Effects of Electron Beam Irradiation on Impact Value of Novolak-Type Phenol CFRTP

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Homogeneous low voltage electron beam irradiation (HLEBI) improved the Charpy impact value (αu) of carbon fiber reinforced thermoplastic novolak-type phenol polymers (CFRTP) composite sheets with 2 mm thickness, although the irradiated depth estimated was 182.5 ± 33.5 μm on both side surfaces. The αu values at low fracture probability (Pf) of 0.06 for CFRTP irradiated at 0.30 MGy (kJg⁻¹) was 60 kJm⁻², which was 32% higher (46 kJm⁻²) than for CFRTP before irradiation. Although the lowest impact values (αu) estimated by three-parameter Weibull equation was zero for CFRTP before irradiation, HLEBI enhanced the αu value. The highest αu value was more than 59 kJm⁻² for CFRTP irradiated at 0.30 MGy. Thus, HLEBI remarkably enhanced the αu value, as well as the αu value at low Pf value. Since HLEBI enhanced the Weibull coefficient (n), it also enhanced the reproducibility of CFRTP samples. The maximum n value was found at 0.22 MGy HLEBI dose. The interfacial friction force, as well as the strengthening of both carbon fiber and novolak-type phenol resin probably contributed to the HLEBI effects to enhance the αu value of CFRTP, as well as enhancement of reproducibility.

(Received May 11, 2010; Accepted September 21, 2010; Published November 3, 2010)

Keywords: carbon fiber reinforced thermoplastic polymers (CFRTP), novolak-type phenol resin, carbon fiber, electron beam irradiation, impact value

1. Introduction

Carbon fiber reinforced polymers [CFRP], which are typical composite materials, have been applied as light structural materials with high strength.1,2) The further strengthening has been always expected to develop high-speed mover machines with tiny energy consumption. Although influences of electron beam (EB) irradiation with high energy on the fracture toughness of plain-woven carbon fiber in thermo-hardened epoxy resin matrix (thermo-hardened CFRP) have been often reported,3) no one has succeeded in strengthening the CFRP irradiated by electron beam.

On the other hand, the homogeneous low voltage electron beam irradiation (HLEBI) often induces not only the stiffness, high wear resistance and sterilization for practical use of polymer, but also the mist resistance.4–6) In addition, the irradiation has improved not only the bending fracture strain,7,8) but also the deformation resistivity, tensile strength and its strain of carbon fiber.9) To apply to high-speed mover transports, HLEBI also enhances the bending fracture stress, its strain and impact value of thermo-hardened CFRP.10,11)

Carbon fiber reinforced thermoplastic polymers (CFRTP) can be easily produced with high productivity, which is its industrial attractive point, for mass production of various forming process. However, it is a serious problem that high viscosity of thermoplastic polymer with low wetting to carbon fiber induces the low strength of CFRTP. HLEBI often enhances the deformation resistivity (elasticity) of polymer12) and carbon fiber.7–9) In addition, it is also possible to enhance the interface strength induced by surface activation, which is generated by charging and dangling bond formation. Since the interfacial area of carbon fiber with 6 μm diameter is extremely large, the enhancement of friction force induces the strength of CFRTP. In order to enhance the interfacial friction force, application of HLEBI to CFRTP is probably effective for the interface.

Novolak-type phenol resin (PF), whose monomer is mainly constructed with phenolic hydroxyl (see Fig. 1), is one of the typical thermoplastic polymers with high resistance to heat and flame.13) Thus, it is generally applied to automotive parts and building insulation. Therefore, the purpose of the present work is to investigate effects of HLEBI on the impact value of CFRTP constructed with novolak-type phenol resin and carbon fiber. On the other hand, if EB-irradiation forms pairs of dangling bonds at the weak...
chemical bonding sites at hydroxyl group (HO-C₆H₅: 431 kJ mol⁻¹) and alkyl group (H-C₆H₅: 431 kJ mol⁻¹, CH₃-C₆H₅: 389 kJ mol⁻¹, and C₂H₅-C₆H₅: 377 kJ mol⁻¹), as well as between monomers (C₆H₅-C₆H₅: 418 kJ mol⁻¹). the volume expansion induced by repulsive force between dangling bonds pairs occurs, as shown in Fig. 1(b). Furthermore, the volume expansion directly generates the compressive stress in the matrix and at the PF/CF-interface, resulting in the strengthening of both PF and CF matrix and high friction force at the PF/CF-interface. Consequently, the impact value improvement may be expected.

