STRATEGY FOR COMPOSITE DEVELOPMENT IN RAPID PROTOTYPING

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ABSTRACT

The polymeric parts built with a stereolithography apparatus (SLA) have good dimensional accuracy, but they cannot be used as functional prototypes because of their low mechanical properties. This paper describes the concept of fabricating fiber composites by 3–D photolithography. In this process, the strength and stiffness of parts are improved over stereolithography by adding fiber reinforcement to the resin. An automated desktop photolithography unit (ADPU) was designed and built in–house, to add continuous E–glass or quartz fibers in situ to the photoresin. The first composite parts made by 3–D photolithography are presented in this paper, the feasibility of curvilinear addition of fibers is demonstrated, and strategies for selective reinforcement are discussed.

INTRODUCTION

The emergence of solid freeform fabrication (SFF) techniques has reduced the processing time of prototypes as compared with those of conventional manufacturing processes. SFF methods create parts by slicing its three–dimensional (3–D) computer aided design (CAD) representation into layers of finite thickness. The part is built layer by layer from the bottom up, by adhering each freshly developed layer to the part, until a three dimensional object is fabricated. Therefore, SFF techniques use selective material addition, whereas conventional methods build parts by material removal. Extensive part dependent tooling and fixtures required in conventional manufacturing make the process time consuming. The absence of tooling and pre/post processing reduces SFF process lead time and allows complicated parts to be built with relative ease.

A true prototype must have required dimensional accuracy and mechanical properties. The dimensional accuracy of an SFF part is achieved by proper selection of slice thickness. However, its mechanical properties are much lower than those developed by conventional manufacturing processes. The mechanical properties of SFF parts are limited by the polymers used in many of these processes [1–3], such as selective laser sintering and fused deposition modeling.

The fabrication of composite prototypes by SFF was first developed at Clemson for photolithography. It was easier to handle liquid thermoset resins and continuous fiber tow reinforcements than powdered thermoplastics (in selective laser sintering [4]) or molten thermoplastics (in fused deposition modeling [3]). The feasibility of integrating fiber reinforcements with stereolithography was demonstrated by fabricating manually test coupons, which were tested for tensile strength, stiffness, and impact strength [6, 7]. We have shown earlier that parts with mechanical properties similar to those of aluminum can be obtained with stereolithography resins by adding 20 vol% of glass or quartz fibers [7]. The next step, automatically adding reinforcement to the resin in a selective and controlled manner, to produce fiber composite prototypes by 3–D photolithography is presented in this paper.

COMPOSITE PROTOTYPE DEVELOPMENT

The preliminary study used two commercial stereolithography resins, Ciba Geigy Cibatool XB5081 (CG) and Desotech Desolite SLR 806 (DS). Both resins were polyacrylates and the main difference between the two resins was the high viscosity of CG (3000 cP at room temperature) as compared to DS (300 cP at room temperature). Most of the newer resins have slightly better mechanical properties, and are notably less brittle, yet none of these resins attain sufficient strength and stiffness for functional applications [8]. The chemistry is the limiting factor, and the easiest way to improve the mechanical properties of these resins by one order of magnitude appears to be with the addition of fibers to the resins.

In a preliminary study, continuous glass and quartz fibers were wound around aluminum plates and impregnated with resin [6]. The mechanical properties of the resins were found to improve by a factor of 10 with approximately 20 vol% of fibers [7]. Discontinuous E–glass and quartz fibers were also used as reinforcements, but the improvement in terms of mechanical properties was found to be smaller [7, 9]. Also, it was not possible to premix the fibers and the resin because of the very high viscosity of the blend. Consequently, short fibers would have to be selectively dispensed in a piecewise continuous fashion, resulting in a smaller improvement. For these reasons the 3–D photolithography for fabrication of composite prototypes have been developed using continuous fibers only. The increase in mechanical properties of the composites depend upon the mechanical properties of the fiber and the resin, volume fraction, fiber orientation, aspect ratio and wetting properties of the fiber in the resin.

