Radiation Resistance of Composite Organic Insulators at Low Temperatures

S. EGUSA
Japan Atomic Energy Research Institute, Japan
M. SUGIMOTO, H. NAKAJIMA, K. YOSHIDA, H. TSUJI
Japan Atomic Energy Research Institute, Nakamachi, Ibaraki, Japan

ABSTRACT

The radiation resistance of composite organic insulators was evaluated with regard to the mechanical strength at 77 K. The radiation resistance is almost independent of the type of fabric weave and the kind of glass fibers so far as the matrix resin is identical. The radiation-resistance evaluation was made also for the bond strength of composite organic insulators to stainless steel at 77 K. The radiation resistance of the bond strength appears to depend primarily on the load transfer mode at the insulator/steel interface.

1. INTRODUCTION

When composite organic insulators are used in the construction of superconducting magnets for Tokamak type fusion reactors, one of the most serious concerns is the radiation resistance in the mechanical and electrical properties at 4.2 K. This is because the fusion magnets are inevitably subjected to substantial quantities of neutrons and γ-rays during the fusion-reactor operation, thus leading to significant degradation of the magnet component materials such as insulator, stabilizer, and superconductors (Kulcinski et al. 1986). Probably the degradation is most serious for composite organic insulators and, consequently, the operation lifetime of the fusion magnets may be virtually determined by the radiation resistance of the insulators.

From this point of view, we have been studying the irradiation effects in polymer matrix composites since 1983, mainly with regard to the mechanical properties at low temperatures (Egusa 1990). In the course of the studies, it was found that an epoxy of tetraglycidyl diaminodiphenyl methane (TGDDM) cured with diamino diphenyl sulfone (DDS) is quite promising as matrix resin of composite insulators to be used in fusion magnets, thus stimulating our interest in studying further the irradiation effects in the TGDDM/DDS epoxy matrix composites.

In the present work, TGDDM/DDS epoxy and polyimide matrix composites were prepared by using various reinforcing fabrics. These composites were irradiated with ^{60}Co γ-rays or 2 MeV electrons at room temperature, and were tested with regard to the mechanical properties at 77 K. The present paper mainly describes the dose dependence of the composite strength at 77 K.

In actual fusion magnets, composite organic insulators are used to separate conductors from each other or to separate them from the magnet case (Nakajima et al. 1988). As design data for fusion magnets, therefore, the radiation-resistance evaluation should be made not only for the insulator

itself but also for the bond strength of the insulator to the conductor or to the magnet case. From this point of view, we studied the irradiation effects on the bond strength between polymer matrix composite and stainless steel by using the so-called lap shear specimens. This paper describes also the dose dependence of the bond strength tested at 77 K.

2. EXPERIMENTAL

Polymer matrix composites prepared in this work are shown in Table 1. The matrix resin was an epoxy of TGDDM/DDS or a polyimide of polyaminobismaleimide (Kerimid 601), and the reinforcing filler was plain-woven glass fabrics shown in Table 2. The E-glass fabrics of KS-1210 and KS-1600 were selected so as to differ from each other in the number of fibers in a yarn and, consequently, in the number of yarns per 25 mm in the warp and weft directions. The T-glass fabrics of WTX-116E and WTA-18W, on the other hand, were selected so as to be the counterparts of KS-1210 and KS-1600, respectively, with respect to the type of fabric weave. The composite plates thus prepared were cut into rectangular specimens of 6.4 mm width and 70 mm length, with the 70 mm axis parallel to the warp direction of the reinforcing fabrics.

Table 1. Polymer matrix composites prepared

Composite	Reinforcing fabric	Matrix resin	Volume fraction of fibers (%)	Average thickness (mm)
Glass/epoxy I	KS-1210	TGDDM/DDS	63	1.81 ± 0.07
Glass/epoxy II	KS-1600	TGDDM/DDS	66	1.98 ± 0.04
Glass/epoxy III	WTX-116E	TGDDM/DDS	63	2.12 ± 0.01
Glass/epoxy IV	WTA-18W	TGDDM/DDS	58	1.99 ± 0.02
Glass/polyimide I	KS-1210	Kerimid 601	62	2.05 ± 0.06
Glass/polyimide II	WTX-116E	Kerimid 601	50	1.99 ± 0.03
Glass/polyimide III	WTA-18W	Kerimid 601	60	1.96 ± 0.01

