MULTI-LAYERED COMPOSITES USING PHOTOLITHOGRAPHY

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Abstract

The mechanical properties of the parts made using solid freeform fabrication technologies are limited by their resins used. Previous research has shown that the mechanical properties of these parts can be enhanced substantially by using glass and fiber reinforcements. However, all of the published data is for single layered composites, which does not demonstrate its feasibility to manufacture multilayered real objects.

In this paper experiments carried out to build multi-layered parts with glass fiber tow as reinforcement in a matrix of photopolymeric resin are described. These specimens are then tested in uniaxial tension and three point bending to determine their improvement in mechanical properties. The experimental data shows that the tensile strength and tensile modulus increased linearly with the volume fraction of the fiber in the composite, thus demonstrating that the trends observed in single layer composites can be also seen in multi-layered composites.

Introduction

In the past 10 years, solid freeform fabrication (SFF) technologies have allowed the design engineer to produce a working model of a part without the need for tooling, advance planning, and often within hours or days, instead of months. As improvements or revisions are necessary, the part can be redesigned easily before it is prototyped again, and the process can be repeated as many times over a period of days to arrive at the final design.

Many of the SFF technologies utilize polymers to make their parts, either using a certain wavelength of radiation (as in photolithography) or applying localized heat of fusion (as in selective laser sintering). One of the drawbacks of these processes is the compromise in mechanical properties due to those of the pure polymers. These parts are of lower strength than those made using commercially viable processes. One way to strengthen these parts is to re-enforce the parts with high modulus glass, quartz or carbon fibers.

In work done at Clemson University over the past five years [1-6], the process of photolithography has been expanded as a rapid prototyping technology by producing composite parts using glass and quartz fiber as reinforcement. The prototype is generated by reinforcing by selectively laying fibers *in situ* to improve the mechanical properties. These studies have shown that the strength of liquid resin based polymer parts can be increased by up to an order of magnitude. with a very small percent of addition of glass or quartz fibers. Because no real component is made up of a single layer, it is necessary to determine the effect of multiple layers in the build process, and to use more than uniaxial testing to determine the mechanical properties of the parts.

Objective

The objective of this experiment was to build and test multi-layered parts to see if the single layer technology could be applied to manufacture multi-layer, real composite parts. The tensile strength, tensile modulus and modulus of toughness would be studied to measure the enhancement of mechanical properties.

Experimental Work

Specimen Preparation

The multi-layered parts for this research were made from DuPont Somos 3100 photopolymer, and continuous quartz fiber tows (tensile strength 1600 MPa), containing 120 fibers (tensile strength of fibers was 2000 MPa) each 9 microns in diameter. Quartz fibers, with a nearly 100% transmissibility of the ultra-violet (UV) light, allow the UV light to pass through and polymerize even below the fiber tow, thus creating a strong bonding between the resin matrix and the reinforcement.

The specimens were made in a special research test bed developed for producing composite components — the Advanced Desktop Photolithography Unit (ADPU). The ADPU is an emulation of the commercially available stereolithography apparatus, and photopolymerizes the resin and produces parts layer by layer. The ADPU has a two-axis positioning table to move a light source in a pattern just above the liquid resin. The light source is a mercury vapor arc lamp with a fiber optic light pipe to provide the UV radiation (at 325 nanometers) at the desired location. A special fiber dispensing device [7, 8] with three degrees of freedom, two translational and one rotational, lays the fiber bundle onto the resin just ahead of the light. A computer program is used to control the positions of the head of the fiber dispensing device and the light source so that the reinforcement can be provided at the right locations in the specimen. The pencil of light passes over the same regions which were reinforced with the continuous fibers and polymerizes the resin along with the fiber tow. Details of the ADPU can be found elsewhere [6 - 8].