We have addressed in previous studies that (a) the influence of the fibers on the photocure of the resin and (b) the wetting of the fibers by the resin are critical to the process. Since the resins have to be exposed to UV light to cure, the choice of the reinforcing fibers is critical. Glass and quartz fiber are completely transparent to UV light at 325 nm, the wavelength used to cure the resin. It was shown that they did not influence the cure kinetics of the resin, and that they could be used as reinforcements [11]. On the other hand, the cure of the resin could not be completed with carbon fibers because of its opacity to UV light. The wetting of the fibers by the resin has also been studied, because if the fibers are not properly wetted, the bond between the fiber and the resin will be poor and result in low mechanical properties. It was found that the main parameter for the wetting process is the viscosity of the resin [12]. If a viscous resin like CG is used the time needed for the resin to impregnate a tow with 800 glass fibers is 2 minutes whereas for a low viscosity resin like DS, it is only 10 seconds. With a long wetting time, the process is slowed down making it unattractive for part production. With low viscosity resins, however, only a few seconds are needed to wet the fibers, and this step is not a problem for 3–D photolithography.

The fabrication of composites by 3–D photolithography is a unique process when compared compared with the traditional techniques used to manufacture composites. Pultrusion, injection molding, resin transfer molding, compression molding, hand lay–up and filament winding all need some kind of tooling, be it a die, mold or a mandrel. Fabricating composites by 3–D photolithography therefore combines the advantages of SFF methods with the improved mechanical properties of composite materials. Another advantage of 3–D photolithography for the fabrication of composite materials is that until recently composites were developed with fibers laid out straight and parallel to each other on any plane, e.g., a 0/90/0 orientation. Although these parts displayed improved mechanical properties, they did not take advantage of the full potential of the fibers. Studies have indicated that for a given volume fraction fibers, laying them in a curvilinear format yields best results [13]. The part will be selectively reinforced with greater percentage of fibers placed in the high stress region. The idea of building parts using fibers laid out in curvilinear format has been hampered by the inability to implement such a design. However, with the development of 3–D photolithography it is now possible to selectively lay down fibers along any curve.

AUTOMATED DESKTOP PHOTOLITHOGRAPHY UNIT

The automated desktop photolithography unit (ADPU) was designed and built in–house to allow *in situ* addition of fibers. A schematic of the current setup of the ADPU is shown in Figure 1. The part is built on an aluminum platform which is immersed in a rectangular vat containing monomeric resin. The platform and the vat are positioned manually to control the thickness of the resin over the plate and the distance of the top layer from the light source. The unique feature of the ADPU is the fiber dispensing device which is used to automatically dispense the continuous fibers into the resin. The light source consists of an optical fiber with a focusing lens connected to a 100W mercury lamp. The light source and the fiber dispensing device are mounted on a circular plate which can traverse in the X–Y direction and rotate about the Z axis. Because the fibers dispensed in the resin have to be wetted before the resin is polymerized, the light source is located at the center of the plate while the fibers are dispensed 1cm off the center. A traverse speed of 1 mm/s allows the fibers to be wetted for 10 s before cure. The translational motion is provided by the X–Y positioning table and the rotation by the rotational drive mounted on the positioning table. The three controllers for positioning table (X, Y) and the rotational drive (theta) are supervised by a computer. The motion of the X and Y axes can be combined to develop any curvilinear path, while the rotation ensures that the fibers are dispensed ahead of the lamp and along the desired path. Each axis is set in motion as soon as a command is received from the supervisory program. With this setup it is possible to dispense fibers in the resin and polymerize the composite in any desired orientation on any layer.

The first step in part building is the creation of data file which consists of the coordinates of all the points that are to be joined sequentially. The location and the order of these points depend on part geometry and loading conditions. This data file along with the translational/rotational speed of each axis form the input to the program to create motion commands for each controller. The output of this program is fed to a supervisory program resident in the computer which distributes the information between the two controllers.

PART BUILDING

Test coupons were built to compare the tensile strength of parts with and without fibers. The samples were 100 mm x 10 mm x 1.5 mm, and were reinforced by 20 fiber tows placed along its length. The concept of curvilinear fiber layout was demonstrated by building a circular ring with one, two, and three concentric passes of fiber, 24, 27, and 30 mm in diameter, respectively. The data file for each circular motion was created by approximating a circle into 36 equal sectors of 10° each joined together. A plate of 100 mm by 40 mm with a centrally placed hole of dia 20 mm was built from pure resin. On top of this plate three concentric rings of DS/quartz composites were built. The desired paths for the fiber dispenser and the lamp are shown in Figure 2 for all these parts.