Table 2. Reinforcing fabrics used

Reinforcing fabric[a]	Fiber type[b]	Fiber diameter (μm)	Number of fibers in a yarn	Weave style	Number of yarns per 25 mm	
					Warp	Weft
KS-1210	E-glass	7	200	Plain	53	48
KS-1600	E-glass	9	400	Plain	41	32
WTX-116E	T-glass	7	200	Plain	60	58
WTA-18W	T-glass	9	400	Plain	44	34
WPT-18D	T-glass	10	400	Satin	45	31
T-0.18S	T-glass	9	400	Satin	40	34

[a] Manufacturer: Kanebo (KS-1210, KS-1600); Nitto Boseki (WTX-116E, WTA-18W, WPT-18D); Arisawa Mfg (T-0.18S).

[b] E-glass composition (wt%): SiO_2(55.2), Al_2O_3(14.8), CaO(18.7), MgO(3.3), B_2O_3(7.3), Na_2O+K_2O(0.5), Fe_2O_3(0.3), F_2(0.3), TiO_2(0.1).
T-glass composition (wt%): SiO_2(65), Al_2O_3(23), CaO(<0.01), MgO(11), B_2O_3(<0.01), Na_2O+K_2O(<0.1), Fe_2O_3(<0.1), Zr_2O_3(<1.0).

Table 3. Prepreg plies used in preparing lap shear specimens

Manufacturer	Reinforcing fabric	Matrix resin	Volume fraction of fibers (%)	Number of prepreg plies used
Arisawa Mfg	T-0.18S	BT-A300[a)]	53	3
Hitachi Chemical	WPT-18D	BT-2160[a)]	63	3
Nitto Boseki	WTA-18W	TGDDM/DDS	60	5

[a)]BT resins manufactured by Mitsubishi Gas Chemical for metal-to-metal adhesive (BT-A300) and tacky prepreg (BT-2160) applications.

Lap shear specimens were prepared by three different manufacturers using the prepreg plies shown in Table 3. In these prepreg plies, the reinforcing filler was T-glass fabrics shown in Table 2 and the matrix resin was bismaleimide-triazine (BT) resin or TGDDM/DDS epoxy resin. These prepreg plies were sandwiched between two semicircular rods of stainless steel and were heated under pressure, thus obtaining a lap shear specimen. The width and length of the lap (bond) area were 13 x 30 mm^2 and the thickness of the lap layer was 0.41-0.57 mm. The shape and dimensions of the stainless steel rods were exactly the same as those used by Poehlchen et al. (1990).

^{60}Co γ-ray irradiations were carried out in air at room temperature with dose rates of 12-17 kGy/hr for composite specimens and 9.6 kGy/hr for lap shear specimens. For some composite specimens, 2 MeV electron irradiations were carried out at the specimen temperature of 53℃ with a dose rate of 11.5 MGy/hr.

Three-point bend tests were conducted at 77 K for composite specimens. The tests were made at a crosshead speed of 0.6 mm/min with a span length of 20 mm. The ultimate flexural strength was calculated from $3P_f(\ell/h)/2bh$, where P_f is the applied load at failure, ℓ is the span length, b is the specimen width, and h is the specimen depth (thickness). For lap shear specimens, on the other hand, compression tests were conducted at 77 K at a crosshead speed of 0.6 mm/min. The bond strength between polymer matrix composite and stainless steel was calculated from P_f/Lw, where L is the lap length and w is the lap width. The three-point bend tests and the compression tests were usually repeated three and four times, respectively, thus obtaining an average value and the standard deviation for each data point.

