 5. The relation between the solidified thickness and scanning speed. The beam diameter is (a) 2.0 mm, (b) 2.4 mm, (c) 3.0 mm.

optimum condition for the beam diameter and the scanning speed to obtain the solidified layer of the desired thickness can be determined from the curves in Fig. 5.

The fabrication time of a solid model is determined by the product of the solidifying time of a layer by the number of layers. In a and b the drawing time of masks is also needed. From Fig. 2 or 5, it is proved that the solidified thickness is not proportional to the exposure time, or is not inversely proportional to scanning speed. So the time needed to fabricate a model of the same height is shorter when the layer thickness is thin and the number of the layers is larger than the time needed in the opposite condition.

IV. RESOLUTION AND DIMENSIONAL ACCURACY

The vertical face obtained by the present method is not flat but sawtoothed as shown in Fig. 6. This inclination of the side face of the layers may be caused by the weakening of UV intensity due to scattering by the polymer. It was found in the present experiment that the sawtoothed pattern disappeared when the layer thickness was smaller than 0.5 mm. A flat side face can be obtained by using dispersing UV rays. By c, the flat side face was obtained for the condition that the dispersion angle of half maximum strength of the beam was between 3.0 and 4.0 d.

For determining the resolution of this procedure, a circular column or a circular hole was grown as shown in Fig. 6 (a) or (b). The minimum diameter to be grown depends on the layer thickness to be grown and the inclination of the side face. It was proved that the
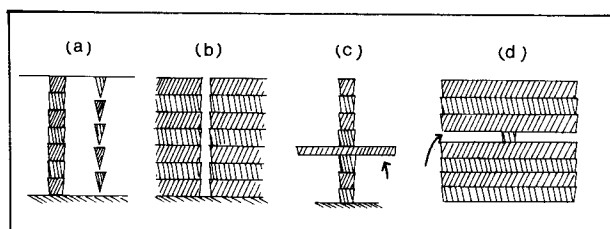

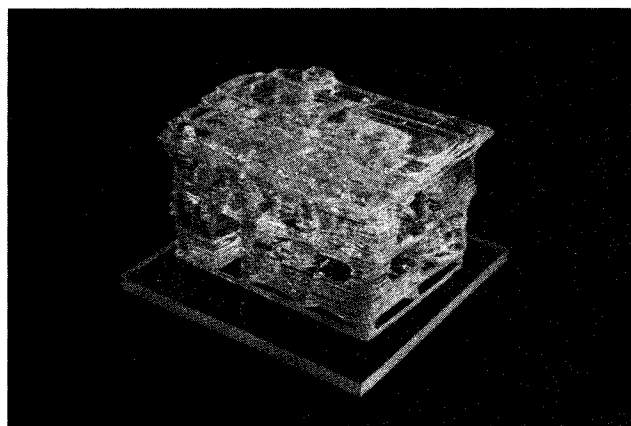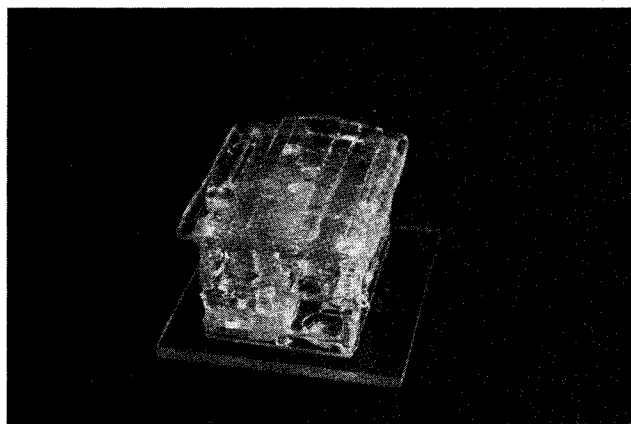FIG. 6. Four factors which affect the resolution of the model.

FIG. 7. A house model fabricated by the equipment a.

minimum dimension of such figures was almost the same as the layer thickness [Fig. 6 (a)]. In the present experiment the layer thickness was decreased to 0.1 mm, and columns of 0.07 mm in diameter and 2.0 mm in height were fabricated. The minimum distance between the columns was 0.1 mm. By the equipment c, an almost vertical side face could be fabricated as mentioned before, so the minimum thickness was depended on the UV beam diameter. A column of 0.2 mm in diameter was fabricated.

When a horizontal thin layer is needed to be solidified [Fig. 6 (c)] or not to be solidified [Fig. 6 (d)], the minimum thickness of the layer is affected by the accuracy of the exposure intensity and time. It was not difficult to obtain a solidified layer with 0.2 mm accuracy in thickness.

The dimensional accuracy of the models is determined not only by the above mentioned factors, but also by one more factor. When the thinness of such column, hole, horizontal layer, or gap is too thin, they are bent in the process of model fabrication, and the shapes of the models are warped. The minimum thickness needed for the model not to be bent is affected by the total shapes of the model, so it is not constant in general.

When the cross-sectional figures change continuously, the layer thickness should be decreased. The thickness could be decreased to 0.1 mm as mentioned before, and it was difficult to make it any thinner than this because of

the viscosity of the liquid. Then large size models should be fabricated to obtain good accuracy.

