



# Synergetic effect of cross-linking and interfacial interaction in carbon fiber reinforced thermoplastic to enhance its tensile strength by electron-beam irradiation

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Received: 2 July 2019 / Revised: 31 July 2019 / Accepted: 7 August 2019 / Published online: 13 August 2019  
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## Abstract

A carbon fiber reinforced thermoplastic (CFRTP) was irradiated with a high energy electron-beam. As a result, the tensile strength of high-density polyethylene (HDPE)-based CFRTPs was significantly improved by gradually increasing the electron-beam dose. It was confirmed that the adhesion between CF and HDPE was improved and the surface properties of CF and HDPE were readily modified by electron-beam. It was verified from spectroscopic analysis that various oxygen-containing functional groups were formed on the surface of CF and HDPE by irradiation and we believe that strong attractive interactions took place among these functional groups at the interface of CFs and HDPE. Finally, it was conclusive that electron-beam irradiation provided two main effects on CFRTPs. One was cross-linking of thermoplastic resin for efficient load transfer from resin to CF and the other was formation of surface functional group and attractive interaction of these functional groups at the interface of fiber and matrix. These two effects showed synergetic contribution to enhance the mechanical properties of CFRTP.

**Keywords** Electron-beam irradiation · Carbon fiber reinforced thermoplastic · Oxygen-containing functional group · Fiber-matrix interface · Interfacial adhesion · Attractive interaction

## 1 Introduction

Carbon fiber reinforced plastics (CFRPs) are composite materials which consist of CF as reinforcing element and a polymeric resin as matrix material [1–3]. Recently, CFRPs have attracted much attention due to the fact that it maintains the advantage (low specific gravity) of plastic materials

while it displays the advantages of reinforcing material (high strength, elasticity) to overcome the disadvantages (low strength, elasticity, etc.) of plastic materials compared with metal. Thanks to these advantages, CFRPs are recently used in wide range of industries, including aerospace, marine, armor, military, automotive, electronic, medical and infrastructural applications [4–6].

In the early days of CFRP research and development, thermosets such as phenolic or epoxy resin were widely studied. However, problems such as low productivity (long manufacturing time due to the curing process) and low impact resistance of thermoset resins are still remained to be solved. In recent years, to overcome these problems, research and development of CFRP production using thermoplastic resin, called as carbon fiber reinforced thermoplastic (CFRTP) has been actively carried out. The advantage of thermoplastic resin is that it does not require any extra curing process or the like, so the productivity can be improved by shortening the overall manufacturing time. However, thermoplastic resins still have disadvantages such as low mechanical properties due to the poor contact behavior between CFs and thermoplastic resin.

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**Electronic supplementary material** The online version of this article (<https://doi.org/10.1007/s42823-019-00082-4>) contains supplementary material, which is available to authorized users.

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Therefore, extensive efforts have been made to enhance the adhesion between CF and thermoplastic resin by tailoring the surface properties of those. In general, CF-polymer matrix adhesion force is originated from chemical and mechanical bonding with each other [7]. Mechanical bonding is mainly due to the friction or mechanical interlocking between CF and polymer matrix. On the other hand, chemical bonds are mainly due to covalent bond or hydrogen bonds (H-bonds) between CF and polymer matrix molecules or functional groups, respectively [8, 9]. Various approaches have been developed to focus on the surface functionalization of CF, such as oxidation, coating and grafting to improve interfacial adhesion between CF and polymer matrix through methods using plasma [10–13], air oxidation [14], electrochemical oxidation [15], acid [16, 17], etc. [18–21]. Each of the above-mentioned methods possess potential draw-backs that it might damage the CF by excessive treatment and increase the pollution risk of our environment by utilizing toxic chemicals.

Meanwhile, electron-beam irradiation technology has been developed from the 1960s to cross-link polymers for cable sheath, foamed plastic, and radial tire industry [22–24]. In addition, thermoset resins such as epoxy and phenolic, could be effectively cured by electron-beam irradiation [25, 26]. The main advantages of this technology are high productivity, low cost, high product purity, eco-friendly, etc. On the other hand, it is also well known that surface modification by introduction of functional groups on various substrates could be conducted by electron-beam irradiation. Several literatures have reported the surface modification of CFs using electron-beam, plasma, etc. [27–30]. In those literatures, the common approach is treating the surface of CFs first and then incorporating the as-treated CFs in the matrix to enhance the adhesive behavior between CF and matrix.

In this work, we report that the tensile strength of high-density polyethylene (HDPE)-based CFRTP can be easily enhanced by simple electron-beam irradiation on the final composite material. Electron-beam irradiation was conducted on CFRTP specimens and their mechanical, physical and chemical properties were measured for different electron-beam doses. Finally, the surface characteristics of each components, i.e. CF and HDPE matrix was estimated and the rationale of the tensile strength enhancement was discussed.

## 2 Experimental

### 2.1 Raw materials

Commercial long fiber thermoplastic (LFT) pellets were purchased from PlastiComp, Inc. (USA). The pellets were

consisted of 30 w% CFs with length of 12 mm which were impregnated in high-density polyethylene (HDPE) resin (photo for LFT pellets are displayed in Figure S1 of Supporting Information). The pellets were dried overnight at 80 °C prior to injection molding for dog-bone specimen preparation to evaporate the adsorbed water. For comparison, pure HDPE pellets were also purchased from PlastiComp, Inc. and handled with identical conditions of the LFTs. Xylene was purchased from Sigma-Aldrich and used without further purification for gel-contents measurement. For the single fiber pull-out test, CFs were kindly provided from PlastiComp, Inc. and used as-received. The specific information (maker and model) of CFs were difficult to obtain due to corporate confidentiality.