Three layered, rectangular 12.7 mm X 102 mm test specimens were built on the ADPU in accordance with ASTM standards D3039-76 [9]. To grip the ends for carrying out tensile testing, tabs were made of the pure resin and then polymerized onto each end of the finished composite specimen made on the ADPU. A sketch of the specimen is shown in Figure 1.

A program was written in C to generate the path plan for the fiber dispensing device and the light source. This path was provided as input to a machine controller code for the translational and rotational motions of the ADPU necessary to generate the composite specimen. The path of the light source and the fiber dispensing device generated by the program is shown in Figure 2.

A total of 17 specimens passed the initial quality control check for proper construction and tolerances. 13 of these specimens contained fiber strands, spaced 1 mm apart, oriented lengthwise (at 0 degree to the test direction). The other 4 specimens were also three-layered but made of pure resin on the ADPU. The polymerized specimens were found to be wider than the 12.7 mm desired, and were therefore sanded smooth until they were parallel and 12.7 mm wide.

Testing Procedure

Two tests were carried out on the 17 specimens: (i) tensile test; and (ii) three point bend test.

The *tensile test* was carried out on a bench top tensile testing machine, with only the upper grips moving at a constant rate of 2.5 mm/min. The effective length of the specimens was 76.2 mm. The temperature was kept constant at 23.3 degree C, and the relative humidity was 14%. The *bend test* was done in a 3-point bend fixture with a beam length of 57.2 mm, in accordance with ASTM standard D790M-86 [10] for specimens in this range of length to thickness ratio, as shown in Figure 3. The velocity of the loading point was set to 7.6 mm/min, and the maximum displacement was 6.27 mm, when the stress strain relationship became non-linear.

Results

Tensile Test

The tensile specimens displayed a brittle linear-elastic stress-strain behavior for the full range of volume fractions. The pure resin specimens, however, displayed some plastic deformation near the failure point, as shown in Figure 4. The *ultimate tensile strength* (UTS) is plotted against volume fraction in Figure 5. The UTS can be expressed in terms of the volume fraction (VF) by the following relationship: UTS (psi) = 130,041(VF) + 5,047.

The standard error of this least square curve fit is 9.9%, which is quite acceptable because of the inherent variabilities in the specimens in dimensions, surface irregularities, void formation, and volume fraction.

The *tensile modulus* was calculated from the plots of tensile tests. For composite specimens, the slope of the linear portion of the curve in Figure 4 was used to avoid the abrupt slippage shown in the figure. The slippage observed at about 60 lbs. for each composite specimen, upon careful analysis, was found to occur at the grips of the testing machine. For pure resin parts, the slope of the linear portion of the curve in Figure 4 was used, excluding the slippage at the lower end and the non-linear behavior prior to fracture at the end of the test. the tensile modulus (E) can be expressed as a function of volume fraction (Figure 6) as: E (psi) = 2,302,133(VF) + 83,664.

The standard error in this fit was 10%, and was attributed to problems with the building of the composite specimens, similar to that for the tensile strength.

Bend Test

The data from the 3 point bend tests was used to calculate the *bending modulus*. The specimens exhibited linear-elastic behavior in bending as in the tensile tests. The modulii of bending for the specimens calculated using Castigliano's method are shown in Figure 7. The bending modulus results are hard to explain because there appears to be no correlation between volume fraction and modulus. This is attributed to variations in specimen dimensions and compositions. The pure resin specimens have a homogeneous structure, so the results are fairly consistent (Figure 7). However the composite specimens showed large differences in bending modulus even in the same range of volume fraction. Since all of the specimens have three layers of fibers, and yet all have different thicknesses, the variability was attributed to the variation in the manufacturing procedure, and the inability to control dimensions in multi-layer parts.

Another possible explanation could be the location of the fibers within the specimens, which would change the location of the neutral axis, thereby the exact bending characteristics in the specimens. Because the modulus of the fibers is much greater than that of the polymer, their location as in Figure 8a or 8b would influence the behavior of the bending properties. A specimen with configuration (a) in Figure 8 will have a higher modulus in bending than that with (b) because more fibers are located close to the surface, which is the location of the maximum strain, although the two specimens may have the same volume fraction. A similar behavior is not expected in tensile test because the location of the fibers in the matrix is not as critical because the strain is constant throughout the cross section.

