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Mechanical properties of the ITER central solenoid model coil insulation under static and dynamic load after reactor irradiation

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Abstract

The candidate insulation system for the central solenoid (CS) model coil of the International Thermonuclear Experimental Reactor (ITER) is CTD-112P, an epoxy with a two-dimensionally woven S-glass-fiber reinforcement. Because of the pulsed operation of ITER, both the static and the fatigue behavior of the material have to be assessed under the actual operating conditions, including the appropriate radiation environment at the magnet location. To obtain information on the radiation-induced material degradation, the material was irradiated at ambient and low temperatures to neutron fluences of 5×10^{22} m^{-2} ($E > 0.1$ MeV). After measurements of swelling and weight loss, all experiments were carried out at 77 K. Half of the 5 K irradiated samples were subjected to a warm-up cycle to room temperature before testing. Tensile and short-beam-shear tests characterize the material in tension and interlaminar shear. Stress–lifetime diagrams of tensile and double-lap-shear specimens were assessed under tension–tension fatigue load up to 10^6 cycles. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Radiation effects on insulating materials for the windings of superconducting magnets in future fusion reactors, i.e. glass-fiber reinforced plastics (FRPs), have been identified as an area of concern for the long-term operation of such magnets [1]. We addressed the influence of the radiation spectrum on the damage process of FRPs and simulated the operating conditions of the magnet insulation in previous work [2,3].

The interlaminar shear strength (ILSS), which is the most sensitive indicator of material failure in FRP laminates [3], was assessed from short-beam-shear (SBS) tests. The small and simple specimen geometry offers advantages in view of the space limitations in low-temperature irradiation facilities. In addition, tensile tests were made for measuring the ultimate tensile strength (UTS).

Because of the pulsed operation of fusion devices such as International Thermonuclear Experimental Reactor (ITER), both the static and the fatigue behavior of the material have to be assessed. We, therefore, started experiments on the tensile and the interlaminar shear behavior also under dynamic loading conditions on small specimen geometries, which are suitable for low temperature irradiation [4,5].

In this contribution, we present results on the candidate insulation system for the primary turn insulation of the central solenoid (CS) model coil of ITER along the lines of our program.

2. Experimental procedures

The samples were cut from a 2 mm thick laminate of CTD-112P, manufactured by Composite Technology Development, CTD, Lafayette, CO, USA. This material consists of a S-2 glass fabric (weave style 6580, silane

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finish, 50 vol.% fiber fraction) in an epoxy matrix (TGDM, 15 wt% Al_2O_3 as filler) and is used as a hot-melt, solvent-less prepreg system.

Irradiations were performed with 2 MeV electrons at ~340 K up to 10, 30 and 100 MGy, and in fission reactors both at ~340 and 5 K to neutron fluences of 10^{21}, 10^{22} and 5×10^{22} m^{-2} ($E > 0.1$ MeV), before testing at 77 K. Table 1 summarizes the selected irradiation facilities. In the case of neutron-induced damage, the total absorbed dose in the laminate was calculated using the computer code SPECTER [2,6].

Tensile (ASTM D638 and DIN 53455) and SBS tests (ASTM D2344) were used for the assessment of the UTS and the ILSS. Because of space limitations in the low-temperature irradiation facility, the UTS was determined on small samples, scaled down from the standard geometries [2]. All static tests were carried out at 77 K using a servohydraulic MTS 810 TestStar II Material Testing System in combination with a cryostat, in which either the tensile grips or the SBS device [3] were used for loading the specimens. The cross-head speed was 0.5 (UTS) and 1.3 mm min^{-1} (ILSS), respectively. For the ILSS, half of the samples were subjected to an annealing cycle to room temperature (~1 day) before testing. In the results, each data point represents an average calculated from four (irradiation at ~340 K) and two measurements (irradiation at 5 K), respectively. The anisotropic FRPs were loaded under their strongest direction, i.e. the fiber orientation with the higher content was parallel to the longer specimen dimension.

For the investigation of the tensile and interlaminar shear behavior under dynamic load at 77 K, the samples were irradiated in the Triga reactor to a neutron fluence of 5×10^{21} m^{-2} ($E > 0.1$ MeV), which represents the specified dose level for the organic insulation systems of ITER. The main parameters of these tension–tension fatigue experiments (ASTM D3479) were set to meet the ITER operating conditions as closely as possible. During sinusoidal loading (load controlled, 10 Hz, up to 10^6 cycles) of the scaled down tensile and double-lap-shear samples [4,5], the stress ratio R was chosen to be 0.1, i.e., the tensile load cycled from a certain starting point to 10% of this value and back. As starting points 85%, 75%, 65%, 55%, 45%, 35% and 25% of the static strengths at 77 K (UTS and ILSS) were chosen and the cycles to failure counted. Five measurements were done at each stress level and stress–lifetime diagrams (S/N curves, Wöhler curves) were plotted.

