Improved Strength in Carbon Fiber Reinforced Plastics due after Electron Beam Irradiation*1

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Carbon fiber reinforced plastics (CFRPs), with their advantages of light weight and high strength, are increasingly being applied as structural materials in the fields of aerospace engineering and rapid transport engineering. To strengthen CFRPs, electron beam (EB) irradiation is performed homogeneously. EB irradiation enhances the bending fracture stress and the bending fracture strain, and also slightly enhances the bending elasticity of CFRP. The analysis based on the Law of Mixture Strength for composites suggests that EB strengthening of CFRPs is chiefly attributable to ductility enhancement of the epoxy resin and carbon fiber.

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1. Introduction

Carbon fiber reinforced plastics (CFRPs) are increasingly commonly used composite materials based on carbon fiber. They are currently being applied as high-strength light structural materials in aerospace and rapid transport engineering.1,2) Stronger and lighter materials enable the development of high-speed vehicles with low energy consumption.

In recent publications we report that electron beam (EB) irradiation enhances the bending fracture strain3) and the tensile fracture stress of carbon fiber.4) However, the influences of EB irradiation on the mechanical properties of CFRP have not hitherto been studied. In the present study, we investigate the effects of EB irradiation on the bending fracture stress and the strain of a CFRP, a composition of carbon fiber and epoxy resin. In addition, the contributions of carbon fiber and epoxy resin to the strengthening improvement in CFRP are discussed.

2. Experimental Procedure

Figure 1 shows a SEM micrograph of cross section of the CFRP. The CFRP sample (25 mm × 5 mm × 0.5 mm) was 3k cross-mat texture impregnated with epoxy resin matrix. The cross-mat texture was constructed by bundles of carbon fibers. The volume fraction of carbon fiber (Torayca M30SC, Toray Ltd., Tokyo, Japan) and epoxy resin (GM6800, Blenny Ltd., Tokyo, Japan) were 57% and 43%, respectively.

In order to evaluate the mechanical properties of CFRP, a bending test was performed, by using a standard setup as shown in Fig. 2. When bending stress \( P \) was applied, bending strain \( \varepsilon \) is expressed by the following equation:

\[
\varepsilon = \frac{dy}{2a} \left( \frac{a^2}{y^2} + 2b - 2ny \right)
\]

where \( a, b, n, d \) and \( y \) are half value of the gauge length.

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between supporting points, curvature diameter, distance from the inner surface to a neutral line, sample thickness, and bending displacement at the sample center, respectively.

The sheets were homogeneously irradiated using an electron-curtain processor (Type CB175/15/180L, Iwasaki Electric Co. Ltd. Tokyo). A tungsten filament in a vacuum generated the sheet beam. The acceleration voltage and the current density were 170 kV and 4.0 mA, respectively. The width of the Ti window was 38.0 mm. The most important feature of a sheet electron beam is that it performs homogeneous treatment of the samples. EB irradiation was performed under a nitrogen atmosphere at 0.1 MPa (1 atm). Contamination by oxygen was below 400 ppm.

To maintain the temperature of the sample surface at below 323 K, the sample was mounted on a conveyor passing through the irradiation region at a speed of 9.56 m/min. Irradiation time was 0.23 s. The irradiation was repeated until the total dose reached the target dose. The dosage in the present condition was determined using the irradiation current (I, mA), the conveyor speed (S, m/min) and the repetition number (N) of irradiations, as follows:

\[
\text{Dosage (MGy)} = 0.216\left(\frac{I}{S}N\right)
\]

Irradiation dose was corrected by using RCD nylon radiometer film (Far West Technology, Inc. 330-D South Kellogg, Goleta, CA 93117, USA). The distance between sample and window was 35 mm. The average irradiation depth (D_{epph} μm), calculated by sample density (ρ, kg/m^3) and irradiation potential (V, kV), was expressed by the following eq. 11:

\[
D_{epph} \cdot ρ = 66.7 \cdot V^{5/3}
\]

The energy of the incident electrons was reduced from 170 to 128 keV due to the nitrogen atmosphere. We employed as the sample density (ρ) the average values of the densities of the carbon fiber (1800 kg/m^3) and the epoxy resin (1100 kg/m^3) in the volume fraction. The estimated average irradiation depth of the CFRP was 158 μm.

3. Results

3.1 Bending fracture stress and strain of CFRP before and after electron beam irradiation

Figure 3 shows the irradiation dose dependence of the bending fracture stress in CFRP. EB irradiation up to 0.30 MGy enhanced the bending fracture stress, whereas excess EB irradiation above 0.30 MGy decreased it. The maximum bending fracture stress (470 MPa) of the 0.30 MGy EB-irradiated CFRP was 2.15 times greater than that before EB irradiation (220 MPa).

Figure 4 shows irradiation dose dependence of the bending fracture strain of the CFRP. EB irradiation up to 0.30 MGy also enhanced the bending fracture strain, whereas excess EB irradiation slightly decreased it. The maximum bending fracture strain (0.022) was 1.7 times greater than that before EB irradiation (0.013).

Figure 5 shows stress-strain curves from bending tests for CFRP before and after 0.30 MGy EB irradiation. The bending elasticity was slightly enhanced by EB irradiation (×1.26).

