AJChE 2007, Vol. 7, No. 2, 157-164

Degradation Behavior of Carbon Fiber Reinforced Plastic (CFRP) in Microwave Irradiation

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Carbon fiber reinforced plastic (CFRP) composites are being used increasingly not only in strengthening structures of civil infrastructures and aerospace or automotive industries but also in many applications such as in medical fields or chemical plants. The present study relates to resin compositions having beneficial physical and mechanical properties, which may include improved resistance to delamination. This study focused on the different behaviors of CFRP composites when subjected to microwave irradiation. Based on the results of the 3-point bending test and SEM images, the delamination tendencies of breaking the CFRP under microwave were discussed. The results can be summarized as follows: (1) CFRP can be degraded under microwave irradiation; (2) two delamination tendency curves of CFRP by microwave irradiation were observed; (3) only the bending strength values of CFRP decreased with increasing microwave power and residence time; and, (4) the degradation of CFRP by microwave was limited.

Keywords: CFRP, degradation, microwave, *and* 3-point bending test.

INTRODUCTION

CFRP have recently attracted much attention as light materials for use in every industry that requires a high strength-to-weight ratio; that is, specific strength, specific modulus, and high value of rigid and durable material. Recently, CFRP has also been utilized in the (1) aerospace industry; (2) automotive industry, such as for racing cars, motorcycles, and racing bicycles; (3) civil engineering applications on buildings and infrastructure materials (Ogi, Tomoyuki, and Makoto 2004). Today, the high performance of CFRP materials is starting to challenge other ubiquitous engineering materials, such as steel, in everyday applications as diverse as automobile bodies and civil infrastructure. Many studies have been done to give more information on the applications of CFRP medical-grade implants, such as cranial implants and cages for vertebral body replacement.

CFRP plastics have been extensively employed in the medical industry since the 1980s (Gabriele et al. 2004). CFRPs principal advantages are as follows: great strength associated with extreme lightness, radiolucence, and an elasticity close to that of bone (Saringer, Huhmann, and Knosk 2002). The specific weight of steel is 7.87g/cm^3 compared to the specific weight of high-strength carbon fiber-epoxy matrix (unidirectional) at 1.55 g/cm^3 and for high-modulus carbon fiber-epoxy matrix (unidirectional) at 1.63 g/cm^3 (Mallick 2007).

The large energy consumption in curing, the difficulty of the recycling process, and the high cost involved in these processes have inhibited CFRP's widespread usage in general industrial field (Suzuki and Jun 2005). On the other hand, CFRP has caused one of the most difficult problems in the treatment of solid wastes due to its many superior mechanical properties, such as high specific stiffness, high specific strength, and chemical stability.

In general, the treatment methods for CFRP wastes are classified into three categories: thermal processes, recycling processes (chemical and mechanical recycling), and land filling. For CFRP and other kinds of fiber composites, such as glass fiber composites and aramid fiber composites, high-temperature process is the applicable method for treatment (Kyle 2004). In this study, the degradation of CFRP using microwave energy was examined for disassembling this type of waste in the future. The carbon fibers in CFRP act as a very good microwave absorber. Microwaves penetrate into the CFRP plastic and the energy absorbed by the carbon fiber will be converted into heat. The matrix of CFRP composites can be heated by heat conduction (Milestone Microwave Synthesis 2006). CFRP plastic can be easily degraded in microwave heating based on this mechanism. It has been proven in the available literature that no microorganism can survive under high temperature using microwave irradiation (Bisson, McRae, and Shaner 1993; Dinh 2005). Microwave pyrolysis is a useful technology for medical plastic wastes treatment.

This paper focused on the degradation behavior of CFRP that was subjected to microwave irradiation using different microwave powers (400 and 700 W) and a residence time that was varied from 10 seconds to 20 minutes. The morphological stability was observed using SEM. The comparison of the bending strength and elastic modulus of the CFRP samples before and after microwave irradiation were also observed.

EXPERIMENTAL METHODS

Materials and Equipment

The CFRP samples used in this study were 12k cloth-type CFRP supplied by Mitsubishi Rayon Co, Ltd. The size of the samples, 60mm by 12.7mm by 2mm, was decided according to the ASTM D-790 standard for 3-point bending test.

