Recent Improvements of Strengthening FRP

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Strengthening carbon and glass fibers reinforced polymers (FRPs) were recently developed by using pre-stress [1-3] and electron beam irradiation [4-10]. Optimal conditions were mainly caused by strengthening polymers matrix and/or fibers, as well as resistance to pull-out by adhesion and/or compressive stress at interface.

Firstly, Since the pre-stressing generates the compressive stress of matrix inside, effects of pre-stressing on tensile strength [1] and impact value [2, 3] of high strength carbon fiber reinforced polymers (CFRP's) with low [1,2] and high [3] volume fraction of carbon fibers were introduced.

In order to strengthen 3 vol% continuous unidirectional 0 degree oriented carbon fiber reinforced epoxy polymer (CFRP), effects of a pre-stressing on mechanical properties in stress-strain curve of tensile and impact tests have been investigated [1, 2]. The pre-stressing remarkably improves the apparent elastic constant, tensile strength, fracture strain and Charpy impact value. Based on micro-hardness test, they probably depend on the residual compressive stress induced by the pre-stressing in CFRP [1]. Optimal conditions were mainly caused by both strengthening polymers matrix induced by compressive stress at matrix inside and resistance to pull-out induced by compressive stress at interface.

Effects of tensile pre-stress level on Charpy impact value (auc) of 50 vol% continuous unidirectional 0 degree oriented carbon fiber reinforced epoxy polymer (CFRP) were investigated [3]. Experimental results showed the auc at mid-fracture probability Pf = 0.50 induced by a large pre-stress of 17.6 MPa (109 kJm^{-2}) was increased 30% over that (84 kJm^{-2}) of slight pre-stress of 0.25 MPa. The statistically lowest impact value as at Pf = 0 calculated by 3-parameter Weibull equation was raised 26% from 73 to 92 kJm^{-2} showing increased reliability of part strength. Fracture surface observation showed a flat surface extending through the thickness from the impact side generally extends deeper as pre-stress level was raised. This may be due to the transition depth in the specimen thickness from compression to tension is deeper during impact as pre-stress level was increased acting to raise the impact values [3].

Although strengthening CFRP induced by pre-stress is for sample inside with long process term of more than one day [1-3], surface strengthening CFRP and GFR induced by homogeneous low potential electron beam irradiation (HLEBI) is for the samples outside near surface with short process term less than one second [4-12]. In order to strengthen CFRPs outside, 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 [4]. 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 [4]. Furthermore, improvements of Charpy Impact of Carbon Fiber Reinforced Polymer (CFRP) of Epoxy [5], PEEK [6] and Phenol [7] by HLEBI and EBI-effects on Elasticity of CFRTP (CF/PEEK) [8] were introduced. In addition, EBI effects on bending modulus and impact value in injection-molded short carbon fiber reinforced PEEK were also introduced [9].

Finally, EBI-strengthening of optical fiber [10], as well as glass fiber reinforced polymers (GFRP) of epoxy [11] was introduced.

Furthermore, effects of HLEBI on Charpy Impact Value of Short Glass Fiber Reinforced Thermoplastic Polymer Bulk Mold Compounds (SGFRTP-BMC) samples were also introduced [12]. Compression-molded short-fiber SGFRTP-BMC panels have random distribution of solidification texture angles from zero to 90 degrees in the center of the mother panels. Hence, there is significantly lower impact strength in the panel center than in the outside. However, experimental results showed HLEBI applied to the center region apparently enhances the Charpy impact values (auc) 5 to 25%. Fracture mechanism was observed to convert at auc > ～5.4-6.7 kJ·m−2 from clean to secondary microcrack proliferation and/or bends near the main crack, with increasing fracture surface area as auc increased. SEM observation revealed 0.86 MGy HLEBI treated SGFRTP-BMC had much more polymer adhering to glass fibers than the untreated. This increased matrix adhesion can be explained by electron spin resonance (ESR) peaks indicating dangling bonds are generated creating repulsive forces between outer shell electrons in the polymer matrix, apparently exhibiting increased compressive stress on the glass fibers increasing adhesion force. Moreover, the lone pair electrons generated in the matrix had bonded with the glass fibers more efficiently. For these reasons, increased glass fiber-polymer matrix adhesion seen in the 0.86 MGy samples appeared to assist for more internal cracking, increasing resilience to impact of the SGFRTP-BMC, raising the auc. [12].

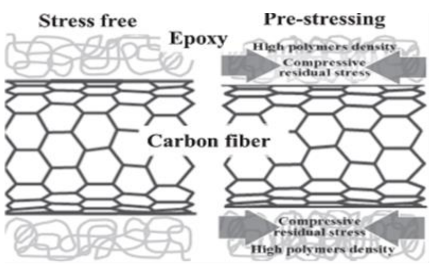
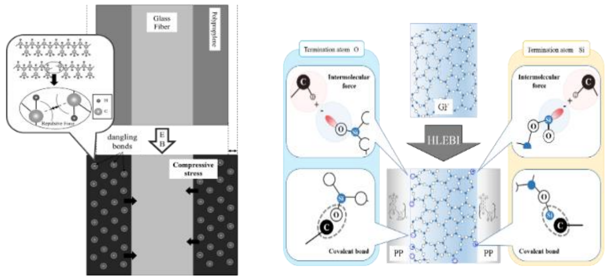


Figure 1: *Schematic drawing of mesoscopic structures of CFRP with and without pre-stressing.*



(a) (b)

Figure 2: *Surface (a) and Bulk (b) HLEBI-strengthening of GFRTP of PP.*

The EBI-surface strengthening of GFRTP with inexpensive thermoplastic polypropylene (PP) [13] was also introduced. HLEBI to surface improved the auc of composites sheets of its GFRTP with 2.5 mm thickness, although the irradiated depth was estimated to be less than 0.3 mm at the both surface. HLEBI from 0.22 to 0.43 MGy mostly improved the auc of more than 50 kJ/m2 at low accumulative probability of fracture (Pf) of 0.06 with smaller variation in the data. On the other hand, a new process of internal activation of GFRTP of PP was achieved by HLEBI to the interlayered glass fiber chopped strand mats (GF-CSM) prior to assembly. Panels were fabricated by hot-press consisting of 5 HELBI-treated GF-CSMs between 6 untreated PP sheets [14]. HLEBI improved the auc of the internally activated GFRTP. HLEBI from 0.22 to 0.86 MGy mostly improved the auc at each Pf. The highest as values at more than 87 kJ/m2 were found for GFRTP irradiated at 0.65 MGy which appears to be at or near the optimum HLEBI dose. induced Bulk-Strengthening the adhesion force at the extremely broad surface area of the fibers increased interfacial friction force to prevent fiber pull out, fiber/matrix debonding and crack generation in the hard to adhere PP matrix GFRTP, resulting in increasing auc of GFRTP with glass fiber surface-activated by HLEBI. Consequently, the surface strengthening FRPs were mainly caused by strengthening polymers matrix within a few hundred μm depth and/or fibers, as well as improving resistance to pull-out by adhesion and compressive stress at interface.

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