2. Experimental Procedure

2.1 CFRTP sample preparation

The CFRTP sample, whose volume was 1500 mm³, was constructed with the bundle of carbon fiber (Diameter = 6 µm, T800HB, Toray Industries, Inc.) and thermoplastic polymer (Novolak-type phenol resin; PAPS-PN2, Asahi Organic Chemicals Industry Co., Ltd.) matrix. Volume fractions of carbon fiber and polymer matrix were 60.8 and 39.2 vol%, respectively.

Matrix was prepared by liquid-resin after mixing the 62.2 mass%-novolak-type phenol resin, 9.0 mass%-hexa-methyleneimine, 3.8 mass%-calcium stearate and 25.0 mass%-organic solvent. Making composites by impregnation of carbon fiber bundles in the liquid-resin before evaporation of solvent under 40°C for 1.0 h. Finally, it was heat-treated under 20 MPa Ar-H₂ gas atmosphere at 180°C for 1.0 min.

Since the bundle direction was the longitudinal direction, a high unidirectional strength can be expected. To evaluate the dynamic fracture toughness, the impact tests of the CFRTP with and without the irradiation were measured using a standard impact test machine (Shimadzu Corporation No. 51735).

2.2 Impact test

In order to evaluate the impact fracture toughness, the Charpy impact values of the CFRTPs with and without HLEBI treatment were measured using a standard impact test machine (Shimadzu Corporation No. 51735) (JIS K 7077-1991). CFRTP sample sizes were 80 mm length, 10 mm width and 2.0 mm thickness. The impact fracture energy (E) was expressed by the following equation.¹⁴

\[
E = WR[\cos \beta - \cos \alpha \cos \beta \alpha / (\alpha + \alpha')] \tag{1}
\]

Here, \(E\), \(W\), \(R\), \(\beta\), \(\alpha\) and \(\alpha'\) were impact fracture energy (J), hammer mass (\(W = 8.43\) N), length (\(R = 0.210\) m) of hammer weight point from rolling center, the maximum angle after impact, start angle before impact (\(\alpha = \pm 132^\circ\)) and the maximum angle of the blank test (\(\alpha' = \pm 128^\circ\)), respectively. The Charpy impact value (\(a_{\text{uc}}\): kJ m⁻²) was expressed by the following equation.

\[
a_{\text{uc}} = [E/(bt)] \times 10^3 \tag{2}
\]

Here, \(E\), \(b\) (= 10 ± 0.2 mm) and \(t\) (= 2.00 ± 0.15 mm) were impact fracture energy (J), sample width (mm) and span distance (sample thickness, mm), respectively. The distance between supporting points was 40 mm.