A NEOVE domestic microwave oven series BRSK-20075/6 was used in this study. This microwave has a 100V AC power supply and its specifications are as follows: 2450MHz frequency,

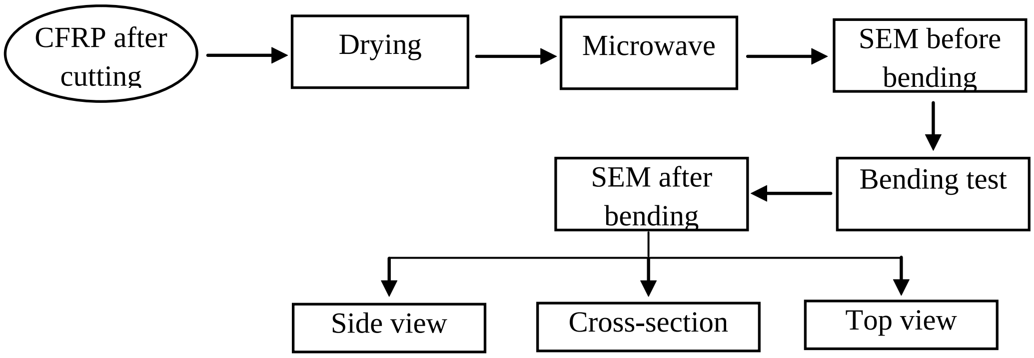

Figure 1. Experimental Flowchart

290mm x 300mm x 194mm cavity dimensions, and 1150W maximum power.

The SEM images of the samples before and after microwave radiation were captured by a JEOL SEM scanning microscope machine model JEM-5310LV. The mechanical properties of the CFRP samples were tested using universal testing machine from Shimadzu corporation, model AGS-1kN-J Autograph. The maximum capacity force of this testing machine is 1kN.

Experimental Procedure

The experimental procedure followed in this study is shown in Figure 1. CFRP samples were cut according to the specified size above and dried in an oven at 50^{o}C until their weight was measured constant for about 72h to make sure that no water exists on the samples before the microwave treatment. The samples were placed in the Teflon holder and positioned at the center of the cavity of the microwave which is 4cm from the bottom of the cavity. After drying, the samples were subjected to microwave energy with varying power supply and residence time. For the 400W microwave energy, the residence time was varied from 20, 30, 40, 50, 60, and 70 sec, to 1.5, 2, 3, 4, 5, 6, 10, 15, 20, and 23 min. For the 700W microwave energy power supply, the residence times were 5, 10, 15, 20, 25, 30, and 40 sec, 1, 2, 3, 4, 5, 10, 15, and 20 min.

A universal testing machine (UTM) was used to estimate the effects of microwave irradiation on the degradation of CFRP through the changing value of 3-points bending strength and elastic modulus of the samples before and after heat treatment. The span of the bending test was adjusted at 40mm. The surface image samples after microwave irradiation were observed using SEM. The SEM images: side view, cross-sectional view, and top view were observed to find out the distribution of the cracks on the samples. The values of the bending strength and elastic modulus were measured to evaluate the delamination tendencies of the samples.

RESULTS AND DISCUSSIONS

Effects of Microwave Irradiation on CFRP Composites

The results of the bending strength and elastic modulus of CFRP composites in different microwave conditions are shown in figures 2 and 3, respectively. It can be observed from the two figures that the initial bending strength and elastic modulus values of CFRP composites before microwave degradation were measured at 834.01MPa and 51.66GPa, respectively. Figure 2 shows that the strength of CFRP decreased with increasing microwave energy and residence time. Increasing microwave power caused the decrease in CFRP strength. This behavior shows that CFRP weakens with microwave irradiation. Figure 2 also shows that there were two delamination tendencies of CFRP degradation in microwave dielectric heating as indicated by the solid line and the broken line. The first tendency curve is

