Processing of Carbon Fiber Reinforced Composites by Three Dimensional Photolithography

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ABSTRACT

The reinforcement of photoresins with continuous carbon fibers is discussed in this paper. The processing was conducted in an automated desktop photolithography unit (ADPU) developed and built in-house. Continuous fibers were added *in situ* to the photoresin to obtain composite samples containing over 20 vol% of the fibers. The tensile strength of these composites improved by at least a factor of 2 as compared to that of the pure photoresins. It is also noted that the photoresin could be partially cured to develop sufficient green strength in the composite samples even though the fibers are opaque to ultraviolet radiation. These results indicate the potential of this technique to produce functional composite components in conjunction with a 3-D photolithography apparatus.

INTRODUCTION

Conventional photolithography is limited to coating applications because the depth of cure of photoresins is limited to a maximum of a few millimeters. However, this limitation has been overcome in, Stereolithography, a free form fabrication technique (1-3). Unfortunately, at the present time, only pure photopolymers can be used in the commercial stereolithography units. The resulting parts do not possess the properties that are needed for functional applications.

In view of the shortcomings encountered in pure resins, improvement of polymer properties was attempted by adding a reinforcing phase. Preliminary research at Clemson University has demonstrated the feasibility of processing of composite materials by 3-dimensional photolithography (4, 5). Our study showed that composite samples prepared manually with 20 vol% glass and quartz fibers had mechanical properties typically an order of magnitude better than those of pure resins. In a recent study (6), the properties of resins reinforced with continuous glass fibers in an automated desktop photolithography unit (ADPU) are discussed.

The objective of this study was to investigate if carbon fibers could be used as the reinforcing phase in conjunction with the automated 3-D photolithography technique. Description and evaluation of the test samples prepared by the above technique are presented, and the mechanical properties of these parts are compared with those of the pure resin.

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EXPERIMENTAL

The photoresin used in this research was Du Pont Somos 3100 (designated "S31"). The resin has a viscosity of less than 1000 cP. The carbon fibers were Thornel T300 (Amoco Performance Products). A 3K tow was split into half and used for preparing samples.

The automated desktop photolithography unit (ADPU) was designed and built in-house to allow *in situ* addition of fibers (7). The part is built on a metal platform that is positioned manually to control the thickness of the resin. The various components of the ADPU are: a fiber dispensing device (FDD), a UV-light source, a silica fiber optic cable, and a focusing probe. The light source and the FDD are mounted on a circular plate which can traverse in the X-Y direction and rotate about the Z- axis; all of the motions are computer controlled.

Pure resin as well as continuous fiber composite samples were prepared in the ADPU. The thickness of the liquid resin layer was about 0.7 mm. The fiber tows were primarily dispensed at a spacing of 1mm, although other tow-spacing intervals can also be realized in the ADPU. The pure resin samples were cured at a speed of 15 cm/min, whereas composites were processed at a velocity of 36 cm/min. The tensile samples were nominally 10 cm long, 1 cm wide, and 0.1 cm thick.

The tensile properties of the samples were evaluated in an ATS Universal Tester 900 at a crosshead speed of 0.1 in/min. Two sets of samples were prepared and tested; each set consisted of 5 samples. Set A was postcured in a postcuring apparatus (PCA) for one hour on each side, whereas Set B was postcured for 2 hours on each side. The width and thickness of specimens were measured to the nearest 0.025 mm at three to five points along their length. However, the surface of most of the composite samples was irregular. Therefore, the determination of the composite strength is subject to an uncertainty of about $\pm$ 20%.

RESULTS AND DISCUSSION

A photograph of the entire set of samples is displayed in Figure 1, whereas a close-up of two samples is displayed in Figure 2. The edges of the samples display irregularity and the effect is more pronounced at the end of the sample. A part of this problem could be attributed to the somewhat irregular 1.5K carbon fiber tow which was obtained manually by splitting a 3 K tow. The interior of the sample appears to be free of gross defects. Uneven surface, however, is evident in all of the samples. Such roughness was a consequence of the rather high volume fraction ($\approx$ 20 vol%) of carbon fibers that were dispensed.

The tensile strength of carbon fiber reinforced S31 resin composites are reported in Table I for both of the sets. Initially it was assumed that because carbon fibers are opaque to UV radiation, they would inhibit the curing of the photoresin. Therefore, samples cured for a longer time would display a higher strength. However, the experimental results were rather surprising in that the samples postcured for a total of 2 hours (Set A) had a higher strength (83.5 MPa) than those cured for 4 hours (42.4 $\pm$ 13.1 MPa). It is surmised that the additional postcuring rendered the samples very brittle and led to an increase in microcracks and defects within the postcured samples. Further, visual inspection of the tested samples revealed that most of the matrix resin had "solidified" in both sets, although its extent of cure remains undetermined. The reasons for these anomalous results are being probed further.