### 2.2 Specimen preparation

The dog-bone specimens for tensile testing were prepared according to ASTM D638 standard (photo for dog-bone specimen is displayed in Figure S1 of Supporting Information). In detail, the dried HDPE-based LFT and pure HDPE pellets were injection molded by an injection molding machine (LGE-110II, LS MTRON Ltd., Republic of Korea). The dog-bone specimens prepared from HDPE based LFT and pure HDPE pellets were named as HDPE\_LFT and HDPE, respectively. These dog-bone specimens were electron-beam irradiated and utilized for further characterization. On the other hand, specimens for X-ray photoelectron spectroscopy (XPS) and single CF pull-out tests were exceptionally prepared. For XPS, specimens were prepared by impregnating a CF tow in HDPE resin for subsequent electron-beam irradiation. After irradiation, the CF tow was pulled out from the resin for XPS measurement. Fifteen points on the surface of pulled out CF tow were measured for each dose and sorted by two groups. The first group represented the surface which CFs were measured and the other group represented the surface of HDPE. For single CF pull-out test, one filament of CF was placed between a glass substrate and HDPE filament. The CF and HDPE filament were crossed at right angle (90 degree) and the HDPE filament was melted and re-solidified by heating the glass substrate on a hot-plate. The as-prepared samples were subjected to electron-beam irradiation prior to pull-out tests.

### 2.3 Electron-beam irradiation

Electron-beam irradiation was conducted at a facility of Korea Institute of Industrial Technology (KITECH, Republic of Korea). The beam energy and current were fixed at 5 MeV and 5 mA, respectively, during all irradiation experiments. The specimens were placed on an aluminum tray and were irradiated by passing below the electron-beam (photo for specimen loading for irradiation is displayed in Figure S1

of Supporting Information). The absorbed dose rate of the specimens was estimated as 6.8 kGy/s (20 kGy/pass) and the total absorbed dose was controlled by repeating the irradiation cycle (by increasing the pass number) to achieve 200, 400, 800, 1200 and 2000 kGy. All electron-beam irradiation was performed under air atmosphere and room temperature. The electron-beam irradiated HDPE\_LFT and HDPE for 200 kGy absorbed dose were named as HDPE\_LFT-200 and HDPE-200, respectively. This naming rule was identically applied for all absorbed doses from 400 to 2000 kGy.

## 2.4 Characterization

The tensile properties of electron-beam irradiated HDPE\_LFT and HDPE dog-bone specimens were measured on a universal testing machine (UTM, INSTRON 5967, USA). The average and standard deviation of tensile strength, Young's modulus, and strain-to-failure were obtained by measuring five samples for each electron-beam doses. All tests were conducted at a gauge length, strain rate, temperature, and humidity of 50 mm, 50 mm/min, 23 °C, and 50%, respectively. The fracture surfaces after the tensile testing of HDPE\_LFT specimens were observed on a scanning electron microscope (SEM, AIS 2300C, Seron Technologies, Republic of Korea). Fourier transform-infrared (FT-IR) spectroscopy was performed on an infrared microscope (IRT 5200, Jasco, Japan). The tensile properties of CFs which were subjected to electron-beam irradiation were measured on an individual fiber test system (FAVIMAT+, Textechno, Germany). The gauge length and testing speed were 25 mm and 5 mm/min, respectively. Fifteen filaments were measured for each sample. The gel-contents of irradiated HDPE\_LFT and HDPE were measured using a modified ASTM 2765 method. In detail, 0.4–0.5 g of irradiated samples were placed in a 400 mesh stainless steel pouch and

extracted in xylene for 14 h at 150 °C. After extraction, the residual was dried for 24 h at 150 °C to completely evaporate the remaining xylene. The gel contents for irradiated HDPE were calculated from the dried residual weight. In case of irradiated HDPE\_LFT, the CF weight was theoretically subtracted from the dried residual weight to calculate the gel contents because CF could not be removed by xylene neither before nor after electron-beam irradiation. The single CF pull-out test was conducted on TXA Texture Analyzer (YEONJIN S-Tech, Republic of Korea) at a tensile testing rate of 0.1 mm/s. The interfacial shear strength (IFSS) was calculated from the measured maximum force value of the force-strain curves for more than five samples for each electron-beam doses. XPS was conducted on a spectrometer system (K-Alpha, Thermo Fisher Scientific Messtechnik GmbH, Germany) with micro-focused Al K $\alpha$  (1486.6 eV). The peak position of C–C bond was calibrated to 285.0 eV during all measurements.

## 3 Results and discussion

The stress–strain (S–S) curves of electron-beam irradiated HDPE\_LFTs are shown in Fig. 1a. The HDPE\_LFT specimens showed a typical curve for CFRTPs regardless of electron-beam irradiation. Interestingly, the S–S curve gradually shifted upward accompanied with an increment of ultimate tensile strength as the electron-beam dose was increased. Figure 1b clearly displays the tensile strength increment of HDPE\_LFTs as a function of electron-beam dose. From the series of electron-beam irradiation experiments, it was found that the tensile strength could be enhanced by 38 MPa (from  $134 \pm 1$  MPa at 0 kGy to  $172 \pm 4$  MPa at 2000 kGy, ~28% increase) by simply increasing the electron-beam dose. Meanwhile, the Young's modulus and strain-to-failure did