V. EXAMPLE OF SOLID MODELS

A house model fabricated by the equipment a is illustrated in Fig. 7. Its size is 70 × 50 × 54 mm, the layer thickness is 2.0 mm, and the model consists of 27 layers. This model was fabricated in these conditions; the mercury lamp was used, the distance between the lamp and the liquid surface was kept at 40 cm, and the exposure time for each layer was 10 m. The total fabrication time was 4.5 h. The internal structures such as partitions, furniture, and stairs are also modeled and can be observed from the outside of the model.

A relief map of a mountain region was fabricated by the equipment b and is shown in Fig. 8. The photography in this figure was taken from the bottom of the model. Its size is 76 × 55 × 18 mm. This model is made with 12 layers and the thickness of the layer is 1.5 mm. It is seen from this photography that the interface between adjoining layers is invisible and the model transparent.

A model fabricated by the equipment c is illustrated in Fig. 9. The size of the model is 20 × 20 × 12.5 mm. This model consists of 5 layers of 2.5 mm thick. The fabricating conditions were that the scanning speed, the beam diameter, and the linewidth were 2.5 mm/min, 2.4 mm, and 1.8 mm, respectively. The time needed to scan one layer was 96 minutes, and the total fabrication time was 8 h.

VI. RESULT

It was found by the present experiment that solid models of rather complex shapes can be fabricated by this technique. It is a benefit of this technique that the shapes which have internal structure can be fabricated at once. These shapes cannot be cut even by computer-controlled lathe, since the cutting tool of the machine cannot be inserted in such shapes. However, it is unable to fabricate a shape which is suspended, and is not supported from below. By changing the sequence of
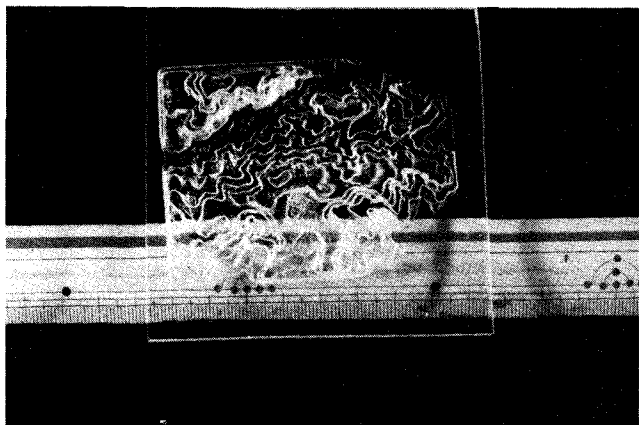

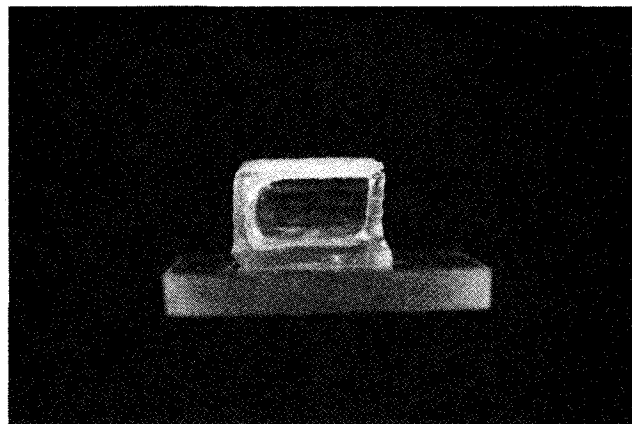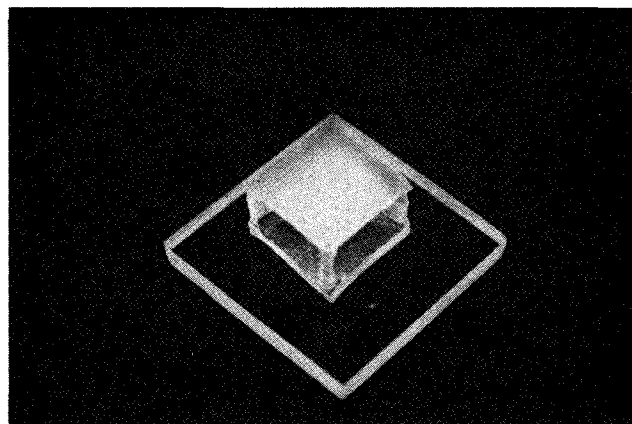FIG. 8. A relief map fabricated by the equipment b.

FIG. 9. An example of solid model fabricated by the equipment c.

solidification of the layers, these problems can be avoided to some degree. But this is a principle limitation of this technique.

For a or b, a number of masks must be prepared. These masks can be drawn by black ink on transparent films by using a computer-controlled XY plotter. Then one can save excessive manual labor. For b, the minimum depth of the liquid polymer needed at the exposure is equal to the layer thickness as shown in Fig. 1 (b). If the polymer is added at the same time when the movable plate is pulled up, the waste of the polymer can be decreased. The fabricating time by b is longer than the time needed by the equipment a, since UV is absorbed in some degree by the basal plate. In c, a model presenting a flat side face can be fabricated. But the fiber speed needed to solidify the polymer is much slower than the motion of XY plotter used to draw the masks. Accordingly by c, a much longer time is needed to fabricate the same model than the time needed by a or b.

The apparatus should be selected by the purpose of the model fabrication and the shapes desired to be modeled.

ACKNOWLEDGMENT