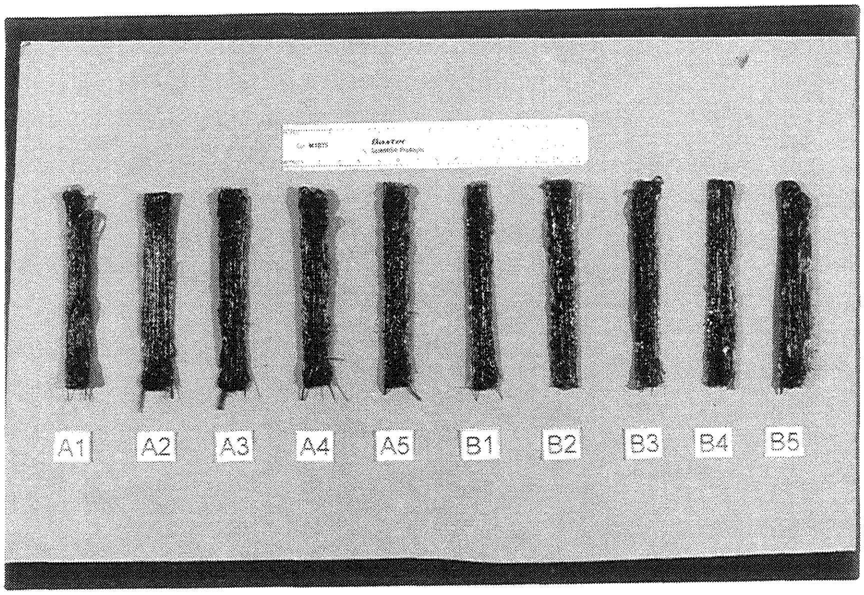

Figure 1. A photograph of the carbon fiber reinforced S31 photoresin samples produced in the ADPU.

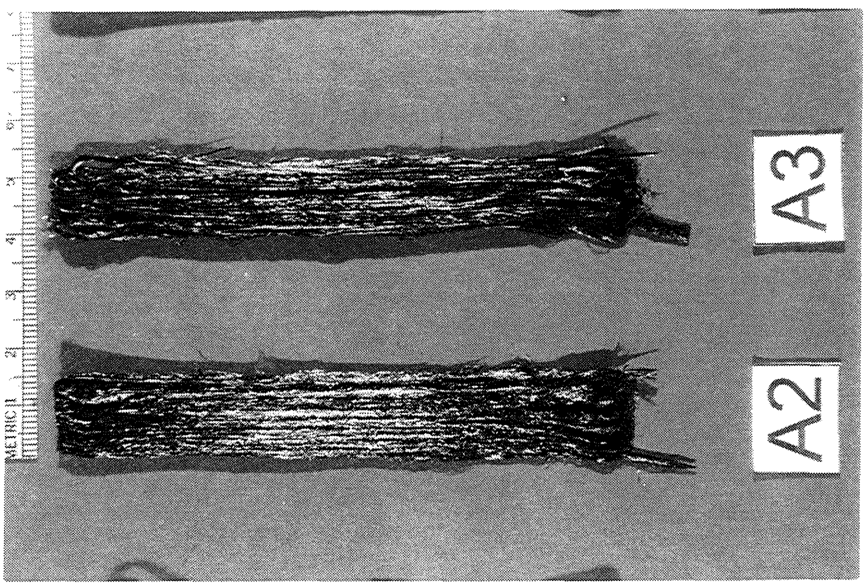

Figure 2. A close-up view of two samples, A2 and A3, from the set that was postcured for a total of 2 hours.

Table I. Tensile strength of pure resin and composite samples prepared in the automated desktop photolithography unit (ADPU). Set A was postcured for a total of 2 hours, whereas Set B was postcured for a total of 4 hours.

Material	Fiber Volume %	Tensile Strength (MPa)
Pure S31	0	34.0
Carbon fibers/A1	30.5	52.5
A2	25.9	122.6
A3	25.7	86.5
A4	26.6	92.3
A5	25.8	63.4
B1	26.4	34.4
B2	24.8	27.4
B3	24.9	41.5
B4	26.3	61.7
B5	23.9	47.0

The tensile strength of unidirectional composites has been predicted with the simple rule-of-mixtures (8,9),

$$\sigma_c^* = \sigma_f^* v_f + \sigma_m' (1-v_f) \qquad (1)$$

where σ_c^* is the strength of the composite lamina, σ_f^* is the strength of the fibers, σ_m' is the stress in the matrix at the fiber failure strain, and v_f is the fiber volume fraction. For a value of 3.0 GPa for the tensile strength of the carbon fiber tows, the strength of the fiber reinforced resins was predicted to be 835 MPa, as described in Table II. It is evident that the strength of the carbon fiber reinforced composites falls very short of the predicted value, and indicates the potential for improvement of the existing process for handling carbon fibers. Additional work is in progress to investigate the behavior of such carbon fiber composites.

Table II. A summary of the tensile strength of pure resin and composite samples prepared in the automated desktop photolithography unit (ADPU).

	v_f (%)	Tensile Strength (MPa)	Predicted Strength (MPa)
Pure S31	0	34.0 ± 2.1	--
S31/carbon (Set A)	26.9± 2.0	83.5 ± 24.4	835

CONCLUDING REMARKS

This paper summarized the development of a three dimensional composite photolithography process to produce carbon fiber reinforced resins. An experimental apparatus, automated desktop photolithography unit (ADPU), was used to produce fiber reinforced samples in near net-shape without the use of molds. For a carbon fiber content ranging up to 30 vol%, the strength of composites displayed a 2-3 fold increase over that of the pure resins. Thus, 3-D composite photolithography combines the advantages of rapid prototyping techniques with the improved mechanical properties of fiber reinforced composites.

ACKNOWLEDGMENT

Financial support through Grant No. DMI-9400213 from the Division of Design, Manufacturing, and Integration, National Science Foundation is gratefully acknowledged.

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