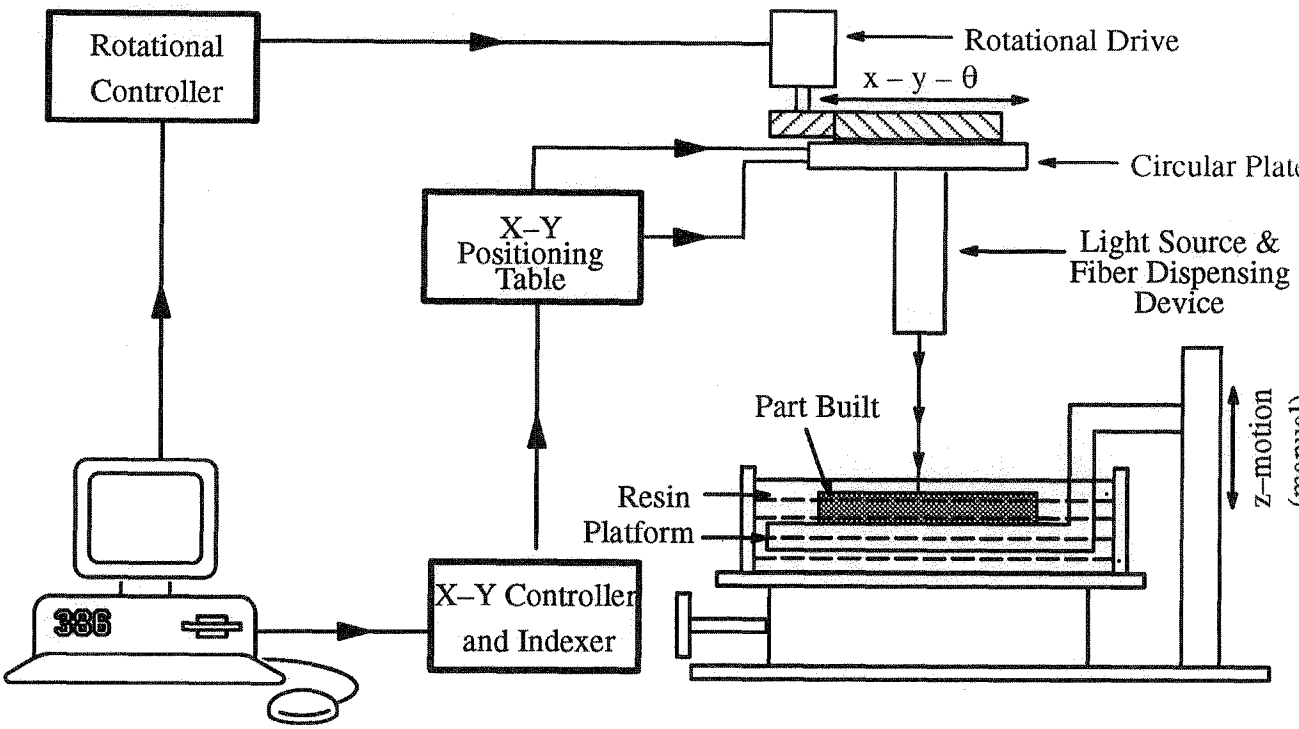

Figure 1. Automated Desktop Photolithography Unit (ADPU)

RESULTS AND DISCUSSION

A photo of a pure DS sample and of a DS/quartz composite is shown in Figure 3. The pure DS resin samples (100 mm x 10 mm x 1.5 mm) built in the ADPU were found to have a tensile strength of 22 $\pm$ 2 MPa. The next batch of samples was a one layer DS/quartz composites with a volume fraction of 5 %. The tensile strength of these samples was 42 $\pm$ 5 MPa. This strength is much lower than the 300 MPa obtained in the preliminary study for samples processed manually with 20 vol% of fibers, and it shows not only a nearly 100% improvement in tensile strength but also the need for incorporating higher volume fraction of fibers. The volume fraction of fibers can be increased either by adding more fibers or by limiting the thickness of the resin. The tensile strength of these samples was measured by dividing the load at break by an average width and thickness of the sample. As shown in Figure 3, because the surface of the composite is not as smooth as that of the pure resin sample, the average thickness is only a rough estimate and the strength of these