3. RESULTS AND DISCUSSION

3.1. Effect of reinforcing fabric type

Fig. 1 shows plots of the ultimate flexural strength at 77 K versus the absorbed dose due to ^{60}Co γ-rays for the glass/epoxy I-IV composites having different reinforcing fabrics shown in Table 2. It is seen that the initial strength of the KS-1210 or WTX-116E fabric composite is 28-40% higher than that of the KS-1600 or WTA-18W fabric composite, thus indicating that the initial strength is dependent on the fabric weave parameters such as the number of fibers in a yarn and the number of yarns in the warp and weft directions. It is also seen that the initial strength is less dependent on whether the reinforcing fiber is E-glass or T-glass. Following irradiation the strengths of these composites decrease monotonically with increasing absorbed dose. Roughly, the dose dependence appears to follow a rather simi-

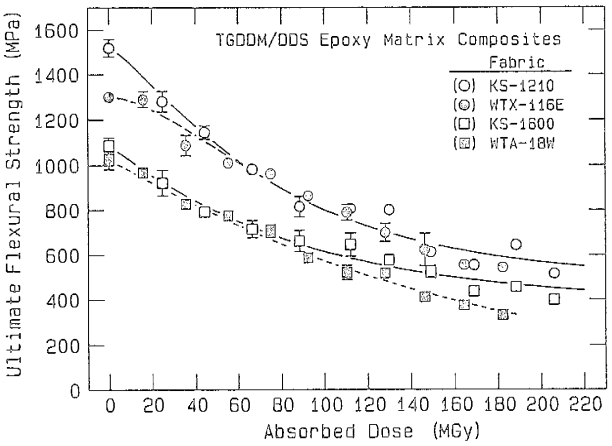

Fig. 1. Plot of the ultimate flexural strength at 77 K versus the absorbed dose due to ^{60}Co γ-rays for the glass/epoxy I-IV composites having different reinforcing fabrics shown in Table 2.

lar pattern for all of these composites, thus suggesting that the degradation behavior of the composite flexural strength depends neither on the type of fabric weave nor the kind of glass fibers. This result is consistent with a degradation mechanism proposed by Egusa (1988) such that the dose dependence of the composite flexural strength is primarily determined by a change in the matrix ultimate strain due to irradiation. In agreement with this mechanism, the composite degradation behavior was essentially independent of the type of reinforcing fabric for the glass/polyimide I-III composites also.

The fact that the T-glass fiber composites are comparable to the E-glass fiber composites in their radiation resistance towards γ-rays is of great importance from the standpoint of their applications to fusion magnets. This is because composite insulators in actual fusion magnets are subjected to neutrons and γ-rays simultaneously, with more than half of the total absorbed dose resulting from neutrons. It is now generally recognized that the neutron irradiation of boron-containing E-glass fiber composites produces additional radiation damage due to a $^{10}B(n,\alpha)^{7}Li$ reaction in E-glass fibers, thus significantly decreasing the radiation resistance of the composites towards neutrons (Egusa et al. 1987a; 1987b). For boron-free T-glass fiber composites (see Table 2), on the other hand, the extent of the radiation damage due the ^{10}B reaction will be negligible, thus leading to a higher radiation resistance towards neutrons compared to the E-glass fiber composites. These considerations lead to a conclusion that the T-glass fiber composites are recommended over the E-glass fiber composites as component materials to be used in fusion magnets.

3.2. Effect of radiation type

Because the dose rate attainable for ^{60}Co γ-rays is relatively low, it often happens that the irradiation time for a desired dose may be longer than 1 year. For electrons from an accelerator, on the other hand, the dose rate is fairly high, and consequently the irradiation time can be shortened considerably. For some purposes such as screening and preliminary tests, therefore, electrons will be preferable to γ-rays if the two types of radiation are equivalent in the irradiation effects in polymer matrix composites.

From this point of view, the irradiation effects of 2 MeV electrons were compared with those of ^{60}Co γ-rays with regard to the composite strength at 77 K. The result is shown in Fig. 2 for the glass/epoxy I and II composites. Comparison of the electron and γ-ray data points for each composite shows

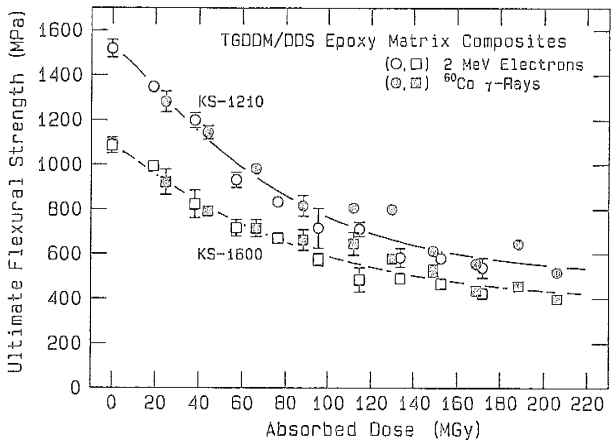

Fig. 2. Plot of the ultimate flexural strength at 77 K versus the absorbed dose due to 2 MeV electrons or ^{60}Co γ-rays for the glass/epoxy I and II composites.

that the dose dependence of the composite strength follows an identical pattern regardless of the type of radiation. Thus it is concluded that the irradiation effects of ^{60}Co γ-rays can be simulated by electron irradiation so far as the mechanical strength of polymer matrix composites is concerned.

