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Mechanical strength of an ITER coil insulation system under static and dynamic load after reactor irradiation

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Abstract

The insulation system proposed by the Japanese Home Team for the ITER Toroidal Field coil (TF coil) is a T-glass–fiber/Kapton reinforced epoxy prepreg system. In order to assess the material performance under the actual operating conditions of the coils, the insulation system was irradiated in the TRIGA reactor (Vienna) to a fast neutron fluence of 2×10^{22} m^{-2} ($E > 0.1$ MeV). After measurements of swelling, all mechanical tests were carried out at 77 K. Tensile and short-beam-shear (SBS) tests were performed under static loading conditions. In addition, tension–tension fatigue experiments up to about 10^6 cycles were made. The laminate swells in the through-thickness direction by 0.86% at the highest dose level. The fatigue tests as well as the static tests do not show significant influences of the irradiation on the mechanical behavior of this composite.

1. Introduction

The TOKAMAK system represents the most successful approach for attaining the conditions of nuclear fusion. The ITER [1] device consists of several superconducting (SC) magnet coils [2,3], which confine the plasma by powerful toroidal and poloidal magnetic fields.

In order to generate high magnetic fields efficiently, an advanced SC coil manufacturing technology is needed. The development of such coils for ITER requires high industrial quality standards as well as an excellent performance of all materials. One of the critical components limiting the lifetime of SC magnets is the insulation material. However, the mechanical properties of these materials are influenced by several critical factors. Firstly, the current of the coils and the pulsed operation of a TOKAMAK lead to strong tension and bending forces and to high mechanical loads. In addition, the magnet is exposed to an environment of combined γ- and fast neutron radiation at cryogenic temperatures.

Wrappable insulation systems and vacuum impregnation have to be employed, in order to ensure a safe coil operation over the entire plant lifetime. Fiber-reinforced composites offer the high strength and stiffness needed for this purpose. Different combinations of special fiber (e.g. glass fibers) and matrix materials (e.g. epoxy resins) lead to various composites with excellent mechanical behavior. Recently, the polyimide material Kapton was combined with the fiber-reinforced composites. Kapton is often used in industrial environments posing high demands on the material properties (e.g. high flexibility, mechanical stability and excellent electrical insulation performance at very high and low temperatures and radiation resistance). Thus, extended mechanical test programs have to be done, in order to assess the material performance of the insulation under the actual operating conditions of ITER. Both the static and the fatigue behavior of the compounds are of importance because of the pulsed operation of the TOKAMAK.

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As a consequence, a test program was initiated to investigate radiation-induced changes in the material properties of potential insulation materials for the SC magnet coils [4–6]. In addition, some research has been done on Kapton/glass–fiber-reinforcements. An assessment of the electrical properties of a Kapton/R-glass–fiber reinforced epoxy, suggested for the toroidal field model coil, was reported by Humer et al. [7]. Fillunger et al. [8] investigated newly developed double layer type insulations with Kapton tapes sandwiched by boron free glass fabrics. All insulation systems were provided by the ITER Hometeams of Japan, the USA and Europe. The paper reports on shear-compression tests of these fiber-reinforced compounds prior to and after reactor irradiation. Details on the development of the CS model coil turn insulation were given by Reed et al. [9].

In the following we present results of an investigation of the mechanical behavior before and after irradiation of an insulation system fabricated by the Japanese Hometeam (JAHT) for the ITER TF coil. The material was tested under tension–tension fatigue load as well as under static load using the SBS test. All experiments were made at cryogenic temperature (77 K). Moreover, results on swelling are reported, which represents another critical parameter for SC magnet coil technology.

2. Materials and test procedures

All samples were manufactured by the JAHT, and prepared from 0.07×0.3 m^2 plates with a thickness of 3 mm. The matrix material is a tetrafunctional tetraglycidyl diamino diphenyl methane–diamino diphenyl sulfone epoxy (with a content ratio of 70: 30 wt%). The resin content is 40 wt% and the normal thickness of one prepreg layer is 0.16 mm at a fiber volume fraction of 50%. The reinforcement is made of two-dimensionally woven boron free T-glass fibers. Further, a Kapton film with a thickness of 25 μm is used as a barrier material between every other glass layer (Fig. 1). The surface of this special polyimide film was plasma treated for stronger adhesion. In order to get an orthotropic fiber compound, the glass plies were laid up alternately, i.e. 0° (warp)/90° (fill), 90°/0°, 0°/90°, etc. The final prepreg was then cured at 170 °C for 4 h.

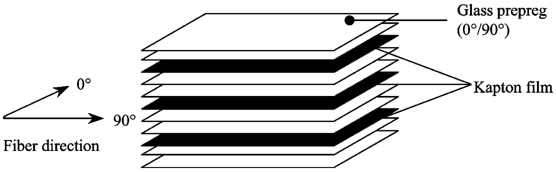

Fig. 1. Lay up order of glass plies with Kapton films.

All irradiations were performed at ambient temperature ($\simeq 340$ K) in the TRIGA reactor (Vienna) to neutron fluences of 5×10^{21}, 1×10^{22} and 2×10^{22} m^{-2} ($E > 0.1$ MeV). The reactor is operating at a γ-dose rate of 1×10^6 Gyh^{-1}, a fast neutron flux density of 7.6×10^{16} m^{-2} s^{-1} ($E > 0.1$ MeV), and a total neutron flux density of 2.1×10^{17} m^{-2} s^{-1}, respectively.