It is conjectured that the consistency of the bending modulus data for composite specimens would increase with the number of layers. As the number of layers increased, the specimen would become more homogeneous, and local variations in layer thickness and exact placement of the fibers would not play a dominant role. This hypothesis needs to be investigated in future when the ADPU is improved to produce multi-layered components with repeatable dimensions.

Concluding Remarks

The results from this preliminary study have shown that the mechanical properties continue to improve with the addition of fibers. In tension, the ultimate tensile strength, and modulus increase linearly as the mass fraction increases. The results for bending are not very conclusive at this time, but they do show an increase in the bending modulus with the addition of the fibers. The location of the fibers in bending may be more important than in tension, and will need to be considered in composite specimen design in photolithography based processes.

The ability to produce multi-layered composite parts in this research project demonstrated the possibility of adding fibers *in situ* in a photolithography based machine, such as in stereolithography, stereophotolithography and other similar processes [11]. An important problem to be addressed in the design of fiber dispensation and composite layer fabrication is the control of geometric dimensions, especially layer thickness. Unless the dimensions can be held to tight tolerance for the composite specimens, it will be quite difficult to make the process commercially viable.

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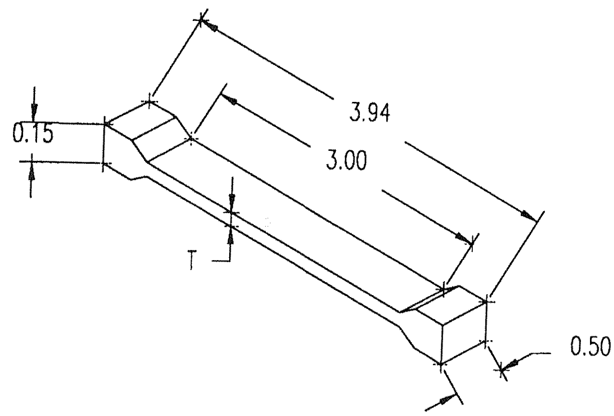

Figure 1. Test specimens used in this study — for both pure resin and composite specimens.

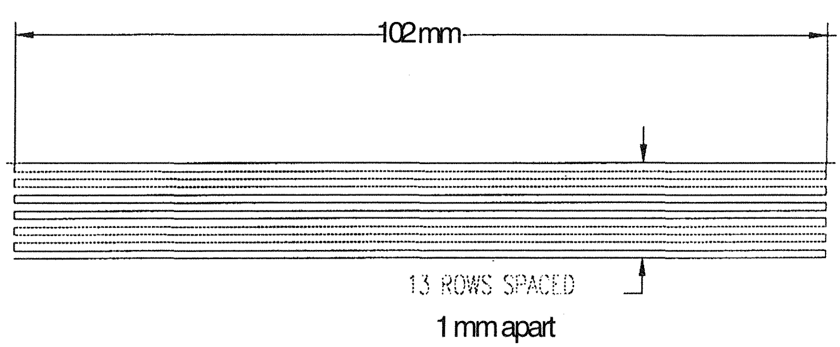

Figure 2. Path of fiber and UV light beam needed to produce a composite (or a pure resin) layer, as generated by the process planning software.