It should be pointed out, however, that the composite degradation behavior for neutrons is essentially different from that for ^{60}Co γ-rays because of a difference in the stopping power between the two types of radiation (Egusa et al. 1987a; 1987b). As sources of design data for fusion magnets, therefore, the radiation resistance of polymer matrix composites should be studied separately for neutrons and γ-rays, although electrons may be used in place of γ-rays to shorten the irradiation time for a desired dose.

3.3. Bond strength between polymer matrix composite and stainless steel

Fig. 3 shows plots of the bond strength at 77 K versus the absorbed dose due to ^{60}Co γ-rays for three kinds of lap shear specimens shown in Table 3. It is seen that the initial bond strength of the Arisawa specimens is about 50% higher than that of the Hitachi or Nitto specimens. Following irradiation the bond strength of the Arisawa specimens decreases monotonically with increasing absorbed dose. For the Hitachi and Nitto specimens, on the other hand, such a decrease in the bond strength is quite small or practically nil even at 50 MGy.

Such a difference in the degradation behavior of lap shear specimens may be ascribed to differences in the mode of load transfer at the interface between polymer matrix composite and stainless steel. In general, such an interface is known to have at least two modes of load transfer, i.e., the chemical bond mode and the friction force (mechanical bond) mode. Possibly the bond strength between polymer matrix composite and stainless steel is due for the most part to the friction force mode, and this mode is much less sensitive to radiation compared to the chemical bond mode. This idea appears to explain why the bond strength is hardly changed by irradiation for the Hitachi and Nitto specimens. For the Arisawa specimens, on the other hand, the chemical bond mode may be added to the friction force mode, thus increasing the initial bond strength and, at the same time, making the bond strength more sensitive to radiation. At present, however, no evidence supporting these speculations is available. Further studies are required for a detailed discussion of this point.

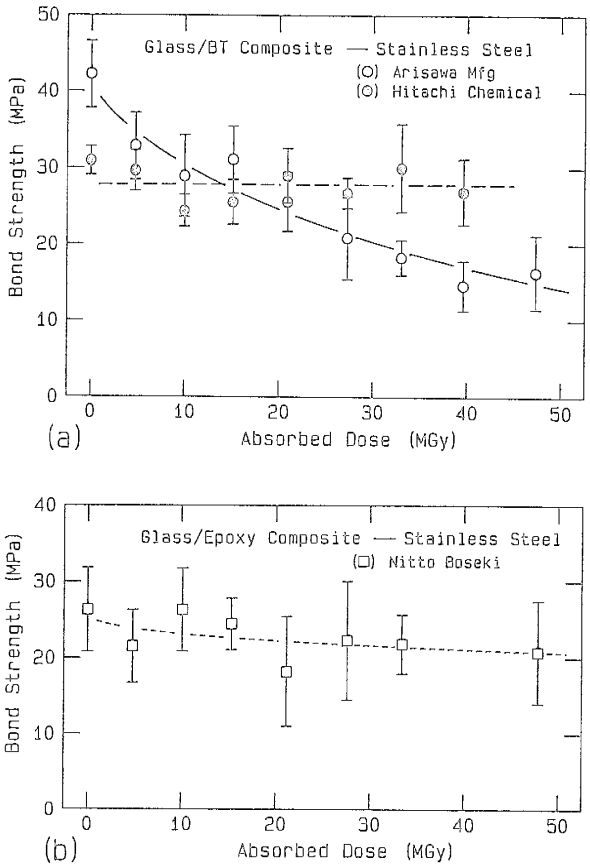

Fig. 3. Plot of the bond strength at 77 K versus the absorbed dose due to ^{60}Co γ-rays for lap shear specimens shown in Table 3.

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