Effects of Electron Beam Irradiation on Charpy Impact Value of GFRP

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Glass fiber reinforced polymers GFRPs are increasingly being applied as structural materials with their advantages of light weight and high strength in the fields of aerospace engineering and rapid transport engineering. To strengthen the GFRPs, sheet electron beam (EB) irradiation under low potential has been performed homogeneously. Effects of EB-irradiation on Charpy impact value of GFRPs have been studied. The irradiation, applied as a short-time treatment at room temperature, enhances the impact value of GFRPs at every fracture probability. The effect of EB-irradiation on the impact value of GFRPs mainly depends on the ductility enhancement of the GFRPs. EB-irradiation also enhances the reliability indicated by the minimum impact value (αₙ), as well as the Weibull coefficient. [doi:10.2320/matertrans.MRA2007050]

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1. Introduction

Fiber reinforced plastics (FRP) are composite materials increasingly being used which are fiber based for heat resistance, have currently been applied as high-strengthened light structural materials in the current fields of mover engineering such as supersonic aerospace.¹,² To develop high-speed transports with small energy consumption, the further strengthening of FRP has always been expected. Although influences of high energy electron beam irradiation on the fracture toughness of FRP have been reported,³ no one has succeeded the strengthening of carbon fiber reinforced polymer (CFRP). On the other hand, low energy sheet electron beam (EB) irradiation often induces hardening, high wear resistance and sterilization,⁴–⁷ In addition, the irradiation has improved not only the bending fracture strain of carbon fiber,⁸ but also the deformation resistivity, strength and fracture strain during static tensile testing.⁹ Our recent publication has succeeded in showing that the EB-irradiation with low energy enhances the fracture stress during static bending testing,¹⁰ tensile strength,¹¹ and the dynamic fracture toughness evaluated by impact value,¹² for CFRP.

On the other hand, when it can be applied for use in health monitoring systems, the glass fiber can be used as not only a reinforced fiber, but also an optical fiber.¹³ The dynamic fracture toughness evaluated by impact testing is also the most important factor in applying the glass fiber reinforced polymer (GFRPs) for high-speed transports. However, the influences of EB irradiation on the mechanical properties of GFRPs have not hitherto been studied. Charpy impact value is a useful tool to evaluate the dynamic fracture toughness. In the present study, the effects of EB irradiation on the Charpy impact value of GFRPs have been investigated. In addition, to discuss the impact strengthening improvement in irradiated GFRPs, stress-strain curves of static bending test are obtained.

![Fig. 1 SEM micrograph of cross section of fractured GFRPs.](image)

2. Experimental Procedure

2.1 Sample preparation

The impact test specimen (60 mm × 2 mm × 2 mm with notch of depth 1 mm) is machined from the GFRPs sheet. Figure 1 shows an SEM micrograph of the cross section of fractured GFRPs. The GFRPs are impregnated with epoxy resin matrix. The volume fraction of glass fiber (E-glass fiber, Vetrotex International Co.) in epoxy resin matrix (DGEBA/MTHPA) are 50 vol%GF.

2.2 Electron beam (EB) irradiation

The GFRP samples are homogeneously irradiated by using an electron-curtain processor (Type CB175/15/180L, Energy Science Inc., Woburn, MA, Iwasaki Electric Group Co. Ltd. Tokyo). The specimen is homogeneously irradiated with the sheet electron beam irradiation with low energy through a titanium thin film window attached to a 240 mm diameter vacuum chamber. A tungsten filament in a vacuum is used to generate the electron beam at a low energy (acceleration potential, V: kV), of 170 kV and irradiating current density (I, A/m²) of 0.089 A/m².
Although the sheet electron beam generation has been in a vacuum, the irradiated sample has been kept under protective nitrogen at atmospheric pressure. The distance between sample and window has been 35 mm. To prevent oxidation, the samples are kept in a protective atmosphere of nitrogen gas with a residual concentration of oxygen below 400 ppm. The flow rate of nitrogen gas is 1.5 L/s at 0.1 MPa nitrogen gas pressure. Each irradiation dose (0.0432 MGy) is applied for only a short time (0.23 s) to avoid excessive heating of the sample; the temperature of the sample surface remains below 323 K just after irradiation. The sample in the aluminum plate holder (0.15 m × 0.15 m) is transported on a conveyor at a speed of 9.56 m/min. The sheet electron beam irradiation has been applied intermittently. Repeated irradiations to both side surfaces of the samples are used to increase the total irradiation dose. The interval between the end of one period of irradiation and the start of the next operation is 30 s. When the irradiation current (I, mA), the conveyor speed (S, m/min) and number of irradiations (N) are determined, the irradiated dosage is proportional to the yield value from the irradiation current (I, mA), the conveyor speed (S, m/min), and number of irradiations (N).