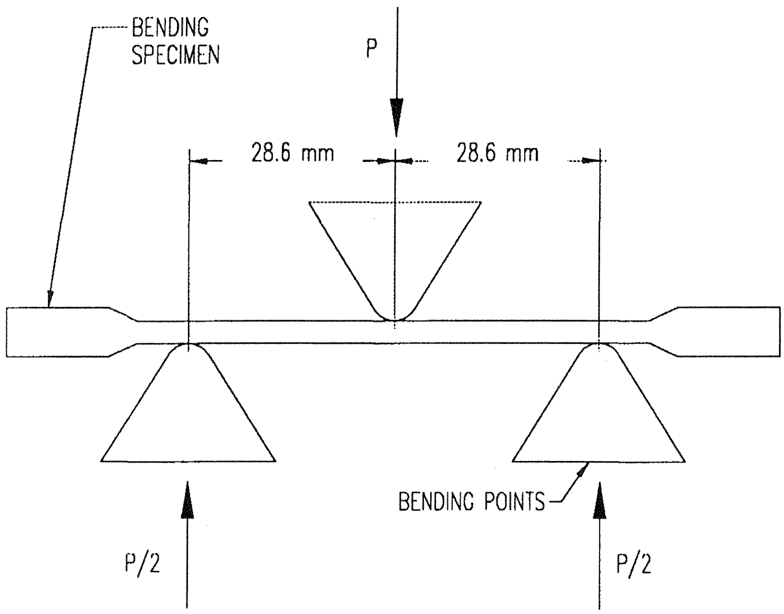

Figure 3. Three point bend test setup, showing the dimensions.

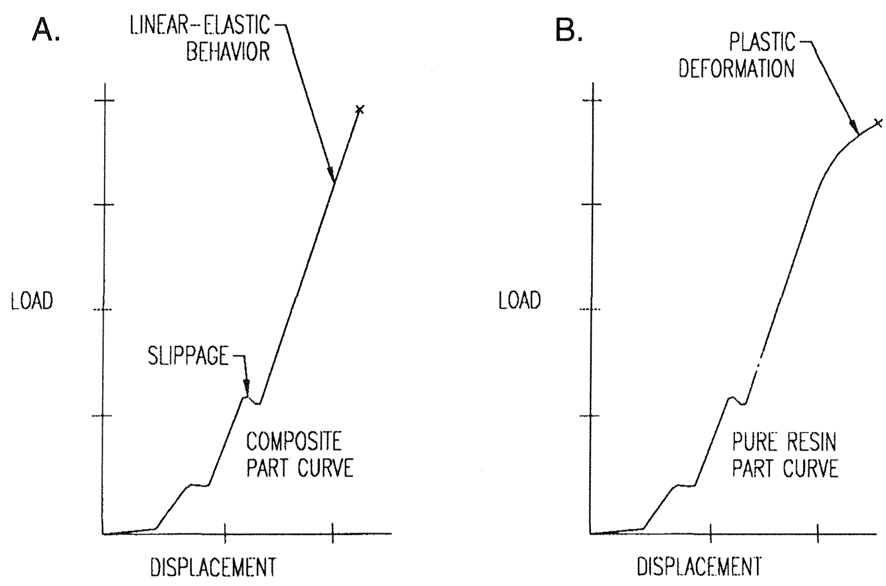

Figure 4. Tensile test results from the experiments; (a) composite specimens, and (b) pure resin specimens. Reinforcement: quartz fiber tows, and resin: Somos 3100.