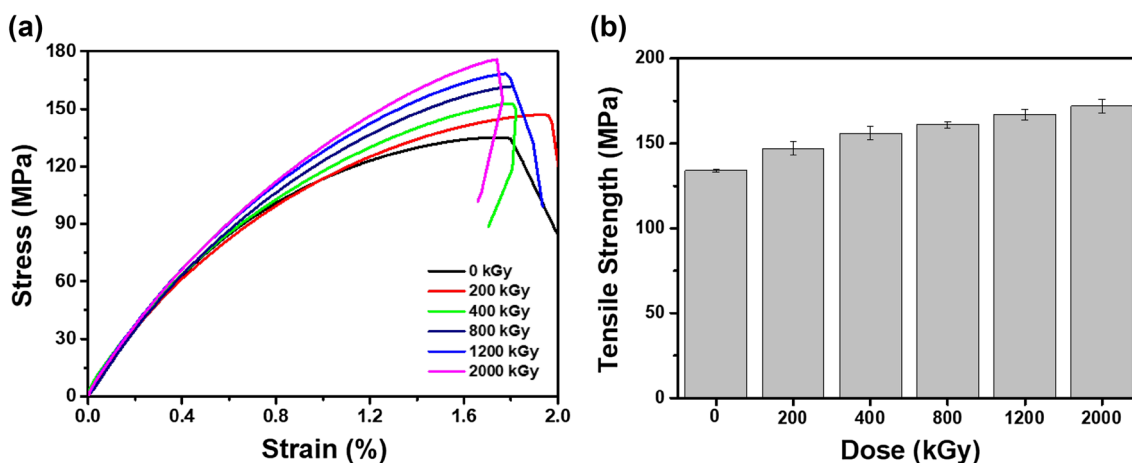
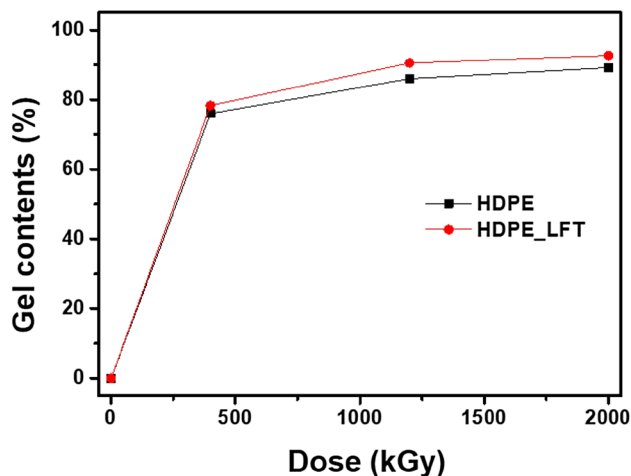


Fig. 1 (a) S–S curves and (b) plot of tensile strength for HDPE\_LFTs irradiated at various electron-beam doses

not significantly change after irradiation (the mechanical properties of all specimens are summarized in Table S1 of supporting information with further explanation). Further chemical and spectroscopic analysis were conducted to focus to reveal the reason of these increment in tensile strength.

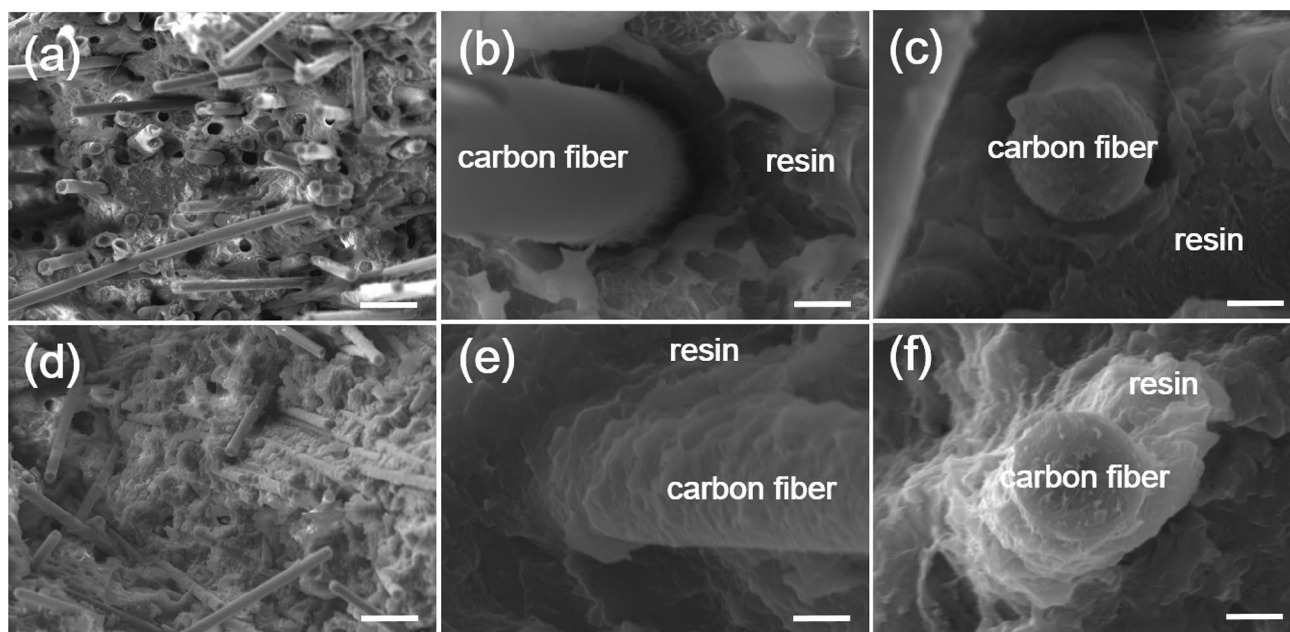
Figure 2 shows the gel contents of irradiated HDPE\_LFT and HDPE at different electron-beam doses. It is well known that several polymers, including HDPE could be easily cross-linked by electron-beam irradiation to form gels and its amount increases as the dose increases [31–33]. In our



**Fig. 2** Gel contents for HDPE\_LFT and HDPE specimens irradiated at various electron-beam doses

study, similar results were obtained for both HDPE\_LFT and HDPE due to the cross-linking of HDPE by irradiation. The gel contents steeply increased as ~80% at 400 kGy and gradually increased to ~90% until 2000 kGy. Therefore, it was estimated that most of the cross-linking was formed for HDPE\_LFT and HDPE at 400 kGy and additional irradiation contributed for minor amount of further cross-linking. Interestingly, the gel contents of HDPE\_LFT samples were higher than that of pure HDPE at same electron-beam doses. From these results, we could be able to speculate that additional gels were formed in case of HDPE\_LFT by irradiation, in other words, additional HDPE gels were remained after resolving in xylene due to the presence of CFs in HDPE\_LFT.

