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Carbon fiber extraction from waste CFRP by microwave irradiation

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ABSTRACT

The present paper proposes an effective method to extract carbon fibers from waste CFRPs with low energy consumption and low processing time. Carbon fibers were extracted from waste CFRPs by irradiating microwaves under different atmospheres. The effect of the atmosphere and field intensity of irradiated microwaves on the efficiency of extraction of carbon fibers was investigated. The mechanism of extraction through microwave irradiation was also studied. Finally, the tensile strength of extracted carbon fibers was investigated and compared with that of carbon fibers extracted using conventional methods. Test results showed that the carbon-fiber extraction through microwave irradiation can be considered to occur in three stages. First, the carbon fibers in CFRP were heated through the antenna effect by microwave irradiation. Then, the gasification of resin was promoted by the heated carbon fibers. Finally, the gasified resin was decomposed by spark glow plasma between carbon fibers.

1. Introduction

For the past three decades, carbon-fiber reinforced plastics (CFRP) have had a wide range of industrial applications, e.g., in automobiles, wind turbines, and aircraft, because they exhibit a high strength even at a low density[1]. Compared with the manufacture of other reinforcing fibers such as glass fiber, the manufacture of carbon fiber requires high energy consumption to carbonize the precursor fiber [2,3]. Therefore, from the viewpoint of energy saving, recycling carbon fibers is highly important. However, in spite of the increase in demand for CFRP, landfill disposal has been the most common method for the disposal of composite materials [4]. To recycle carbon fibers from CFRP, matrix resins need to be removed for extracting carbon fibers. Conventional methods for removing resin are divided into three: chemical removal, thermal removal, and mechanical removal methods [4]. Okajima et al. [5,6] proposed the application of a supercritical fluid to decompose the resin matrix chemically for extracting carbon fibers. Several researchers [7,8] proposed the incineration of waste FRPs to remove the resin matrix. Other researchers [9,10] proposed mechanically crushing CFRPs by using a cutter. However, these conventional methods require a large amount of energy or high processing time.

The present paper proposes an effective method to extract carbon fibers from waste CFRPs with low energy consumption and low processing time. Carbon fibers were extracted from three types of model waste CFRPs by irradiating microwaves under different atmospheres. At first, the effect of the atmosphere and field intensity of irradiated microwaves on the efficiency of extraction of carbon fibers was investigated by using unidirectional CFRPs. The mechanism of extraction through microwave irradiation was also studied by using single fiber embedded CFRPs. Finally, the tensile strength of extracted carbon fibers was investigated and compared with that of carbon fibers extracted using conventional methods by using plain woven CFRPs.

2. Experimental

2.1. Materials

In this study, two types of CFRPs, in which the matrix consisted of heat-set epoxy resin, were used to simulate CFRP waste. To examine the effect of microwave irradiation onto CFRPs, unidirectional CFRP (Uni-CFRP) made from prepreg (Toho-tenax, Q1112) was used, and 10 layers of prepreg was stacked and heat pressed to fabricate 1.5-mm-thick Uni-CFRP. The fiber volume fraction of the fabricated Uni-CFRP was approximately 65%. For comparison with conventional extraction methods, practical CFRP (PW-CFRP) was prepared with plain woven cloth (Maruhachi, MW1076). The PW-CFRP was fabricated using the hand lay-up method with conventional epoxy resin (jER-828), and 10 layers of carbon cloth and epoxy were stacked in the laminate configuration $[0–90°]_{10}$ to fabricate 3.0-mm-thick PW-CFRP. The fiber volume fraction of the fabricated PW-CFRP was approximately 50%. The fabricated

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CFRPs were cut in parallel with the fibers by using a diamond cutter, and finally, a strip-shaped specimen of size 30 × 17 mm was prepared. Here, the length of specimen 30 mm was determined as a quarter wave length of microwave. Configurations and physical properties of materials were described in Tables 1–3.

2.2. Microwave irradiation

Fig. 1 shows the testing apparatus used in this study. Microwaves were irradiated to the specimen by using a simplified microwave irradiation apparatus (AMIL, HTMW700). The power and frequency of microwaves was set to 700 W and 2.45 GHz, respectively. In this study, three different atmospheres were used: argon, nitrogen, and air. In order to control the atmosphere during irradiation, the specimen was placed in a quartz-glass chamber, as shown in Fig. 2. The specimen was set on the quartz glass platform and fiber direction was aligned to x direction as shown in Fig. 2. The atmosphere gas was provided using a mass-flow controller with a flow rate of 2.5 L/min. The emission spectrum during microwave irradiation was measured by using a fiber-type spectroradiometer (ASD, FieldSpecPro). The fiber optic receiver was set at just above the chamber and the distance between fiber sensor and specimen was controlled to 150 mm. The number of integration time and bandwidth for emission spectrum measuring was set to 34 and 336–1067 nm, respectively. In order to evaluate the amount of resin removal, an effective parameter of resin elimination ratio, E_r, was introduced.

$$E_r = \frac{m_b - m_a}{V\left(1 - \frac{V_f}{100}\right)\rho_r} \tag{1}$$

Here, m_b, m_a, V, V_f and ρ_r denote the mass of the specimen before microwave irradiation, mass of the specimen after microwave irradiation, volume of specimen, fiber volume fraction and density of resin, respectively. To investigate the effect of the field intensity irradiated onto specimen on the resin elimination ratio, the chamber position was varied as shown in Fig. 3. The chamber was set at the center of each region, here, coordinate for specimen $x-y$ and coordinate for apparatus $\xi-\eta$ were aligned.