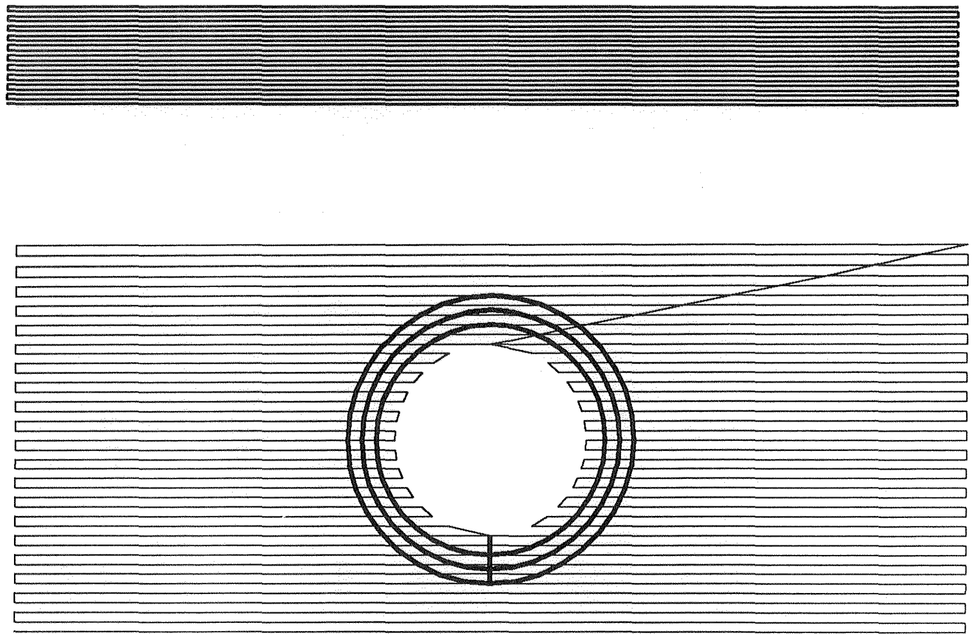

Figure 2. Path of the lamp and the fibers generated by computer simulation for
(a) composite tensile test coupon
(b) ring with three concentric passes of fiber (thick lines) over a layer of plate with hole in the center

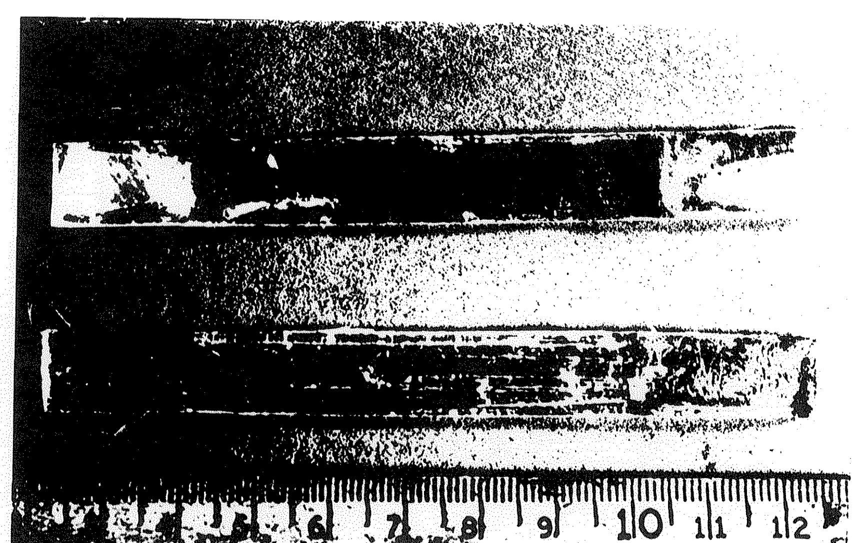

Figure 3. Tensile test coupons of pure DS resin (top) and DS/ Quartz composite (bottom) made in ADPU

composites might actually be higher than the 42 MPa reported here. To get a better estimate of the cross sectional area, an image analysis technique will be used to measure the cross–section of the samples. The surface of the composites samples can be greatly improved if layers of pure resin are added at the bottom and on top of the composite. Samples with one layer of DS/quartz composite between 2 layers of pure DS resin were built, but the volume fraction of fibers was limited to 1%. The tensile strength of these samples was therefore similar to pure resin.