After tensile testing of HDPE\_LFT dog-bone specimens, the fracture surface was observed by SEM before and after irradiation on HDPE\_LFT to investigate the interface of carbon fiber and HDPE resin. By comparing Fig. 3a, d, it was obvious that the fracture surface before and after irradiation of HDPE\_LFT showed a significant difference. First of all, many carbon fibers were pulled out from the resin to leave holes in the resin before irradiation of HDPE\_LFT. Furthermore, a great portion of carbon fiber were protruded from the fracture surface. These results reflected the poor interfacial adhesion between the cylindrical surface of carbon fiber and HDPE resin. Higher magnification observation clearly revealed this poor adhesion by the existence of small gaps between the fiber cylindrical surface and resin (Fig. 3b, c). However, after electron-beam irradiation on HDPE\_LFT, the



**Fig. 3** SEM images of fracture surface for HDPE\_LFT specimens. (a–c) HDPE\_LFT before electron-beam irradiation and (d–f) HDPE\_LFT irradiated at 2000 kGy. (b, e, c, f) Shows the side and vertical

view of the CF, respectively, along with the surrounding HDPE resins. The scale bar for a, d and b, c, e, f are 30 and 3  $\mu$ m, respectively

fracture surface showed that holes in the resin due to fiber pull-out had significantly diminished and the carbon fiber protruded from the fracture surface was still covered with HDPE resin. Figure 3e, f showed that the fiber cylindrical surface and the small gap between fiber and resin were covered with the resin. Based on the gel contents measurement and SEM observation results, it could be deduced that the interfacial adhesion between carbon fiber and HDPE resin was enhanced due to electron-beam irradiation.

To quantitatively investigate the improvement of CF-resin interfacial adhesion, single CF pull-out test was performed and the results are shown in Fig. 4. By increasing the electron-beam dose, the IFSS increased from  $34.8 \pm 10.4$  at 0 kGy to  $60.6 \pm 13.8$  MPa at 2000 kGy, which finally gave  $\sim 26$  MPa enhancement in interfacial shear strength. The increment of IFSS was significant for 1200 and 2000 kGy, yet negligible for 400 kGy compared to non-irradiated samples. Reminding the fact that the tensile strengths of

irradiated HDPE\_LFTs were gradually increased by increasing the electron-beam dose, it was further studied by evaluating the contribution of each components of HDPE\_LFT, i.e. CF and HDPE resin at different electron-beam doses. The mechanical properties of pure HDPE and CFs due to electron-beam irradiation are shown in Fig. 5. It was found that the tensile strengths of CFs were consistent despite of irradiation which were subjected to various electron-beam dose. However, the tensile strength of HDPE was enhanced by irradiation. By increasing the electron-beam dose as 0, 400, 1200, and 2000 kGy, the tensile strength of HDPE increased as 23.1, 24.6, 25.9, and 27.3 MPa, respectively. Therefore, the tensile strength was gradually enhanced by electron-beam irradiation on HDPE and total 4.2 MPa ( $\sim 18\%$ ) was increased at 2000 kGy. Based on these results, it was conclusive that the tensile strength enhancement of HDPE\_LFTs by irradiation was partially attributed by the HDPE component. However, this result could not solely

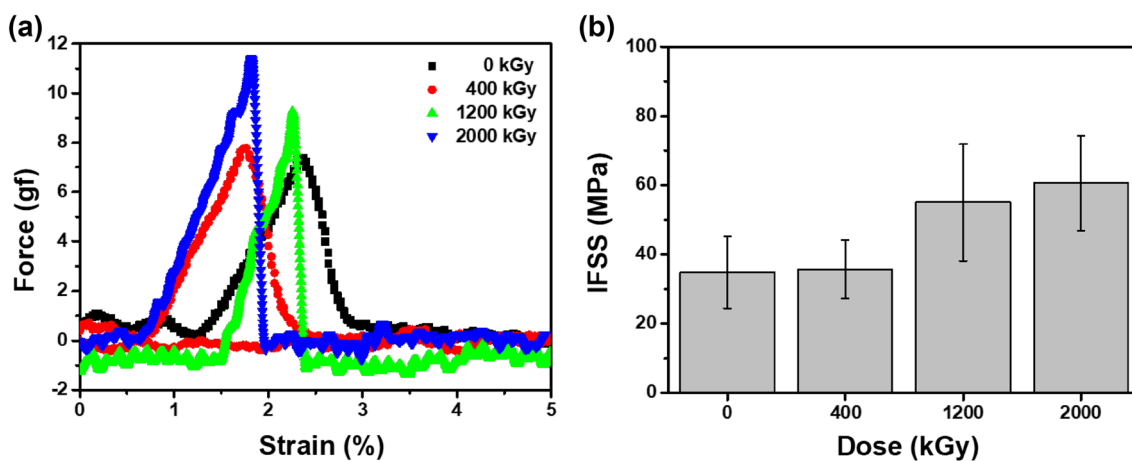


Fig. 4 (a) Force-strain curve and (b) calculated IFSS for single CF-HDPE resin pull-out test at various electron-beam doses