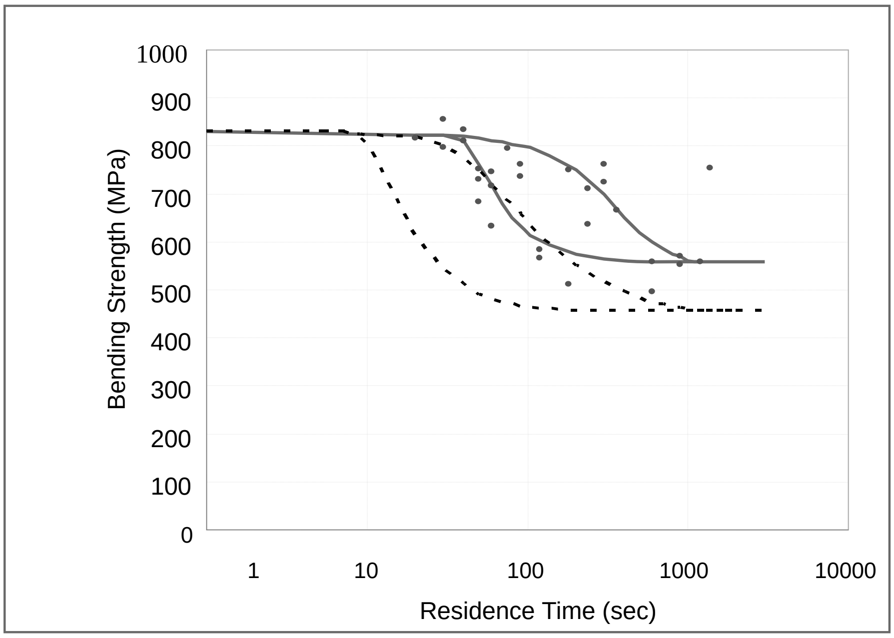

Figure 2. Bending Strength of CFRP under 400 and 700 W Microwave Irradiation

indicated by the curve above while the second tendency curve is indicated by the curve below. The first delamination curve (tendency 1) in CFRP strength showed constant line behavior; that is, a very small amount decreased in a very short time after applying microwave energy. It was a before 40sec in the case of 400W, and it was before 10sec for 700W microwave power supply. The strength decreased dramatically to the minimum value of the bending strength. The second delamination curve (tendency 2) show a slight decrease in the strength when applying microwave irradiation for a longer time before reaching the minimum value. It is also worth mentioning that two delamination tendency curves of CFRP degradation show that the CFRP's strength reached the minimum value after a certain time which is about 20min for both cases. The minimum value of the bending strength of CFRP samples was measured at 558MPa after 20min microwave application using 400W microwave power, while it was measured at 458MPa after 20min using 700W microwave power. The strength of the CFRP samples could not be decreased after this time even though microwave energy was supplied continuously.

The elastic modulus values of the CFRP samples seemed unaffected by the microwave energy as compared to the bending strength values. Figure 3 shows that these elastic modulus values were unchanged remarkably with the increasing residence time as well as increasing power supply.

Both figures 2 and 3 show that microwave irradiation has a certain effects on the degradation of the CFRP samples. The bending strength values of CFRP composites decreased as both residence time and microwave power supply were changed. In contrast, the elastic modulus of the samples did not change significantly by varying the microwave power supply and residence time. This can be explained by the microwave irradiation's weakening the matrix of the composite by creating some cracks, delaminations, or voids inside the composites. These cracks, as shown in the SEM images, influenced the total bending strength value of the