2.3 Condition of EB-irradiation

Sheet electron beam irradiation with low energy had been homogeneously performed using an electron-curtain processor (Type CB175/15/180L, Energy Science Inc., Woburn, MA).⁴ The specimen was machined from the sheet heat-treated for making composites and was homogeneously irradiated with the electron beam through a titanium thin film window attached to the vacuum chamber, 240 mm in diameter. Since HLEBI treatment was after forming interface between carbon fiber and PF matrix, improvement of adhesive force could be expected. A tungsten filament in a vacuum was used to generate the electron beam at a low energy (acceleration potential, \(V\): kV), of 170 kV and irradiating current density (\(J\): Am⁻²) of 0.089 Am⁻². Although electron beam generation was done in a vacuum, the irradiated sample was kept under protective nitrogen at atmospheric pressure. The distance between sample and window was 35 mm. To prevent oxidation, the samples were kept in a protective one atmosphere of nitrogen gas with a residual concentration of oxygen below 400 ppm. The flow rate of nitrogen gas was 1.5 L s⁻¹ at 0.1 MPa of nitrogen gas-pressure. Each irradiation dose (0.0433 MGy (kJg⁻¹)) was applied for only a short time (0.23 s) to avoid excessive heating of the sample; the temperature of the sample surface remained below 323 K just after irradiation. The sample in the aluminum plate holder (0.15 m × 0.15 m) was transported on a conveyor at a speed of 10.0 m min⁻¹. The sheet electron beam irradiation was applied intermittently. Repeated irradiations to both side surfaces of samples were used to increase the total dose of irradiation. The interval between the end of one period of irradiation and the start of the next operation was 30 s. When the irradiation current (\(I\): mA), the conveyor speed (\(S\): m min⁻¹) and number of irradiations (\(N\)) were determined, the irradiated dose (\(D\): MGy) was expressed by a following equation.¹⁶

\[
D = 0.216(I/S)N \tag{3}
\]

The irradiation dose was controlled by the integrated irradiation time in each of the samples. Here, irradiation dose was corrected by using FWT nylon dosimeter of RCD radiometer film (FWT-60-00: Far West Technology, Inc. 330-D South Kellogg Goleta, California 93117, USA) with irradiation reader (FWT-92D: Far West Technology, Inc. 330-D South Kellogg Goleta, California 93117, USA). The dose was 0.0432 MGy at each irradiation.

2.4 Evaluation of dangling bonds

To obtain more precise information on atomic-scale structural changes in the CFRTP, the density of the dangling bonds was obtained using an electron spin resonance spectrometer (ESR, JES-FA200, JEOL Ltd. Tokyo). The microwave frequency range used in the ESR analysis was the X-band at 9.45 ± 0.05 GHz with a field modulation of 100 kHz. The microwave power was 1 mW. The magnetic field was varied from 317.0 to 327.1 mT. The spin density was calculated using a Mn²⁺ standard sample. Only ESR spectra, instead of spin densities, were given.
3. Results

3.1 Effects of HLEBI on impact value

Evaluating the probability of fracture ($P_f$) is a convenient method of quantitatively analyzing experimental values relating to fracture. $P_f$ is expressed by the following equation, which is a generalized form of the median rank method: $P_f = (i - 0.3)/(N_s + 0.4)$ (4)

where $N_s$ and $i$ are the total number of samples ($N_s = 11$) and the order of fracture of each sample, respectively. Here, the order of fracture is the aligned number of fractured samples from low to high impact value. When the $i$ values are 1, 6, and 11, the $P_f$ values are 0.06, 0.50, and 0.94, respectively.

Figure 2 shows changes in impact value ($a_{uc}$) of CFRTP against $P_f$ value at each dose of HLEBI.

Remarkable effects of HLEBI on $a_{uc}$ value of CFRTP have been obtained at low $P_f$ value of less than 0.06. The direct irradiation of more than 0.13 MGy remarkably enhances the $a_{uc}$ value of the CFRTP at low $P_f$ value of less than 0.06.

Figure 3 shows changes in $a_{uc}$ value of CFRTP against HLEBI dose at each $P_f$ value. The irradiation less than 0.13 MGy and more than 0.30 MGy enhances the $a_{uc}$ value of the CFRTP at high $P_f$ value of 0.94. Irradiation less than 0.13 MGy slightly enhances the $a_{uc}$ value of the CFRTP at mid $P_f$ value of 0.50.