The irradiation dose has been controlled by the integrated irradiation time in each of the samples. Here, irradiation dose has been corrected by using an FWT nylon dosimeter of RCD radiometer film (FWT-60-00: Far West Technology, Inc. 330-D South Kellogg Goleta, California 93117, USA) with an irradiation reader (FWT-92D: Far West Technology, Inc. 330-D South Kellogg Goleta, California 93117, USA). The dose is 0.0432 MGy at each irradiation. Based on the density (ρ: kg/m³) and irradiation voltage (V: kV), the penetration depth (Dₚ: m) of EB-irradiation is expressed by the following equation.

\[
Dₚ = 66.7V^{5/3}/\rho
\]  

(1)

The surface electrical potential (128 keV) is estimated from the electrical potential (170 keV), the 10 μm thickness of the titanium (density: 4540 kg m⁻³) window, and the 30 mm distance between the sample and the window in the nitrogen gas atmosphere (density: 1.13 kg m⁻³). Figure 2 shows density dependent penetration depth values of electron beam irradiation are 8.52 × 10⁻² m (85.2 μm) for glass fiber (2.60 kg m⁻³), 1.90 × 10⁻³ m (190 μm) for the polymer (1.16 kg m⁻³) and 1.18 × 10⁻⁴ m (118 μm) for and GFRPs (1.88 kg m⁻³), in which the volume ratio of glass fiber in polymer is 47 vol%GF. Since the mean density of the GFRPs sample is 1880 kg m⁻³ (1.88 g/mL), the EB-irradiation depth estimated from eq. (1) is 1.18 × 10⁻⁴ m (118 μm). By using this relation and density, the penetration depth of the sheet electron beam irradiation is 0.118 mm. Thus, the irradiated depth from each sample surface is about 6% in the sample of 2.0 mm thickness.

2.3 Impact test to measure impact value

To evaluate the dynamic fracture toughness, the Charpy impact values of the GFRPs with and without the irradiation are measured using a standard impact fracture energy measurement system (JIS K 7077-1991) and Charpy impact tester (FC-3002, Fuji-Shikenn seisakusyo, Japan). The Charpy impact value is expressed by the following equation:

\[
E = WR[(\cos \beta - \cos \alpha) - (\cos \alpha' - \cos \alpha'(\alpha + \beta)/\alpha - \alpha')] 
\]

(2)

Here, E is the impact fracture energy (kJ), W is the hammer mass (N), R is the length (m) of hammer weight point to rolling center, β is the start angle before impact, α is the maximum angle after impact, and α’ is the maximum angle of the blank test. The Charpy impact value (auc/kJ/m²) is expressed by a following equation.

\[
auc = E/(b \times t)
\]

(3)

Here, E is the impact fracture energy (J), b is the sample width (= 1.0 mm) and t is the span distance (sample thickness, 2.0 mm), respectively. The distance between supporting points is 40.0 mm.

3. Results

Figure 3 shows changes in mean impact values against EB irradiation with respect to EB irradiation dosages. EB-irradiation below 0.8 MGy increases the mean impact values. The impact value of GRFPs irradiated from 0.6 to 0.9 MGy is higher than that before EB irradiation, whereas excess EB irradiation over 1.0 MGy decreases the impact values. The maximum impact value of irradiated sample at 0.8 MGy is about 16% higher than that before irradiation. On the other hand, excess EB irradiation from 1.0 to 1.3 MGy clearly decreases the impact values, which is lower than that before irradiation.

An integrated fracture probability (Pᵣ) is a convenient way to analyze fracture stress value (σᵣ) quantitatively, and is expressed by the following equation which uses a generalized form of the Median Rank method.

\[
Pᵣ = (I - 0.3)/(n + 0.4)
\]

(4)

Here, n is the total number of samples and I is the order of fracture of each sample. The electron beam irradiation from 0 to 0.8 MGy apparently enhances the impact value at each fracture probability.

Figure 4 shows changes in the Charpy impact values of
GFRPs before and after EB-irradiation at each fracture probability ($P_f$). The 0.8 MGy-irradiation increases the impact value from 325 to 405 kJ/m$^2$ at the mid point (0.5) of $P_f$ value. The EB-irradiation also increases the impact values from 235 to 340 kJ/m$^2$ at 0.06 of the lowest $P_f$ value and from 385 to 470 kJ/m$^2$ at 0.967 of the highest $P_f$ value, respectively. The electron beam irradiation from 0 to 0.8 MGy apparently enhances the impact value at each fracture probability.