3. Results and discussion

The dose dependence of the UTS and the ILSS of CTD-112P irradiated in the Triga reactor prior to testing at 77 K is presented in Fig. 1. The UTS (unirradiated 938 MPa) remains nearly constant up to ~60 MGy and decreases to ~85% of its initial value at the highest dose (~280 MGy). The ILSS (unirradiated 80 MPa) remains nearly constant up to ~6 MGy, but decreases considerably (to ~30% of its initial value) at ~280 MGy.

A comparison of the dose dependence of the ILSS following irradiation under various radiation environments is shown in Fig. 2. The irradiation in the FRM Garching leads to a severe degradation of the ILSS above a dose of ~35 MGy. The cold-transferred samples (i.e. 5 → 77 K) show slightly higher ILSS values (5–20%) than the warm-transferred samples (i.e. 5 → 293 → 77 K) over the whole dose range. However, these warm-up

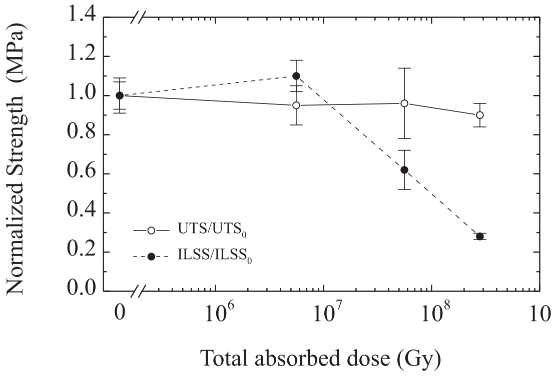

Fig. 1. Normalized UTS and ILSS as a function of total absorbed dose.

Table 1
Characteristic data of irradiation facilities

Irradiation source location	Irradiation temperature (K)	Radiation parameters		
		Dose rate (Gy h^{-1})	Fast neutron flux density ($E > 0.1$ MeV) (m^{-2} s^{-1})	Total neutron flux density (m^{-2} s^{-1})
Triga Mark II Vienna, Austria	Ambient	1×10^6	7.6×10^{16}	2.1×10^{17}
FRM Munich Garching, Germany	5	2.8×10^6	2.9×10^{17}	9.5×10^{17}
2 MeV electron accelerator JAERI, Takasaki Japan	Ambient	3.6×10^6	–	–

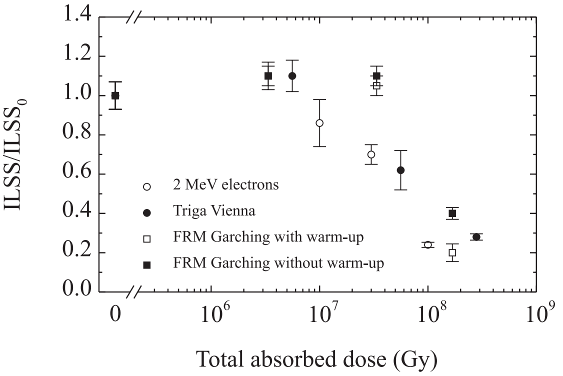

Fig. 2. Normalized ILSS of short-beam-shear specimens as a function of total absorbed dose following electron and reactor irradiation. ILSS$_0$ is the ILSS before irradiation (80 MPa).

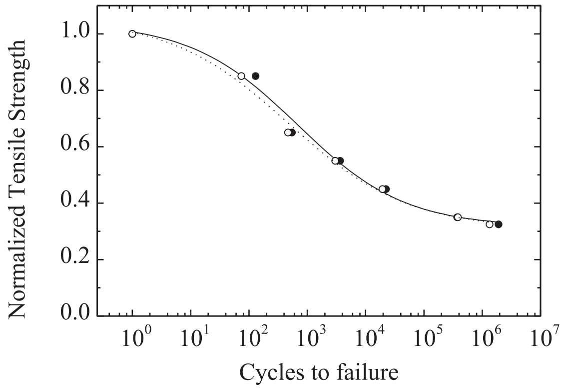

Fig. 3. S–N curves of unirradiated (solid circles) and irradiated (open circles) tensile specimens. The curves are normalized by the UTS (938 MPa unirradiated, 890 MPa irradiated).