Although the irradiation didn’t tremendously increase the $a_{uc}$ value at high $P_f$ value, remarkable effects of HLEBI from 0.13 to 0.43 MGy on $a_{uc}$ value of CFRTP have been obtained at low $P_f$ value of 0.06. The irradiation less than 0.30 MGy apparently enhances the $a_{uc}$ value of the CFRTP at low $P_f$ value of 0.06. 0.30 MGy HLEBI enhances the $a_{uc}$ value from 46 to 60 kJ/m$^2$. The $a_{uc}$ value of CFRTP irradiated at 0.30 MGy is about 32% higher than that without irradiation at low $P_f$ value of 0.06.

3.2 Dangling bond formation

From the conventional X-ray diffraction patterns of the carbon fiber before and after the EB irradiation, remarkable differences cannot be observed. On the other hand, EB irradiation in fact produces detectable dangling bonds. 7–9) To discuss the influences of electron beam irradiation on the Charpy impact values, ESR signals related to dangling bonds have been observed.

Figure 4(a) shows the ESR signals at 322.8 mT of PF with and without EB irradiation. ESR signals are observed for the PF samples before and after irradiation corresponding to dangling bonds (see Fig. 4(a)). As shown in Fig. 4(a), the
electron beam irradiation increases the intensity of ESR signal, which exhibits to generate the dangling bonds in PF. Figure 4(b) shows the ESR signals at 322.5 mT of carbon fiber with and without EB irradiation. A sharp ESR signal, corresponding to dangling bonds, is detected in the carbon fiber before irradiation (see Fig. 4(b)). EB-irradiation decreases the height of sharp ESR signal of carbon fiber.

4. Discussion

4.1 Influence of HLEBI on Weibull coefficient (n) of impact value of CFRTP

The Weibull coefficient (n) is one of the standard and traditional factors to compare with many other structural materials.\(^{18}\) When \(a_{uc}\) and \(a_0\) are the measured Charpy impact value and a constant, the fracture probability (\(P_f\)) as a function of the risk of rupture (\(a_{uc}/a_0\)) is expressed by the following equation.\(^{18}\)

\[
P_f = 1 - \exp[-(a_{uc}/a_0)^n] \tag{5}
\]

The linear relationship can be obtained as the following equation.

\[
\ln(-\ln(1 - P_f)) = n \ln a_{uc} - \ln a_0 \tag{6}
\]

Figure 5 shows Weibull plots of CFRTP irradiated by the electron beam at each dose. The n value corresponds to the slopes of the relationships of Weibull plots.

Figure 6 shows the change in n value against EB irradiation dose. The EB irradiation enhances the n value. The highest n value of CFRTP is obtained at 0.22 MGy. EB irradiation from 0.13 to 0.30 MGy apparently enhances the reliability related to the n value of impact value of CFRTP.

4.2 Effects of HLEBI on the lowest impact value

On the other hand, since the experimental impact values at less than 0.2 of low \(P_f\) value have largely deviated from the linear relationship (see Fig. 5), the practical impact value at low \(P_f\) value cannot be estimated.

If the statistic equation is assumed to be applicable to the measured \(a_{uc}\) value, the \(P_f\) value depends on the risk of rupture ([\(a_{uc} - a_s\)]/\(a_{III}\)).\(^{19,20}\)

\[
P_f = 1 - \exp[-([a_{uc} - a_s]/a_{III})^m] \tag{7}
\]

In predicting the required impact value of the new structural material, the lowest impact value (\(a_s\)), the coefficient (m) and constant (\(a_{III}\)) are key parameters. The \(a_{III}\) is the \(a_{uc}\) value at \(P_f\) of 0.632 when the term (\(\ln(-\ln(1 - P_f))\)) is zero. A change in the \(a_{III}\) value with respect to EB irradiation dose is also shown in Fig. 3. The \(a_{III}\) values of EB irradiated CFRTP are slightly less than that before treatment.

As the \(P_f\) value is equal to zero, the \(a_{uc}\) value is defined as the \(a_s\) value. When a correlation coefficient (F) of eq. (7) shows the maximum value, the potential (\(a_s\)) value can be determined to be as the lowest impact value (\(a_s\)) applied. Figure 7 shows changes in the F value with respect to EB irradiation dose. Since the F value is from 0.91 to 0.99 in Fig. 7, the relationships in Fig. 8 exhibit the high linearity.