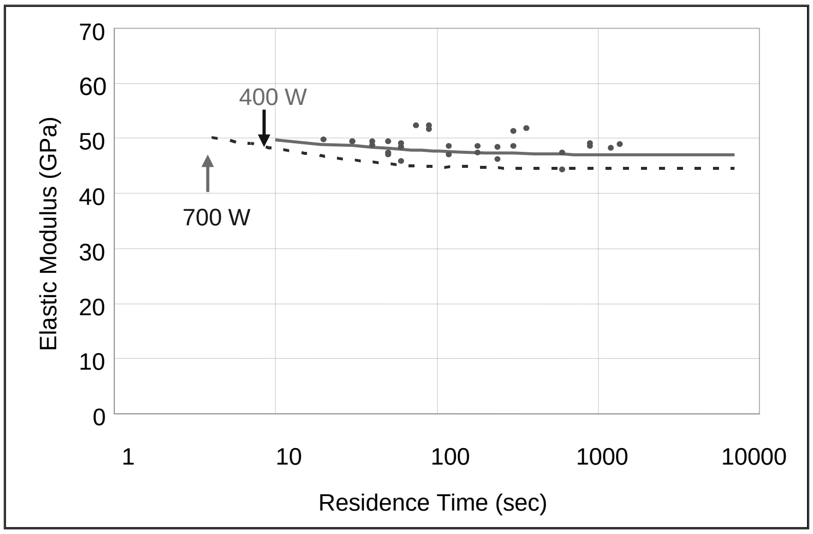

Figure 3. Elastic Modulus of CFRP under 400 and 700 W Microwave Irradiation

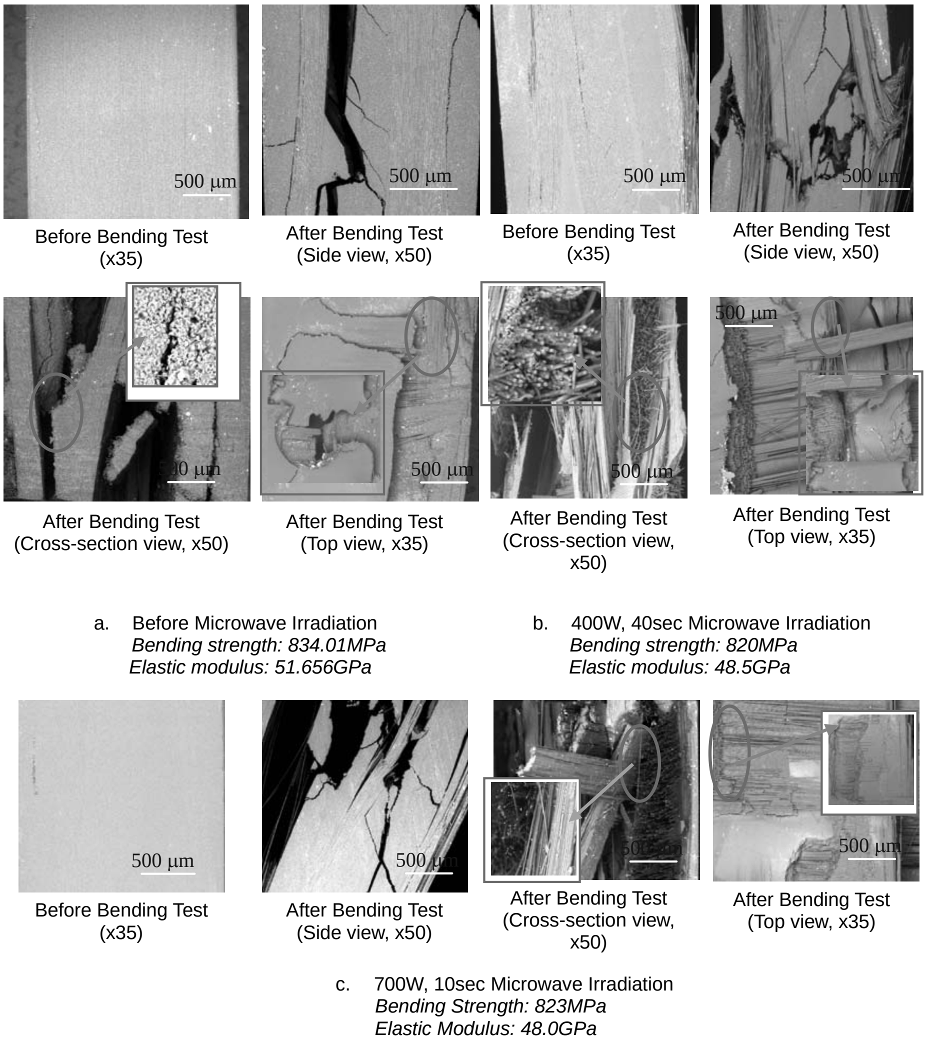

Figure 4. SEM Observations of Samples in a Short Residence Time

samples. However, these cracks did not affect the modulus values since the elastic extension of CFRP does not depend on the samples' small cracks or voids.

SEM Image Analyses

SEM was used to observe the surface images of the samples in order to understand how microwave affected the CFRP samples before and after microwave irradiation. Figures 4 and 5 show the SEM images of the CFRP sample surfaces before and after the bending test. It can be seen that the distribution of the cracks on the samples were related to the values of their bending strength values. Figure 4 shows all the SEM photos of those samples having almost the same value of total bending strength and elastic modulus. The figure shows that there are only minor cracks and delaminations on the surfaces of the samples before bending both for 700W at 10sec and 400W at 40sec. That is the reason why the bending strength value of those samples did not change significantly when both the microwave energy and residence time were increased. It can be seen from figures 4 and 5 that microwave delaminates the interface of the fiber and the matrix. The fibers were pulled out from the matrix after being exposed to microwave energy.