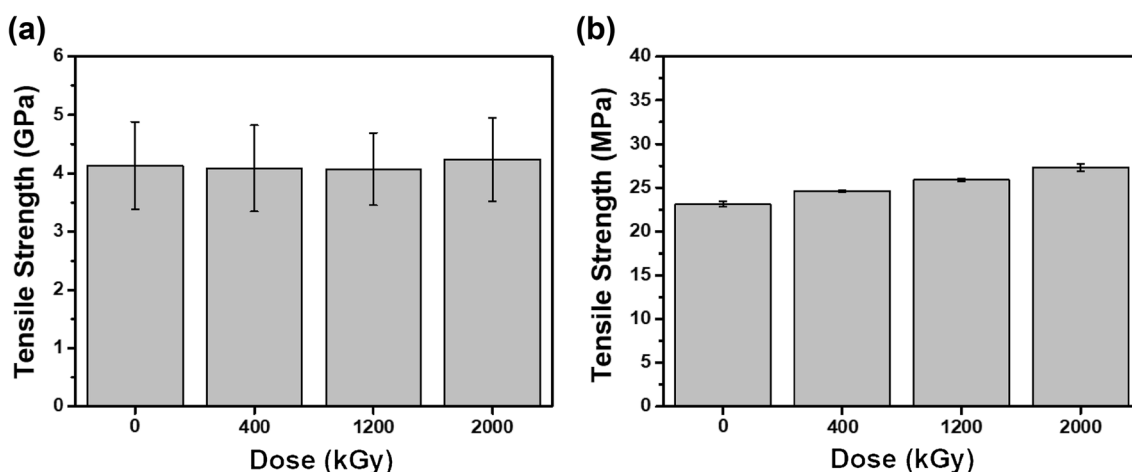


Fig. 5 Plot of tensile strength for (a) CF and (b) HDPE irradiated at various electron-beam doses

explain the tensile strength increment of HDPE\_LFTs for all electron-beam doses, especially high doses such as 1200 and 2000 kGy.

Therefore, the physiochemical and surface properties of HDPE, CF and HDPE\_LFTs were further evaluated. First, the surface functional groups of each samples were analyzed by FT-IR. Figure 6 shows the FT-IR spectra of HDPE, CF, and HDPE\_LFT irradiated at various electron-beam doses. HDPE exhibited typical vibration modes at 2914, 2847, 1462, and 719  $\text{cm}^{-1}$  corresponding to C-H stretching,  $\text{CH}_2$  bending and rocking, respectively. By increasing the electron-beam dose, a new vibration mode developed at 1714  $\text{cm}^{-1}$  which corresponded to ketone C=O stretching (pointed in Fig. 6a). In addition, the development of alcoholic O-H stretching (3200–3500  $\text{cm}^{-1}$ ) could be noticed at especially high doses (1200 and 2000 kGy). In case of CF, CFs exhibited various vibration modes before irradiation (Fig. 6b). Typical vibration modes indicated the existence of amide (N-H and C=O stretching at 3542 and 1683  $\text{cm}^{-1}$ ), alcohol (O-H stretching, bending and C-O stretching at 3200–3500, 1396 and 1049  $\text{cm}^{-1}$ , respectively) and carboxylic acid (O-H and C=O stretching at 2500–3000 and 1775  $\text{cm}^{-1}$ ) groups on the CF surface [19, 21, 34]. These functional groups originate from the sizing material which are generally coated on commercialized CF products. After irradiation, the development of alcoholic O-H and C-O stretching at 3200–3500 and 1049  $\text{cm}^{-1}$ , respectively, could be clearly observed (pointed in Fig. 6b). Based on these observations, it was found that HDPE and CFs were modified with oxygen-containing functional groups such as ketone, alcohol and carboxylic acid. Finally, by analyzing HDPE\_LFT after irradiation, the development of alcoholic O-H stretching (3200–3500  $\text{cm}^{-1}$ ), ketone C=O stretching (1710  $\text{cm}^{-1}$ ), carboxylic acid/alcoholic O-H bending

(1410/1369  $\text{cm}^{-1}$ ) and alcoholic C-O stretching (1143–1000  $\text{cm}^{-1}$ ) vibration modes were observed (pointed in Fig. 6c). It is noteworthy that the wavenumbers of ketone C=O stretching (1710  $\text{cm}^{-1}$ ) and alcoholic O-H bending (1369  $\text{cm}^{-1}$ ) of HDPE\_LFT were down-shifted compared to its wavenumber measured for HDPE (1714  $\text{cm}^{-1}$ ) and CF (1396  $\text{cm}^{-1}$ ), respectively, after irradiation. Therefore, it was evident that specific functional groups were formed on HDPE and CFs which strongly interacted with each other in HDPE\_LFT after irradiation.

Further in-depth analysis of the surface properties (chemical state and composition) were evaluated by XPS. Figures 7 and 8 shows the XPS spectra of HDPE and CF, respectively, before and after electron-beam irradiation. The survey scan clearly verified that the O1 s signals of HDPE and CF were significantly increased by irradiation (the atomic percentages of carbon and oxygen for HDPE and CF are summarized in Table 1). Detailed peak deconvolution revealed that C-O and O-C=O bonds were strongly developed by irradiation for both HDPE and CF [35–40]. For HDPE, the development of C=O and C-O bonds were obvious in the C1 s and O1 s spectra which were consistent with the FT-IR results due to the formation of ketone and alcoholic groups by irradiation. Moreover, it was noteworthy that the peak positions up-shifted for 0.3–1.3 eV at 2000 kGy (Table 2). In case of CF, the development of C-O and O=C-O bonds were significant which verified the formation of alcoholic and carboxylic acid groups by irradiation. Up-shifts in peak positions for 0.3–0.6 eV were measured, however, down-shift of 0.4 eV for O=C-O was observable at 2000 kGy (Table 2). We believe that these shifts were originated from the strong interaction of functional groups formed by irradiation on HDPE and CF. It could be properly explained that the C-OH formed on HDPE and C-OH/C-OOH formed on CF acted as