Figure 9 shows variations of the \(a_s\) value against EB irradiation dose, together with the experimental \(a_{uc}\) value at the low \(P_f\) value of 0.06 for each sample. Since the \(a_s\) is the \(a_{uc}\) value at the lowest \(P_f\) value of 0, it is always lower than the experimental \(a_{uc}\) value at low \(P_f\) value of 0.06. Although the \(a_s\) value is zero for CFRTP before irradiation, HLEBI enhances the \(a_s\) value. HLEBI from 0.22 to 0.30 MGy, which exhibits the high \(a_s\) value of more than 50 kJ m\(^{-2}\), enhances the \(a_s\) value. Furthermore, the highest \(a_s\) value is more than 59 kJ m\(^{-2}\) for CFRTP irradiated at 0.30 MGy.

4.3 Effects of dangling bonds induced by HLEBI on impact value improvement of CFRTP constructed with carbon fiber, PF and their interface

Improvement of the impact value of CFRTP by HLEBI probably depends on strengthening carbon fiber, ductility enhancement of polymer matrix and enhancement of interfacial friction.
Based on the ESR signals of carbon fiber in Fig. 4, dangling bonds have been observed in carbon fiber before treatment. Based on the standard calibration material TEMPO (2,2,6,6-tetramethyl-4-piperidinol-1-oxyl) and Mn$^{2+}$ in the MnO, the density of dangling bonds is estimated by the double integrated intensity of ESR signal.\(^7\)-\(^9\)

Dangling bonds generally exist in carbon fiber before irradiation. Based on the ESR signals in Fig. 4(b), the densities of dangling bonds of carbon fibers before and after EB irradiation are \(5.63 \times 10^{15}\) and \(3.88 \times 10^{15}\) spins m\(^{-3}\), respectively. HLEBI often decreases the density of dangling bonds by annihilating them in the hexagonal atomic structure of graphite.\(^8\)-\(^9\) hence, it probably prevents the generation of cracks and often enhances the tensile fracture stress, and elasticity, resulting in ductility enhancement and strengthening of the carbon fiber.\(^7\)-\(^9\)

In addition, HLEBI often enhances the ductility and strengthening of the polymer matrix.\(^10\) Based on the ESR signals of PF in Fig. 4(a), dangling bonds have been also observed in PF before treatment. Based on the ESR signals in Fig. 4(a), dangling bonds are remarkably found in PF after HLEBI treatment, although they are slightly observed in PF before treatment. The densities of dangling bonds of PF samples before and after HLEBI are \(2.78 \times 10^{12}\) and \(5.39 \times 10^{14}\) spins m\(^{-3}\), respectively. HLEBI increases the density of dangling bonds. When the dangling bonds generated by HLEBI exist, the volume expansion of covalent bonded silica glass by HLEBI has been simultaneously obtained by using both mean atomic distance and coordination number estimated by the radial distribution function of XRD.\(^2\) Since the HLEBI forms the dangling bonds of mostly covalent bonded PF atoms, HLEBI probably expands the volume of PF. Namely, when HLEBI cuts the weak chemical bonds of PF, the repulsive force between terminated atoms with dangling bonds occurs, resulting in generating volume expansion at dangling bonds. The expansion induced by HLEBI generates the compressive stress in the PF matrix, which prevents generating and propagating the crack in the PF matrix.

When the compressive stress induced by HLEBI also enhances the friction force at the interface between carbon fiber and PF, it prevents the pull out of the carbon fiber from the PF matrix.

Based on both effects of compressive stress, HLEBI enhances the impact values of CFRTP. The interfacial friction force, as well as the strengthening of both carbon fiber and novolak-type phenol resin probably contributed to the HLEBI effects to enhance the \(a_s\) value of CFRTP.