Figure 5 shows the difference in the distributions of the cracks on the samples that led to two tendencies of degradation. It can be stated that with all of the samples where the cracks were along two edges, the bending strength values were higher than those that had the cracks distributed in the middle of the sample surfaces.

Figures 5(a) and 5(b) show the SEM images of the sample surfaces that follow tendency 1 where it was observed that the bending strength values of CFRP samples decreased dramatically to get the minimum value after a certain time. On

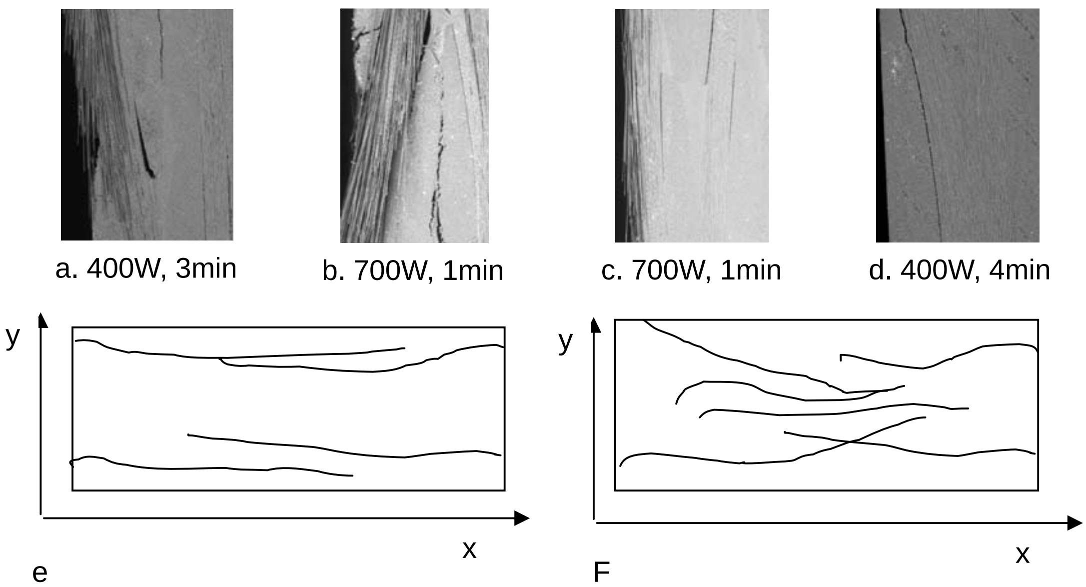

Figure 5. Side View SEM Observations and Two Degradation Tendencies of CFRP by Microwave Dielectric Heating

a. Side view, degradation at 400W, 3min b, c. Side view, degradation at 700W, 1min
d. Side view, degradation at 400W, 4min e. Delamination tendency 1
f. Delamination tendency 2
(x-axis = length of the samples
y-axis = thickness of the samples)

the other hand, figures 4(c) and 4(d) show the SEM images of the samples that follow tendency 2 where the bending strength values of the CFRP samples slightly decreased with microwave irradiation. From this observation, figures 5(b) and 5(c) show that even though these samples were treated to the same conditions of microwave and residence time, the cracks were not the same and followed two different tendencies. However, the degradation tendency for each case could be predicted based on the delamination of the samples, as shown in figures 5(e) and 5(f).

CONCLUSIONS

The following conclusions were derived based on all the results of the study:

CFRP composites can be degraded by microwave irradiation;

There were two delamination tendency curves observed when the CFRP samples were subjected to microwave irradiation. Microwave did not have a significant effect on the composite within a short time; however, the influence of microwave on CFRP became significant after 40sec at 400W and 10sec at 700W.

The bending strength values of CFRP decreased dramatically with increasing microwave power and residence time. Microwave did not have an effect on the values of elastic modulus on CFRP composites.

The degradation of CFRP by microwave is limited. After 20min residence time, increasing the residence time and microwave energy gave no remarkable effect on the degradation process.

The delamination tendency of the CFRP samples in microwave irradiation can be predicted by observing the samples' surface images.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the JICA/AUNSeed-Net project for the financial support; Mitsubishin Rayon Co., Ltd., for providing the CFRP samples; De La Salle University, Philippines; and, the Tokyo Institute of Technology, Japan, for assisting in the coordination of this study.

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