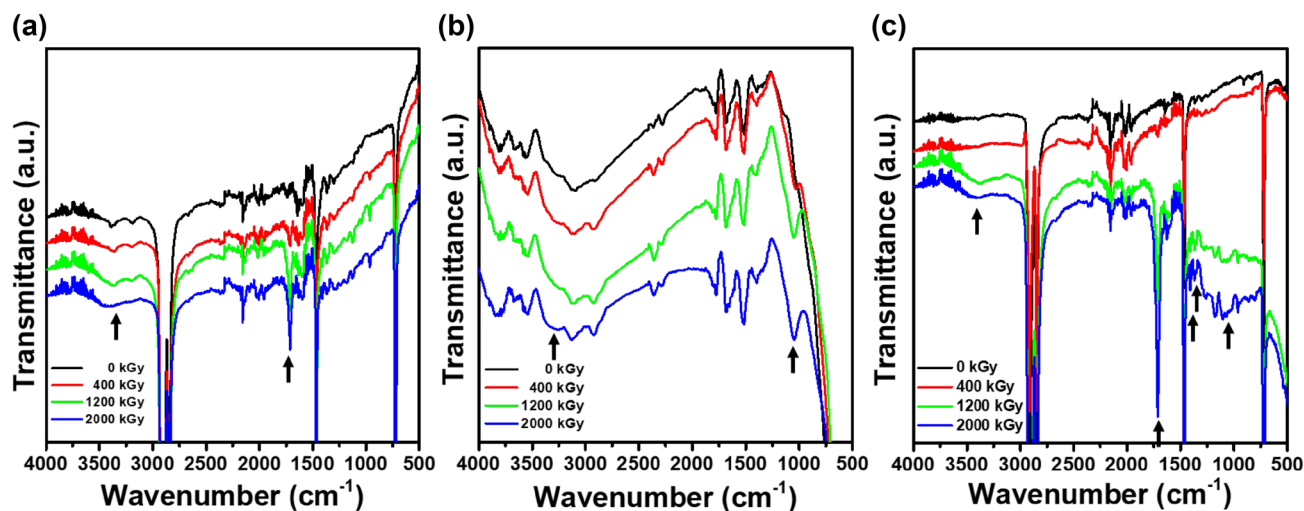
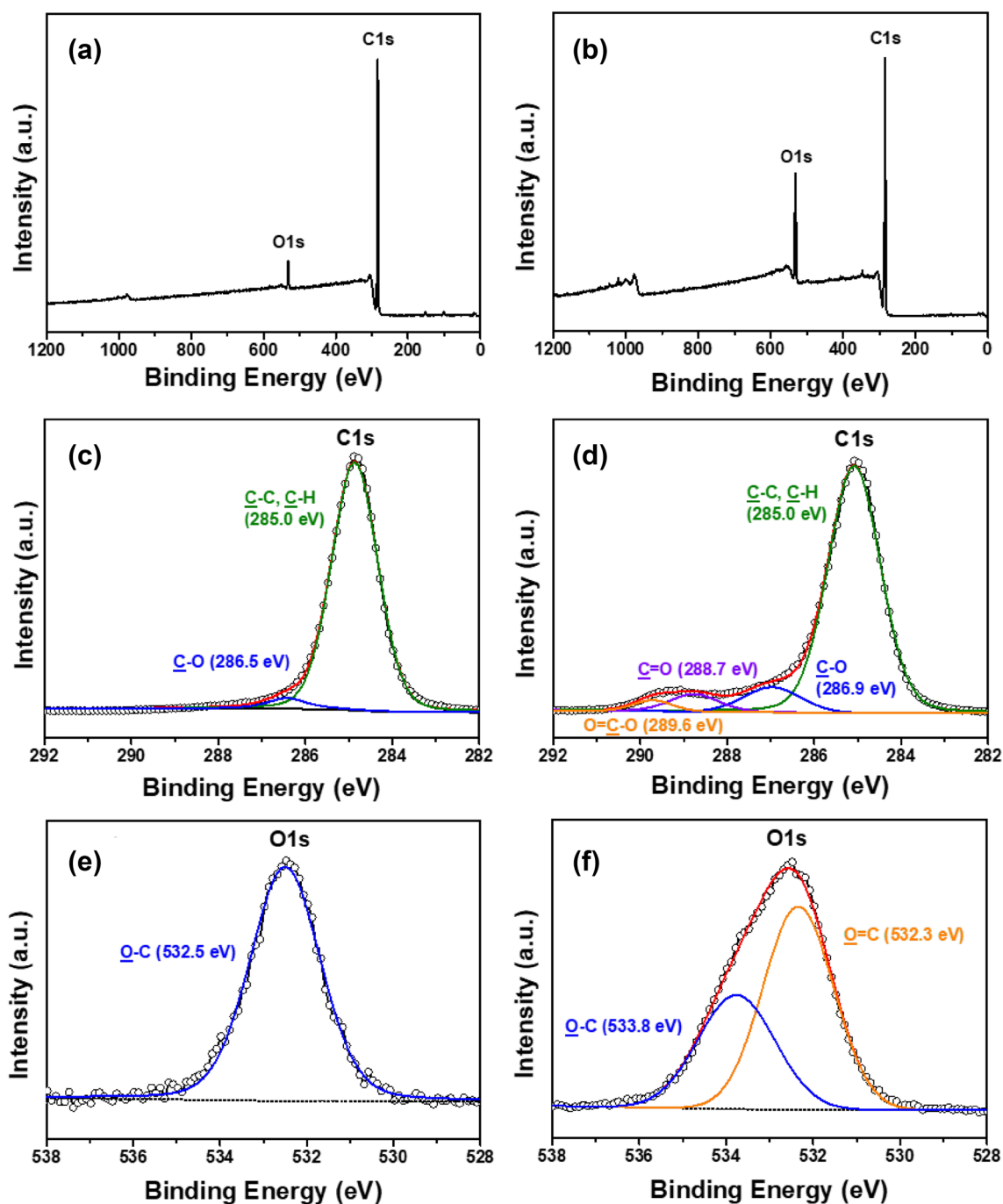


Fig. 6 FT-IR spectra of (a) HDPE, (b) CF and (c) HDPE\_LFT irradiated at various electron-beam doses