On the other hand, additional EB irradiation of more than \(0.43\) MGy apparently decreases the impact value at low \(P_f\) value, as shown in Figs. 2 and 3.
carbon fiber, it probably not only generates many crack origins, but also links cracks with crack propagation. The decay of impact values of CFRTP irradiated at 0.43 MGy can be explained by the excess formation of dangling bonds.

### 4.4 Penetration depth of electron supplied from HLEBI system in CFRTP

Penetration depth of the electron beam is one of the serious challenges for dominating productivity and CFRTP thickness choice to apply for practical use. Based on the density ($\rho$: kg m$^{-3}$) and irradiation voltage ($V$: kV), the EB-irradiation depth ($D_{th}$: m) is expressed by the following equation.$^{16}$

$$D_{th} = 66.7V^{5/3}/\rho$$

$$\log D_{th} = \log 66.7 + 5/3 \log V - \log \rho$$ \hspace{1cm} (8)

The surface electrical potential (128 kV) is estimated from the electrical potential (170 kV), the 10 $\mu$m thickness of the titanium ($\rho = 4.54$ Mgm$^{-3}$) and irradiation voltage ($V$: kV) in the nitrogen gas atmosphere ($\rho = 1.13$ kg m$^{-3}$). Since the measured density of the CFRTP sample is 1.50 Mgm$^{-3}$, the EB-irradiation depth estimated from eq. (9) is $1.49 \times 10^{-4}$ m (149 $\mu$m). Figure 10 shows density dependent effective depth of EB-irradiation for carbon fiber ($\rho = 1.81$ Mgm$^{-3}$), PF ($\rho = 3.0$ Mgm$^{-3}$) and CFRTP, in which the volume fraction of carbon fiber in PF is 60.8 vol%. By using the relation and density, effective depth of EB-irradiation for carbon fiber, PF and CFRTP are 122, 170 and 148 $\mu$m. Since the effective depth of the sheet electron beam irradiation is 0.296 mm in the CFRTP, the irradiated depth from each sample surface is 14.8% of the CFRTP sample thickness of 2.0 mm.

On the other hand, the HLEBI depth ($D_{th}$: m), related to the mass thickness ($l_0$: gm$^{-2}$) and irradiation voltage ($E$: kV), is also expressed by the following equation suggested by Libby.$^{22}$

$$l_0 = E^{5/3}/150$$ \hspace{1cm} (10)

The estimated mass thickness is 348 gm$^{-2}$, when initial irradiation voltage is 170 keV. Since the mass thickness values of Ti foil ($l_0 = 17.8$ gm$^{-2}$) and N$_2$ gas ($l_0 = 1.50$ gm$^{-2}$) reduce the EB-irradiation depth, the mass thickness of CFRTP sample is 328 gm$^{-2}$. In addition, the irradiation voltage on sample surface is expressed by the following equation.

$$E = (150l_0)^{5/3}$$ \hspace{1cm} (11)

Based on the both concepts suggested by Christenhusz and Reimer (see eq. (9)$^{16}$) and Libby (see eq. (10)$^{22}$), the estimated depths of nylon6 ($\rho = 1.13$ Mgm$^{-3}$) are 196 and 290 $\mu$m, respectively. When the nylon6 sheets with 25 $\mu$m thickness are laminated, the ESR signals have been found at all nylon6 thin sheets of the irradiated laminated nylon6 sample with 250 $\mu$m thickness. The experimental depth (225 $\mu$m) approximately corresponds to the mid point (243 $\pm$ 47 $\mu$m) of both estimated values.$^{23}$ Thus, the experimental depth of other polymers can be probably predicted by both assumptions of Christenhusz and Reimer (see eq. (9)$^{16}$), and Libby (see eq. (10)$^{22}$).