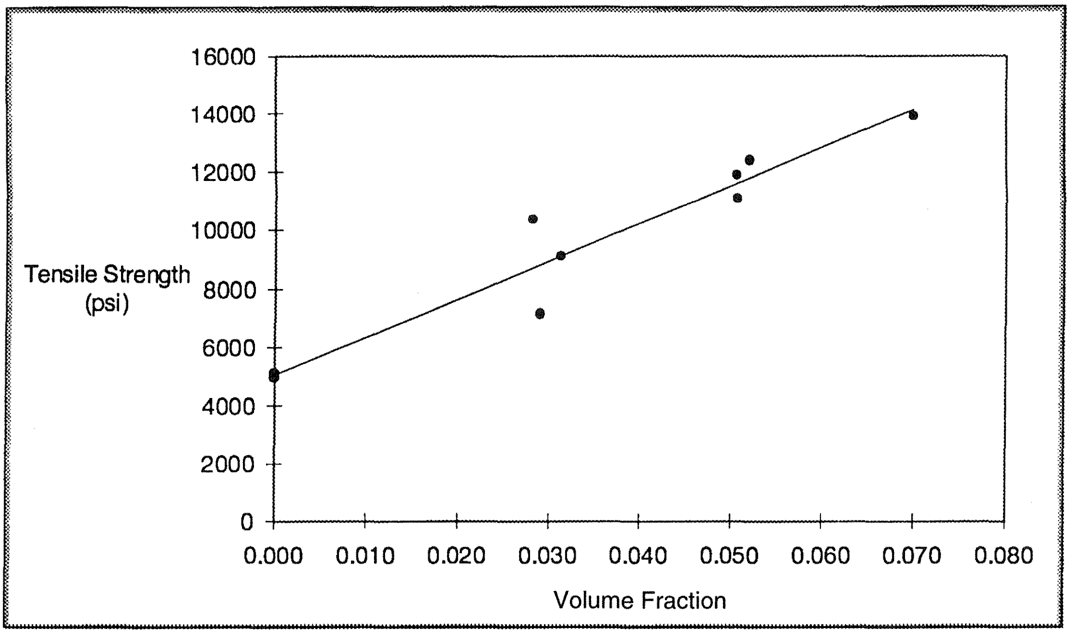

Figure 5. Ultimate tensile strength variation with respect to volume fraction of fiber in the composite specimens. Reinforcement: quartz fiber tows, and resin: Somos 3100.

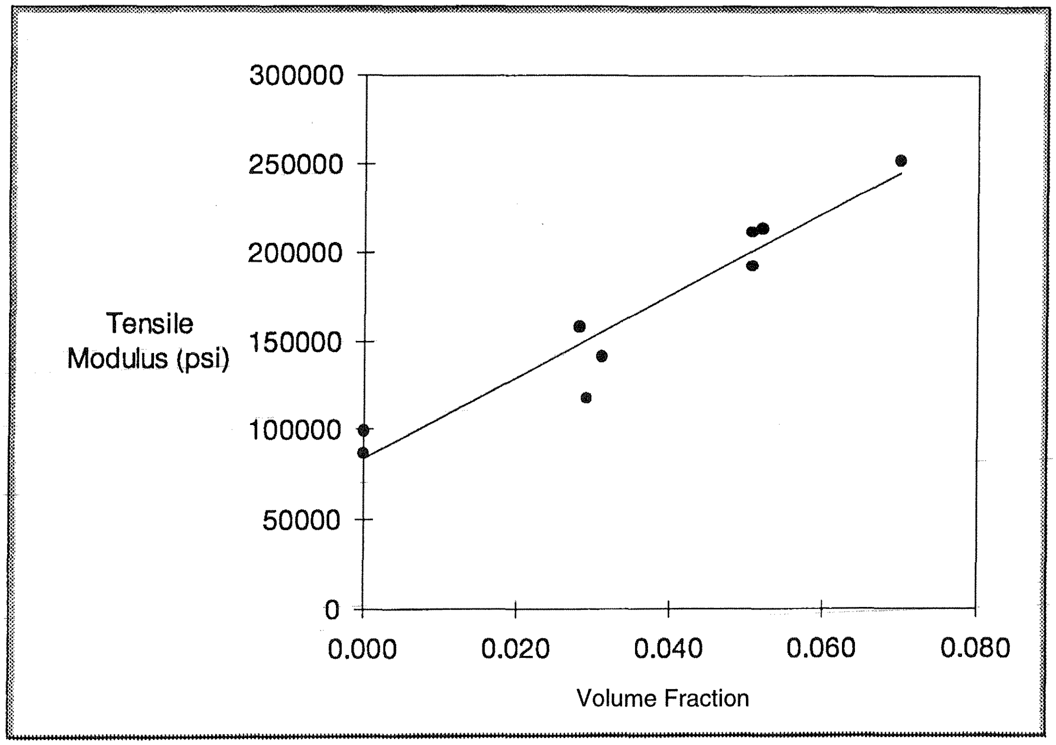

Figure 6. Tensile modulus variation with respect to volume fraction of fiber in the composite specimens. Reinforcement: quartz fiber tows, and resin: Somos 3100.