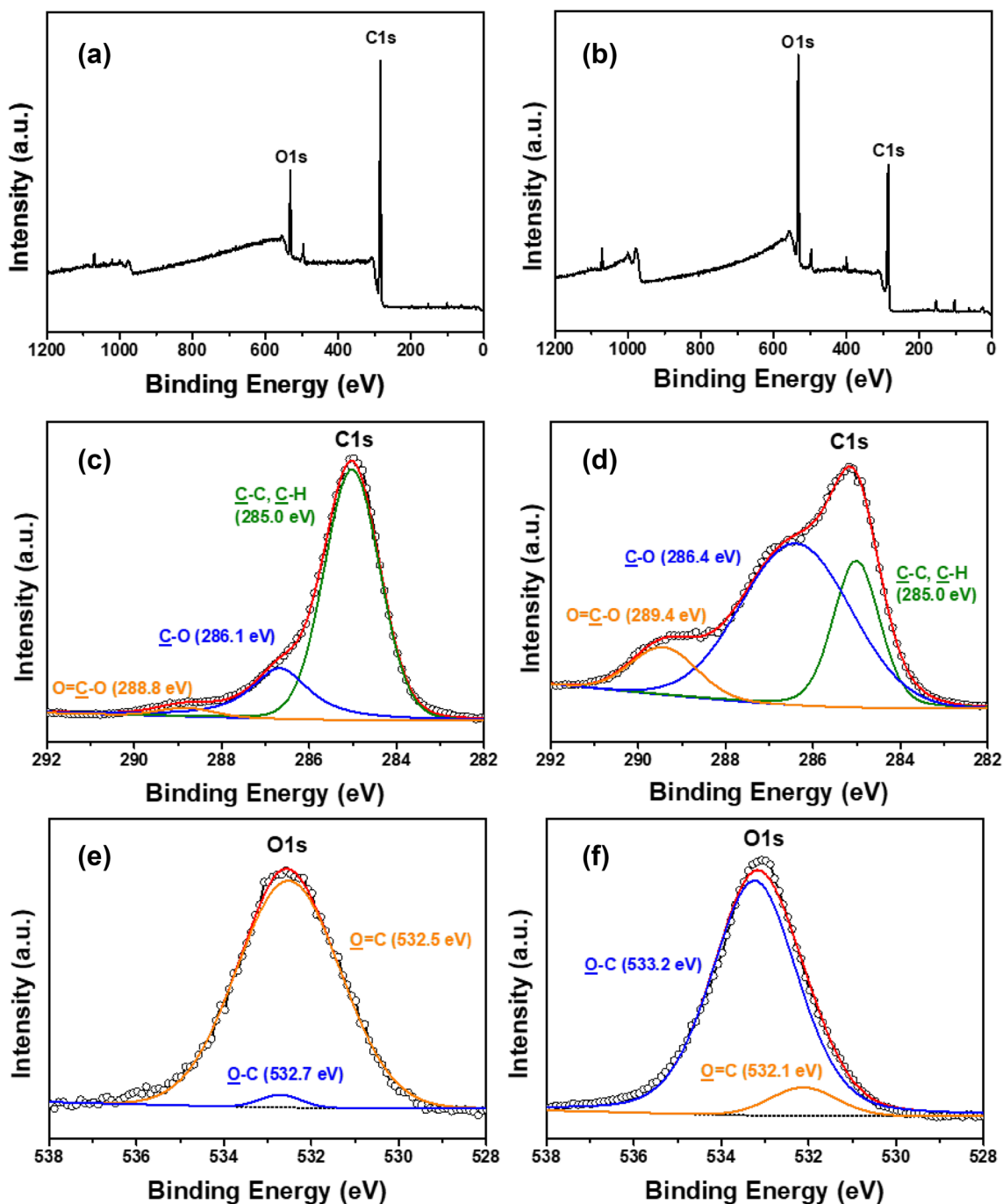


**Fig. 7** (a, b) Survey, (c, d) C1 s, and (e, f) O1 s scan XPS spectra of HDPE, a, c, e before and b, d, f after electron-beam irradiation at 2000 kGy

a hydrogen bond donor ( $\delta^+$ ), therefore, increased the binding energy of C1 s and O1 s orbital electrons. On the other hand, the C=O of C–OOH formed on CF acted as a hydrogen bond acceptor ( $\delta^-$ ) which decreased the binding energy of O1 s orbital electrons.

The formation and interaction of these functional groups in a composite material are due to the fact that the whole irradiation process was conducted under air

atmosphere with certain level of humidity. It is well known that radical species created by irradiation (from oxygen, water vapor and the irradiating material) could be easily recombined to form oxygen-containing functional groups on the surface of the irradiating material [41–43]. Therefore, it was conclusive that the surface of HDPE and CFs in HDPE\_LFT were modified with oxygen-containing functional groups by irradiation and those polar groups



**Fig. 8** (a, b) Survey, (c, d) C1 s, and (e, f) O1 s scan XPS spectra of CF. a, c, e Before and b, d, f after electron-beam irradiation at 2000 kGy

**Table 1** Atomic composition of HDPE and CF before and after electron-beam irradiation

	0 kGy		2000 kGy	
	C (at%)	O (at%)	C (at%)	O (at%)
HDPE	91.17	5.56	81.25	16.45
CF	83.69	12.71	61.16	29.96

formed strong attractive hydrogen bonds to enhance the tensile strength of HDPE\_LFTs.