2.3. Single-fiber tensile test

The tensile strength of extracted fibers was determined using the testing machine shown in Fig. 4. The specimen for tensile test was also shown in Fig. 4. Individual fibers with a length of 20 mm were glued by epoxy adhesive and aligned on cardboard fixtures. The cardboard fixture was cut on both sides as illustrated in Fig. 4 and the two pieces were held with clamps. The diameter of fibers in the gage section was measured using a laser micrometer (Mitsutoyo, LSM-500S) at steps of 0.5 mm in the longitudinal direction. The maximum load at fiber breakage was measured using a load cell (Kyowa dengyo, DT-20D). The gage length and test speed were 12 mm and 10 mm/min, respectively. The Weibull distribution considering the variation in diameter [11] was used to evaluate the tensile strength of extracted fibers.

$$F = 1 - \exp\left(-\frac{\overline{A_i}}{A_0}\cdot\frac{L}{L_0}\left(\frac{\overline{\sigma}}{\sigma_0}\right)^m \cdot R\right) \tag{2}$$

$$R = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\overline{A_i}}{A_i}\right)^{m-1} \tag{3}$$

Table 1
Configuration of carbon prepreg (Toho-tenax, Q1112).

Filament	HTA40
Areal weight (g/cm^2)	156 ± 5

Table 2
Configuration of carbon cloth (Maruhachi, MW1076).

Warp yarn	TC33-3K
Fill yarn	TC33-3K
Warp ends (count/25 mm)	12.5
Fill picks (count/25 mm)	12.5
Areal weight (g/cm^2)	200

Table 3
Physical properties of epoxy (Mitsubishi chemical, jER828).

Density (kg/m^3)	1160
Viscosity (Pa s)	12–15
Epoxide equivalent weight	170–180

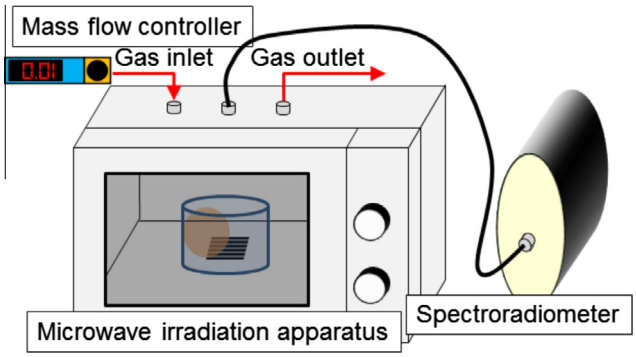

Fig. 1. Test apparatus. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The cumulative probability F was calculated using the mean-rank method. Here, $\overline{A_i}, A_0, L, L_0, \overline{\sigma}, \sigma_0$ and R denote the average cross-sectional area of each specimen, the average cross-sectional area of all specimens, the length of each specimen, the average length of all specimens, the average stress of each specimen calculated by dividing the maximum load by the average cross-sectional area, the average stress of all specimens, and a parameter representing the variation in cross-sectional area, respectively. At least 20 specimens were tested and using all specimen, the Weibull distribution was evaluated to investigate the tensile strength. Because of difficulties of evaluating the strain of fiber, the tensile modulus of fibers was not discussed in this study.

3. Results and discussion

3.1. Effect of field intensity on resin elimination ratio

Fig. 5 shows the resin elimination ratio defined at 2.2 after irradiation for 20 s with respect to the nominal field intensity of microwaves under different ambient atmospheres. In this study, the nominal field intensity of irradiated microwaves was varied by changing the chamber position as shown in Fig. 3. The nominal field intensity of irradiated microwaves at each position was estimated by measuring the temperature change caused by microwave irradiation in 50 $\times 10^{-3}$ L of water poured into the apparatus described in Fig. 2. The nominal microwave field intensity was calculated using the following equation:

$$E = \sqrt{\frac{P}{f \times 0.556 \times 10^{-10} \times \epsilon_r \times \tan\delta}} \tag{4}$$

$$P = \frac{\rho c(T_2 - T_1)}{t} \tag{5}$$

$$\epsilon_r \times \tan\delta = \left(\frac{3.31 \times 10^7}{fD}\right)^2 \tag{6}$$