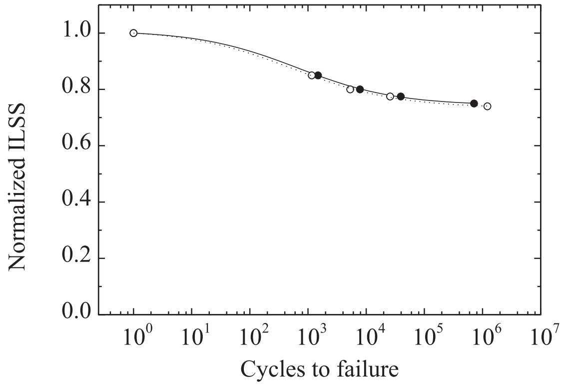

Fig. 4. S–N curves of unirradiated (solid circles) and irradiated (open circles) double-lap-shear specimens. The curves are normalized by the ILSS (33 MPa unirradiated, 32 MPa irradiated).

effects are close to experimental accuracy and less representative, because only two samples could be investigated for each data point. At ~ 170 MGy only ~20–40% of the initial ILSS is retained. Similar trends are observed after irradiation in the Triga reactor, where the ILSS increases slightly (~ 5%) at ~ 6 MGy, but degrades continuously in the higher dose range. The ILSS at ~ 280 MGy is ~30% of the unirradiated value. On the other hand, electron irradiation leads to a slight decrease of the ILSS (~ 15%) already at ~10 MGy. With increasing dose the ILSS drops again severely (to ~ 25% of its initial value). Within experimental accuracy, all data show a similar trend. Some enhancements are found after neutron irradiation to low doses and the degradation following electron irradiation seems to be higher in this dose range.

Fig. 3 compares the tensile *fatigue* behavior normalized by the UTS prior to and after irradiation in the Triga reactor to a neutron fluence of $5 \times 10^{21} \mathrm{m}^{-2}$ ($E > 0.1$ MeV), i.e. a total absorbed dose of ~30 MGy. While the irradiation leads to a decrease of the UTS by ~5%, the fatigue behavior does not change significantly. Each point is the average value of cycles to failure at a certain stress level obtained on four samples. The resulting statistical error is ~20%. At a maximum stress level of 0.33 UTS the fatigue life of the material is ~10^6 cycles, which corresponds to a maximum stress level of 310 MPa (unirradiated) and 295 MPa (irradiated).

Irradiation also does not show a systematic influence on the results for the ILSS and the S–N curves at this dose level as shown in Fig. 4. At a maximum stress of 0.75 ILSS, the fatigue life of the material is ~10^6 cycles. This corresponds to a maximum stress level of 25 MPa in both the unirradiated and the irradiated state. This value meets the conditions set for ITER [7]. Fracture surfaces of (un)irradiated double-lap-shear specimens made in an SEM can be found in Ref. [5]. A comparison of the ILSS measured on SBS and double-lap-shear specimens shows a remarkable disagreement of results (80 and 33 MPa, respectively). This may be explained as follows. The stresses measured by the SBS test are a complex combination of tension, compression and shear stresses and, therefore, do not represent the 'true' ILSS ('apparent' ILSS) [3]. On the other hand, the determination of the ILSS with double-lap-shear samples depends on the ratio of the shear length to the sample thickness [4,8,9]. Our results of the ILSS were obtained using a ratio of one and may, therefore, be close to the 'true' ILSS [9].

Swelling and weight loss were measured after the irradiation in the Triga reactor to a neutron fluence of 5×10^{21} m^{-2} ($E > 0.1$ MeV). We found swelling by $0.11 \pm 0.05\%$ and a weight loss of $0.11 \pm 0.08\%$. Both effects are very small at this relatively low neutron fluence and can, therefore, be neglected as a critical parameter of the material performance.

4. Summary

Mechanical tests on irradiated CTD-112P were carried out in tension and in interlaminar shear at 77 K both under static and dynamic load. The influence of the radiation spectrum, the irradiation temperature, warm-up effects and the load conditions were investigated with regard to the mechanical strength, the swelling and the weight loss of the laminate.

These aspects can be summarized as follows:

1. The UTS remains nearly constant up to ~60 MGy and decreases to ~85% of its initial value at ~280 MGy. The ILSS is constant up to ~6 MGy, but decreases considerably down to ~30% of the unirradiated value at ~280 MGy.
2. After low temperature irradiation, the cold-transferred samples (i.e. $5 \rightarrow 77$ K) show a higher ILSS (5–20%) than the warm-transferred samples (i.e. $5 \rightarrow 293 \rightarrow 77$ K) at all doses. However, this effect is close to experimental uncertainty because of the small number of samples investigated at each dose level.
3. Regarding the influence of the radiation environment, all data show a similar trend. Some enhancements are found after neutron irradiation to low doses. The degradation following electron irradiation surprisingly seems to be higher in this dose range. This may be due to different experimental conditions, e.g. local heating, and must be investigated further.
4. The tensile fatigue behavior does not change significantly after irradiation.
5. No systematic influence of the irradiation is found on the interlaminar shear strength and its fatigue behavior.
6. Reactor irradiation to a neutron fluence of 5×10^{21} m^{-2} ($E > 0.1$ MeV) leads to swelling and weight loss by ~0.1%.

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