Finally, based on our results, we believe that the tensile strength increment of HDPE\_LFTs by electron-beam irradiation was originated from two factors. The first factor is the mechanical property enhancement of the matrix itself. Due to cross-linking of HDPE by electron-beam irradiation, the tensile strength of HDPE matrix was enhanced and this



**Table 2** XPS peak positions before and after electron-beam irradiation of HDPE and CF in HDPE\_LFT

	Binding energy (eV)	C 1 s				O 1 s	
		C–C/C–H	C–O	C=O	O=C–O	Q=C/O=C–O	Q–C
HDPE	0 kGy	285.0	286.5	–	–	–	532.5
	2000 Gy	285.0	<u>286.9</u>	288.7	289.6	532.3	<u>533.8</u>
CF	0 kGy	285.0	286.1	–	288.8	532.5	532.7
	2000 kGy	285.0	<u>286.4</u>	–	<u>289.4</u>	<b>532.1</b>	<u>533.2</u>

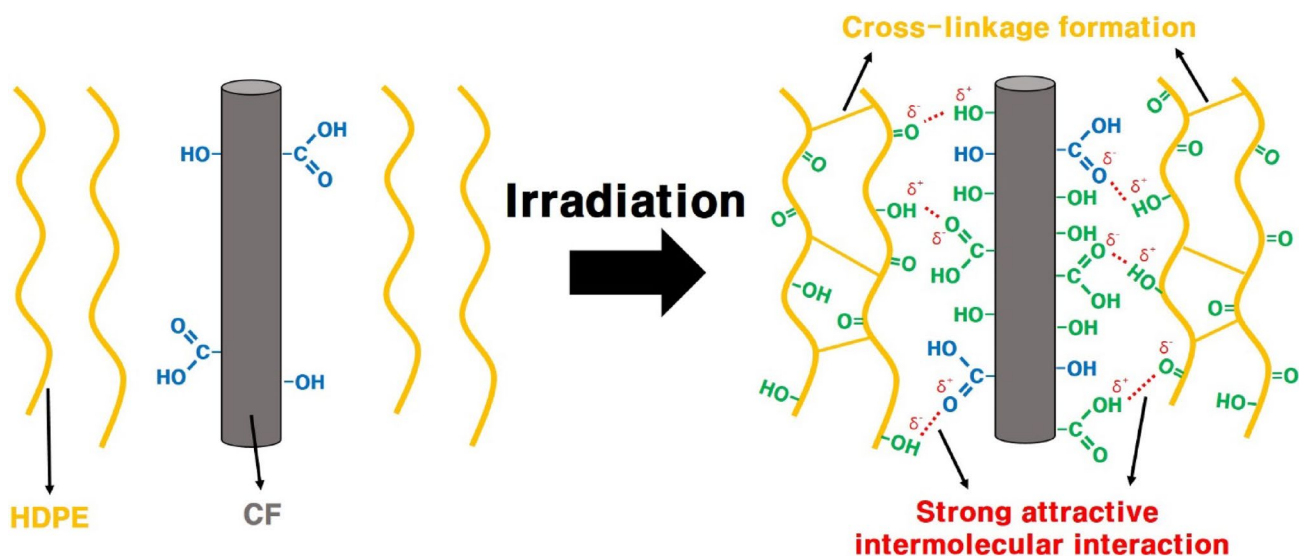
Underlined and bolded value indicates the up-shifted and down-shifted peak positions after irradiation, respectively

consequentially contributed to the final mechanical properties of the composite material. It is well known that for two phase composites, a certain proportion of the load would be carried out by the fiber and the remainder by the matrix [44, 45]. Therefore, by enhancing the mechanical properties of HDPE matrix by radiation cross-linking, a certain amount of additional external load could be carried by the improved matrix material. The second and crucial factor is the formation and interaction of oxygen-containing functional groups to enhance the interfacial adhesion force between the CF and resin material. Figure 9 illustrates the interaction between the surface functional groups of CF and HDPE resin proposed by this work. The electron-beam irradiation on HDPE\_LFTs led to the formation of various functional groups throughout the whole specimen, including the surface of each components, i.e. CF and HDPE. Therefore, we assume that these polar functional groups have strongly interacted with each other to finally enhance the tensile strength of HDPE based CFRTP. To verify our assumption, we have conducted several subsidiary experiments and the results are summarized in Table S1 of supporting

information. The results showed that by introducing an antioxidant in HDPE\_LFT and conducting electron-beam irradiation under relatively dry air atmosphere, the tensile strength enhancement was suppressed by restraining the formation of oxygen-containing functional groups. In conclusion, the tensile strength of HDPE\_LFT was simply enhanced by electron-beam irradiation which was due to the cross-linking effect of resin material and attractive interaction of polar oxygen-containing functional groups formed on the surface of CF and resin material.

## 4 Conclusions

A HDPE based CFRP (HDPE\_LFT) was irradiated by an electron-beam to enhance its mechanical properties. By increasing the electron-beam dose, the tensile strength of HDPE\_LFT gradually increased. However, the Young's modulus and strain-to-failure showed no statistically significant difference despite of irradiation. It was found that the adhesion between CFs and HDPE resin was improved



**Fig. 9** Illustration of functional group formation in HDPE\_LFT by electron-beam irradiation and its suggested intermolecular interaction. Green characters correspond to the formed functional groups by irradiation

by electron-beam irradiation which was verified qualitatively and quantitatively by microscopy and single fiber pull-out test, respectively. HDPE could be easily cross-linked by irradiation which partially contributed to the tensile strength enhancement of HDPE\_LFTs at relatively low dose (400 kGy). However, the cross-linking effect of the resin did not solely enhance the tensile strength of HDPE\_LFTs. By irradiation to higher doses (1200 and 2000 kGy), various polar oxygen-containing functional groups were formed in HDPE\_LFTs. In detail, ketone C=O and alcoholic C–OH groups were remarkably developed in HDPE and alcoholic C–OH/carboxylic acid C–OOH groups were additionally formed on CFs. It was verified that these functional groups strongly interacted with each other at the interface of HDPE and CFs to enhance the tensile strength of HDPE\_LFT at high irradiation doses. Based on our results, we believe that electron-beam irradiation could be a powerful and simple method to enhance the mechanical properties of other thermoplastic based CFRPs.

**Acknowledgements** This work was supported by a Grant from the National Research Foundation (NFR) of Korea (NRF-2017M2A2A6A02071124), Republic of Korea.

## Compliance with ethical standards

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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