The rings with one, two, and three passes of fibers are shown in Figure 4. These rings demonstrate that it is possible to add fibers along a curvilinear path with good accuracy and repeatability. The 'beads' on the rings are due to the pauses that were imposed between each translation and rotation. As shown in Figure 5, they are also present at both ends of the plate made of resin. A ring with three passes was built on this plate with a hole. This is the first step towards the reinforcement of a plate with a hole. In future, fibers will be dispensed along the stress contours, and the mechanical properties of this part with and without fibers will be compared.

In this study the concept of reinforcement is applied to parts built by photopolymerization of resins used in the SLA. Like stereolithography, other SFF techniques also build parts layer by layer. However, Cubital's solider cures the resin in bulk through a mask and Helysis's laminated object manufacturing cuts the paper in the required shape. Since the layers are not prepared by hatching, *in situ* fiber reinforcement can be difficult for these processes. Nevertheless, it is feasible in concept to fabricate reinforced composites with other freeform fabrication processes such as DTM's selective laser sintering and Stratasys's fused deposition modeling, which prepare layers in a process similar to stereolithography. In selective laser sintering, the thermoplastic powders used would have to be melted by the laser to impregnate the fibers, a process that is theoretically feasible, but might be difficult to implement experimentally. A better method might be to use fiber tows that are precoated with thermoplastics, although these materials might be too stiff to bend at sharp corners. The process might be more readily suited for fused deposition modeling, where a wire of thermoplastic is fused and deposited through a tip.

CONCLUDING REMARKS

A new process to fabricate composite prototypes by 3–D photolithography is presented in this paper. This method is unique because it can process composite parts with improved mechanical properties without the need for tooling. Also the fibers can be added selectively and in a curvilinear path. A new automated desktop photolithography unit (ADPU) was used to automatically build fiber reinforced parts by 3–D photolithography. At the present time, the fiber content added to the resin was limited to 5 vol%, and the improvement in the mechanical properties was limited; future work will attempt to increase the fiber volume fraction. Parts with fiber dispensed in a curvilinear format were fabricated to prove the feasibility of the concept. However the issues pertaining to identification of optimum curvilinear fiber layout still need to be addressed.

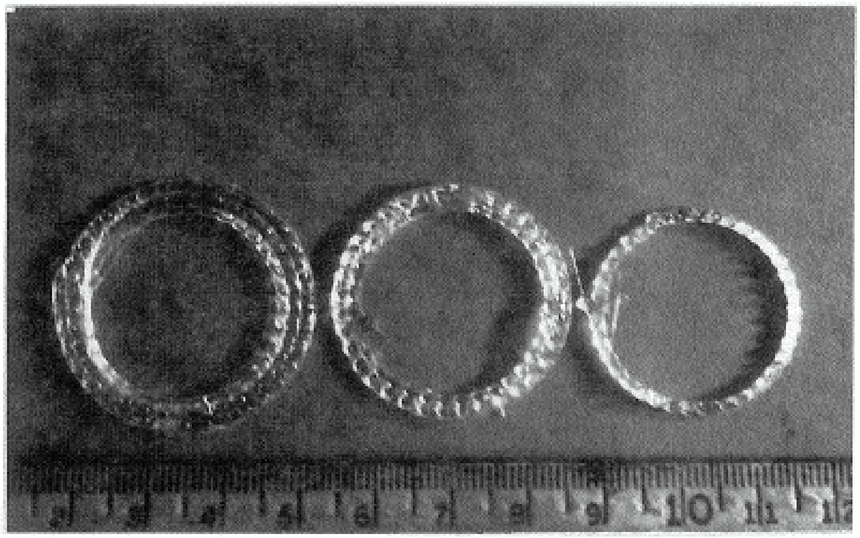

Figure 4. DS/ Quartz composite rings fabricated on the ADPU. From right to left fibers were laid down in:
(a) one circle of 24 mm dia.
(b) two concentric circles of 24 and 27 mm dia.
(c) three concentric circles of 24, 27 and 30 mm dia.