3.2 Stress-strain curves of epoxy resin before and after electron beam irradiation

To estimate the contribution of the epoxy resin matrix in the mechanical properties of the CFRP, bending tests were performed for epoxy resin samples (25 mm × 5 mm × 0.5 mm) before and after 0.30 MGy EB irradiation. Figure 6 shows the bending stress-strain curves of epoxy resin before and after EB irradiation. The bending elasticity was not improved by EB irradiation in the bending strain region below the bending fracture strain of the CFRP. On the other hand, the bending fracture stress and strain were enhanced from 59.4 to 115 MPa (×1.9), and from 0.036 to 0.052 (×1.4), respectively. The ductility and fracture stress were improved by EB irradiation.
4. Discussion

When the shift of the neutral axis is neglected, the stress-strain curve for the carbon fiber can be estimated by assuming the Law of Mixtures:12)

$$\tau_{\text{CFRP}} = \beta V_{\text{CF}} \tau_{\text{CF}} + V_{\text{resin}} \tau_{\text{resin}}$$

(4)

where $\tau_{\text{CFRP}}$, $\tau_{\text{CF}}$ and $\tau_{\text{resin}}$ are the bending stress of CFRP, carbon fiber and resin, respectively. $V_{\text{CF}}$ and $V_{\text{resin}}$ are the volume fractions of carbon fiber and resin, respectively. Since the 3k cross-mat texture vertical to the direction of deformation contributes little but that parallel to the direction of deformation does contribute to resistance to the bending stress, $\beta$, the shape factor for the 3k cross-mat texture in the CFRP sheet samples, is set at 0.5. Substituting the experimental values of the CFRP (see Fig. 5) and the epoxy resin (see Fig. 6) allowed the stress-strain curve of the carbon fiber to be estimated.

Since the irradiated depth was less than the sample thickness, the stress-strain curve for the carbon fiber after the EB irradiation was estimated by the following equation:

$$\tau_{\text{CFRP}} = (2D_{\text{eth}}/T_h) (\beta V_{\text{CF}} \tau_{\text{CF}} + V_{\text{resin}} \tau_{\text{resin}}) + (T_h - 2D_{\text{eth}}/T_h) \tau_{\text{CFRP}}$$

(5)

where $\tau_{\text{CFRP}}$, $T_h$ and $D_{\text{eth}}$ are the bending stress of CFRP before EB-irradiation, sample thickness and irradiation, respectively. In the present study, the values of $T_h$ and $D_{\text{eth}}$ estimated by eq. (3) were 500 $\mu$m and 158 $\mu$m, respectively.

Figure 7 shows the estimated bending stress-strain curve of the carbon fiber before and after 0.3 MGy EB irradiation. The EB irradiation slightly enhanced the elasticity. If the bending fracture strain of carbon fiber was equal to that of CFRP, the estimated bending fracture stress of irradiated carbon fiber should be about double that before EB irradiation. EB irradiation probably enhances the ductility of carbon fiber.

The EB strengthening of bending fracture stress for carbon fiber is likely to be dominated by enhancement of ductility. Bending fracture strain3) and the tensile fracture stress4) of fine carbon fiber have been obtained in our previous work. EB irradiation generally enhanced the bending fracture strain3) and the tensile fracture stress.4) The strengthening of carbon fiber is assumed to be based on the annihilation of vacant sites with dangling carbon bonds in graphite hexagonal atom structure.4) Vacant sites are likely to be associated with stress relaxation and crack origins. The stress relaxation of graphite is generated by repulsive forces between inter-
sigma bonding electrons of carbon atoms with dangling bonds.\textsuperscript{13} EB irradiation lowered the dangling bond density\textsuperscript{4} due to vacant site annihilation by migration of unstable terminal carbon atoms. Although production processes tend to dictate the mechanical properties and strongly affect the quantitative values of EB reinforcement of carbon fiber, EB reinforcements were qualitatively observed in all kinds of carbon fibers.\textsuperscript{14} Thus, EB reinforcement of carbon fibers is probably a universal pattern.

Finally, we discuss the influences of interfaces between carbon fiber and matrix on strengthening. Fine fibers experience compressive stress caused by solidification of the matrix. Although carbon fiber is connected with other materials, a high joining fracture stress has been observed in our recent studies.\textsuperscript{13} Fractures always occurred starting from carbon fibers. Since a fine carbon fiber $6 \times 10^{-6}$ m in diameter has a large specific surface area to which compressive stress is applied, the interface area between a carbon fiber and the matrix is large enough to obtain a large friction force. Thus, the joining fracture stress was mainly dominated by carbon fiber fracture stress. Therefore, we suggest that the contribution of the interface is negligibly small in the CFRP sample. Based on the law of mixtures, the experimental results (see Figs. 5 & 6) and our observations of the interface, we conclude that EB strengthening of CFRP is probably dominated by ductility enhancements of epoxy resin and carbon fiber.

5. Conclusion

EB irradiation was homogeneously performed to enhance the fracture toughness of CFRP. EB irradiation significantly increased the bending fracture stress and bending fracture strain of CFRP. EB irradiation slightly enhanced the bending elasticity of CFRP. EB strengthening of CFRP is probably dominated by ductility enhancement of the epoxy resin and carbon fiber.

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14) Unpublished data.