4. Discussion

4.1 Enhancement of Impact value by EB-irradiation

Based on the static bending test for CFRP, stress-strain curves on bending test have also been obtained for GFRPs samples before and after EB-irradiation, as shown in Fig. 5. EB-irradiation doesn’t largely changes the static bending strength. Although the irradiation remarkably softens the elasticity, EB-irradiation remarkably enhances the static bending fracture strain. The effect of EB-irradiation on the impact value of GFRPs at every fracture probability depends on the ductility enhancement of CFRPs samples, including the enhancement of interfacial adhesive (friction) force in the polymer and ductility enhancement of polymer matrix, rather than that of strengthening the glass fiber.

4.2 Reliability enhancement by EB-irradiation

Based on Weibull analysis, the reliability has been evaluated for the GFRPs samples with and without the sheet electron beam irradiation with low energy. To discuss influences of electron beam irradiation on the typical fracture, Weibull equation has been applied for Charpy impact values at each fracture probability. When the fracture probability ($P_f$) depends on the risk of rupture ($a_{uc}/a_0$), the Charpy impact value ($a_{uc}$) can be expressed by a following equation.

$$P_f = 1 - \exp\left[-\left(\frac{a_{uc}}{a_0}\right)^m\right]$$

In order to predict the required impact value, the expectant fracture stress ($a_o$) is one of the key parameters in the development of structural materials. If the $P_f$ value is equal to 0.967, the defined expectant fracture stress ($a_o$) can be obtained. $m$ is a constant. The $m$ value, estimated by the slope of Weibull plots as shown in Fig. 6, is a useful factor to evaluate the distribution of the experimental errors in the impact values. Figure 6 shows the Weibull plots of GFRPs samples with and without the sheet EB irradiation (0.8 MGy) with low energy against $a_{uc}$. The $m$ value of the 0.8 MGy-irradiated GFRPs sample is higher than that of the untreated sample. The irradiation (0.8 MGy) enhances the Weibull modulus and then decreases the experimental errors of GFRPs. Thus, the sheet electron beam irradiation with low energy enhances the reliability, which is indicated by Weibull coefficient.

To discuss influences of electron beam irradiation on the typical fracture, a modified Weibull equation has also applied for Charpy impact values at each fracture probability. When the fracture probability ($P_f$) depends on the risk of rupture ($a_{uc}/a_0$), the Charpy impact value ($a_{uc}$) can be expressed by the following equation.

$$P_f = 1 - \exp\left[-\left(\frac{a_{uc}}{a_0}\right)^m\right]$$

In order to predict the required impact value, the expectant
fracture stress ($a_0$) and $m'$ are key parameters in the development of structural materials. When the $P_i$ values are equal to 0.967 and zero, the $a_0$ and $a_i$ values are defined to be the expectant and the minimum impacted values estimated. Figure 7 shows changes in the correlation coefficient ($F$) against the tentative $a_i$ value of GFRPs with and without the sheet electron beam irradiation under low energy. When a correlation coefficient ($F$) shows the maximum value, the minimum impact value ($a_i$) can be obtained. The linear relationships of GFRPs with and without electron beam irradiation are also obtained, as reported for CFRP. As shown in Fig. 7, the $a_i$ value at the maximum $F$ value is about 250 kJ m$^{-2}$ of the irradiated GFRPs and is higher than that at zero of the tentative $a_i$ value. Since the $F$ value increasing from zero to 250 kJ m$^{-2}$ of the tentative $a_i$ value exhibits the linearity enhancement, the reliable and reproducible $a_i$ values can be estimated by eq. (6) related to the minimum impact value ($a_i$).

On the other hand, the sheet electron beam (EB) irradiation from zero to 0.8 MGy enhances the minimum impact value ($a_i$) from zero to 250 kJ m$^{-2}$, as shown in Fig. 7. Therefore, we concludes that the sheet electron beam irradiation with low energy enhances the reliability, which is indicated by not only the Weibull coefficient ($m$), but also the minimum impact value ($a_i$).

5. Conclusion

In summary, the effects of sheet electron beam (EB) irradiation on Charpy impact value of glass fiber reinforced polymers (GFRPs) have been investigated. EB-irradiation under low energy has been performed homogeneously to strengthen the GFRPs. EB irradiation significantly increases the bending fracture stress and bending fracture strain of CFRP. The irradiation enhances the impact value of GFRPs at every fracture probability. Although the irradiation significantly softens the GFRPs, EB-irradiation increases the bending fracture strain of GFRPs. Therefore, we concludes that the effect of EB-irradiation on the impact value at every fracture probability depends on the ductility enhancement of GFRPs. The sheet electron beam irradiation with low energy enhances the reliability, which is indicated by the Weibull coefficient ($m$) and the minimum impact value ($a_i$) of GFRPs.

REFERENCES