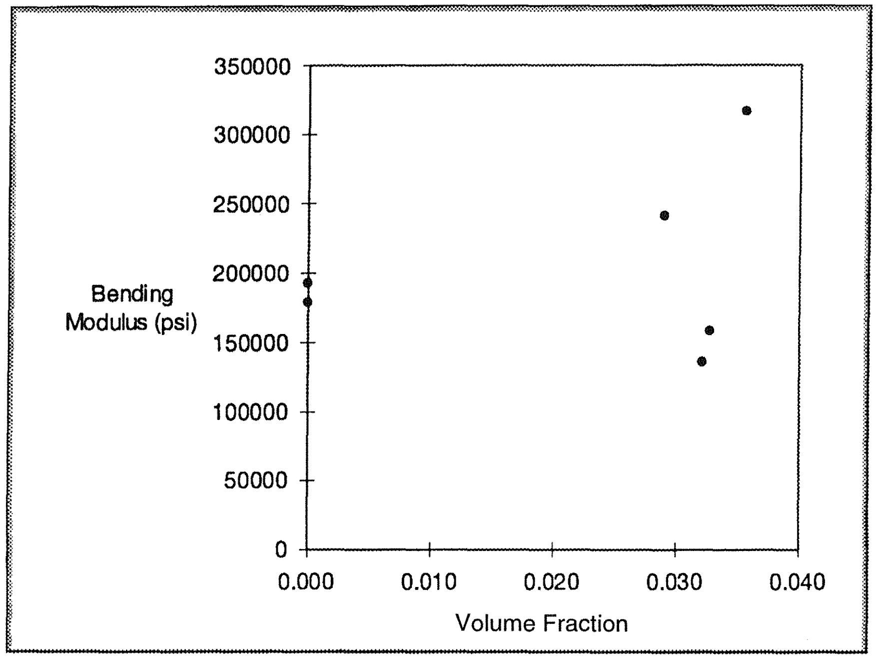

Figure 7. Bending modulus variation with respect to volume fraction of fiber in the composite specimens. Reinforcement: quartz fiber tows, and resin: Somos 3100.

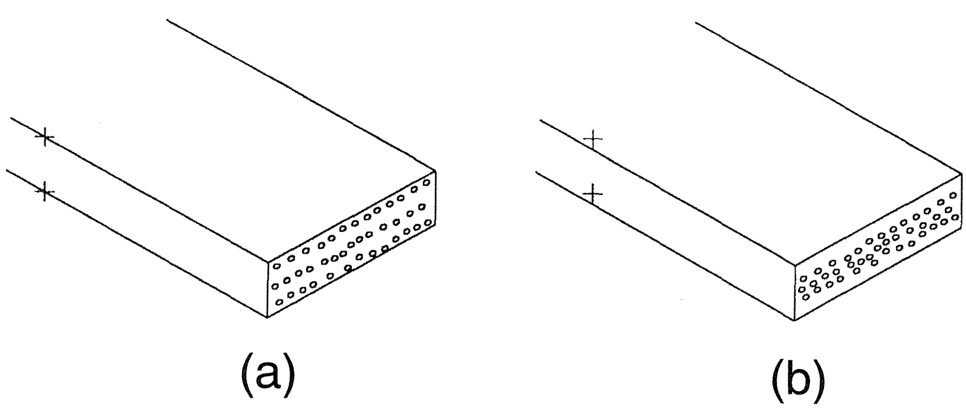

Figure 8. Possibilities of different fiber layouts inside the multilayer composites.