On the other hand, the EB-irradiation depth of the present sample of carbon fiber reinforced thermoplastic novolak-type phenol resin (CFRTP) is predicted by both assumptions. The estimated depth of carbon fiber, PF ($\rho = 3.0$ Mgm$^{-3}$) and CFRTP are 122, 170 and 148 $\mu$m by using the assumption of Christenhusz and Reimer (see eq. (9)$^{16}$), and are 181, 252 and 219 $\mu$m by using the assumption of and Libby (see eq. (10)$^{22}$). Consequently, the effective irradiation depth of carbon fiber, PF and their CFRTP are probably 152 $\pm$ 30, 211 $\pm$ 41 and 182 $\pm$ 34 $\mu$m, respectively.

Although the irradiated depth estimated is 182 $\pm$ 34 $\mu$m on both sides’ surfaces of composite sheet with 2.0 mm thickness, we concludes that the HLEBI improves the impact value of the present CFRTP samples.

Based on the results of impact fracture of CFRTP at each $P_I$ value,$^{11}$ the interfacial fracture between fiber and matrix as well as bending fracture at the impact point occurs at high $P_I$ value, whereas the bending fracture mainly occurs at low $P_I$ value. Figure 11 shows photographs of fractured CFRTP samples before and after irradiation. The delamination fracture is shown for all untreated CFRTP samples. In addition, the pull-out phenomena is often observed for the untreated sample at high fracture probability of 0.94. Thus, the delamination, that is, inter-layer crack propagation mainly dominates the impact fracture for untreated CFRTP.

On the other hand, treatment at 0.30 MGy-HLEBI decreases the delamination fractured area without pull-out, because it perfectly prevents the delamination fracture at the CFRTP outside surface within 300 $\mu$m depth from the surface, which is slightly more than the penetration depth of irradiation in CFRTP. Therefore, 0.30 MGy-HLEBI is the good tool to enhance the $\alpha_{uc}$ value because of strengthening of the phenol CFRTP surface.

On the other hand, HLEBI doesn’t improve the $\alpha_{uc}$ value at high $P_I$ value within experimental errors, because the interfacial adhesive force of the CFRTP sample before irradiation is near the maximum value. Therefore, HLEBI improves the $\alpha_{uc}$ value at low $P_I$ values of the CFRTP samples.
5. Conclusion

In summary, the effects of homogeneous low voltage electron beam irradiation (HLEBI) on the impact value of novolak-type phenol CFRTP have been found, although the irradiated depth estimated is 182.5 ± 33.5 μm at both sides’ surfaces of composite sheet with 2 mm thickness.

(1) The experimental impact value ($a_u$) at low fracture probability ($P_f$) of 0.06 for CFRTP irradiated at 0.30 MGy (kJ g$^{-1}$) is 60 kJ m$^{-2}$, which is 32% higher than that of CFRTP before irradiation (46 kJ m$^{-2}$). Thus, the HLEBI enhances the fracture toughness related to impact values at low $P_f$ values.

(2) Although the $a_u$ value is zero for CFRTP before irradiation, HLEBI enhances the $a_u$ value. This is for the HLEBI from 0.22 to 0.30 MGy, which exhibits the high $a_u$ value of more than 50 kJ m$^{-2}$. Furthermore, the highest $a_u$ value is more than 59 kJ m$^{-2}$ for CFRTP irradiated at 0.30 MGy.

(3) Since HLEBI enhances the Weibull coefficient ($n$), it also enhances the reproductivity of CFRTP samples, as well as increasing the $a_u$ value. The maximum $n$ value is found at a HLEBI dose of 0.22 MGy.

(4) The interfacial friction force, as well as the strengthening of both carbon fiber and novolak-type phenol resin, probably contributes to the HLEBI effects to enhance the $a_u$ value of CFRTP.

Acknowledgement

Authors would like to thank Profs. Akira Tonegawa and Michael Faudree of Tokai University for their useful help. This work is partly supported by the Minister of Industry and ENSM-SE in France. The Phenol CFRTP was put up by Mr. Takahisa Nozawa of Tatsuo-syoikai, Ltd. and Asahi Organic Chemicals Industry Co., Ltd.

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