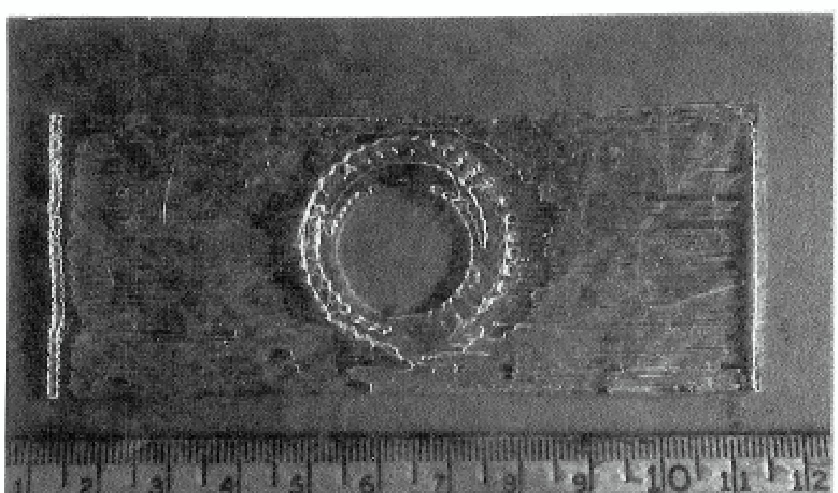

Figure 5. DS/ Quartz composite ring made of three concentric circles over a plate of pure resin with a hole made in ADPU

REFERENCES

1. Deitz, D., "Stereolithography Automates Prototyping," Mechanical Engineering, Feb 1990, pp.34–9 (1990).

2. Feygin, M., "LOM System goes into Production," Proc. of Second International Conference on Rapid Prototyping, pp. 351–7 (1991).

3. Crump, S., "The Extrusion Process of Fused Deposition Modeling," Proc. of Third International Conference on Rapid Prototyping, pp. 91–102 (1992).

4. Barlow, J. W., "Metallic and Ceramic Structures from Selective Laser Sintering of Composite Powders," Proc. of Third International Conference on Rapid Prototyping, pp. 73–6 (1992).

5. Sachs, E., M. Cima, and J. Cornie, "3–D Printing: Ceramic Shells and Cores for Casting and Other Applications," Proc. of Second International Conference on Rapid Prototyping, pp. 39–54 (1991).

6. Renault, T., A. A. Ogale, R. L. Dooley, A. Bagchi, and C. C. Jara–Almonte, "Photolithography for Composites Manufacturing: Continuous Glass Fiber/Polyacrylate Composites," SAMPE Quarterly, 22 (2), pp. 19–25 (1991).

7. Renault, T. and A. A. Ogale, "3–D Photolithography: Mechanical Properties of Glass and Quartz Fiber Composites, " Proceedings ANTEC 92, Detroit, Michigan, May 3–7, pp.745–7(1992).

8. Chartoff, R. P., P. T. Weissman, and S. M. Linden,"Advances in Polymer Technology for Stereolithography," Proc. of Second International Conference on Rapid Prototyping, pp. 55–68 (1991).

9. Ogale, A. A., T. Renault, A. Bagchi, C. C. Jara–Almonte and R. L. Dooley, "3–D Photolithography for Composites Development: Discontinuous Reinforcements, " SAMPE Quarterly, 23 (1), pp. 28–38 (1991).

10. Charan, R., A. Bagchi, T. Renault, and A.A. Ogale, "Fabrication of Composite Prototypes by 3–D Photolithography," Proc. of Fourth International Conference on Rapid Prototyping, pp. 15–23 (1993).

11. Renault, T., A. A. Ogale, and M. J. Drews, "Influence of Reinforcements on Photocuring: Photo Dynamic Mechanical Analysis," Proceedings ANTEC 93, New Orleans, May 9–13, pp.1252–4 (1993).

12. Ogale, A. A., T. Renault, A. Bagchi, C. C. Jara–Almonte and R. L. Dooley, "Processing of Composites by 3–D Photolithography," Proceedings of International Conference on Transport Phenomena in Processing, S. Guceri, Ed., Waikiki, Hawaii, March 22–26, pp.1342–52 (1992).

13. Hyer, M.W. and R.F. Charette, "Use of Curvilinear Fiber Format in Composite Structure Design," AIAA Journal, 29(6), pp. 1011–15 (1991).