All experiments were carried out at 77 K using a MTS 810 TestStar II Material Testing System, which is equipped with a liquid nitrogen cryostat. The SBS-test (ASTM D 2344) was used for the assessment of the interlaminar shear strength (ILSS) under static loading conditions. The tests were carried out at a crosshead-speed of 1.3 mm min^{-1} on 3 mm thick samples with a span-to-thickness ratio of 5:1. Further details about the SBS-testing device were reported by Humer et al. [10].

In order to investigate the fatigue performance of the insulation system, tension–tension fatigue experiments were done according to ASTM D 3479. The actual conditions of the pulsed ITER operation over the plant lifetime, i.e. pulse duration (200–500 s) and number of pulses (3×10^4 cycles), have to be simulated as closely as possible. All fatigue tests were run at 10 Hz in load control with a sinusoidal load function at a minimum-to-peak stress ratio of $R = 0.1$. Various load levels from 85% to 15% of the static strength were chosen and investigated up to 10^6 cycles to failure. Four samples were measured at each load level and stress-lifetime diagrams (S/N curves, Wöhler curves) were obtained for unirradiated and irradiated samples.

3. Results

The results for the ultimate tensile strength (UTS) and the ILSS as well as on swelling in the through-thickness direction following reactor irradiation and testing at 77 K are summarized in Table 1.

3.1. Interlaminar shear strength

The results on the ILSS (Fig. 2), obtained from the SBS test, show a slight degradation of the ILSS by 5% at a fast neutron fluence of 5×10^{21} m^{-2} ($E > 0.1$ MeV). Further irradiation to the highest dose level leads to a

Table 1
Mechanical properties and swelling of the laminate before and after reactor irradiation

Fast neutron fluence ($E > 0.1$ MeV) (m^{-2})	UTS (MPa)	ILSS (MPa)	Swelling (%)
Unirradiated	805 ± 20	78 ± 3	–
5×10^{21}	–	74 ± 10	-0.21 ± 0.15
1×10^{22}	–	65 ± 7	$\pm 0.00 \pm 0.15$
2×10^{22}	795 ± 17	60 ± 3	$+0.86 \pm 0.25$

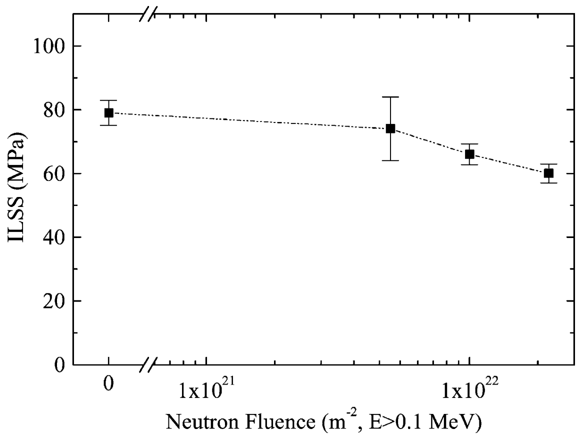

Fig. 2. ILSS of the laminate measured at 77 K as a function of the fast neutron fluence.

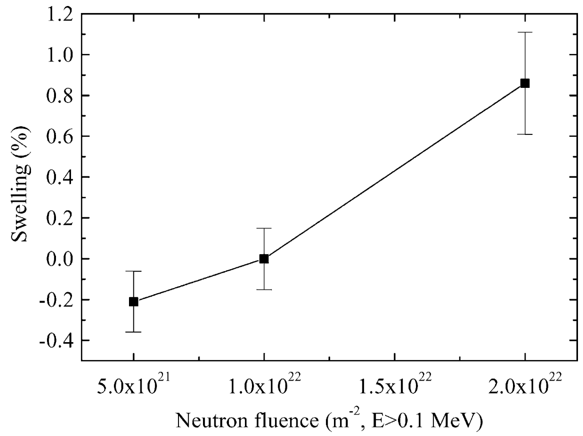

Fig. 3. Swelling in the through-thickness direction as a function of the fast neutron fluence.

decrease of the ILSS by approximately 20%, which indicates rather moderate radiation damage.

This behavior corresponds well to earlier shear-compression tests of the same Japanese prepreg system studied by Fillunger et al. [8]. The ultimate shear-compression strength was measured prior to and after reactor irradiation to fast neutron fluences of 5×10^{21} and 1×10^{22} m^{-2} ($E > 0.1$ MeV). Axial compression of 45° and 60° samples under different test conditions demonstrated that this insulation material does not show significant degradation of the mechanical stability, even at the highest dose level.

3.2. Swelling

As can be seen from Fig. 3, swelling in the through-thickness direction does not play any role at fluences up to 1×10^{22} m^{-2}. After irradiation to a neutron fluence of 2×10^{22} m^{-2} we find swelling by (0.86 ± 0.25)%.

3.3. Tensile fatigue

The tensile fatigue data shown in Fig. 4 are normalized by the average static UTS, obtained on four samples prior to and after irradiation. Each data point presents the average value of cycles to failure at a certain stress level, obtained at least on four samples. The standard deviation is <20%. After irradiation to a neutron fluence of 2×10^{22} m^{-2}, the UTS degrades by $\simeq$2% (Fig. 4). However, both Wöhler curves show a rapid decrease by 60% in the range from 85% to 30% of the static UTS. Therefore, the fatigue behavior is rather poor, in contrast to the good radiation resistance of these laminates under static load. A maximum stress value of 0.2 UTS (161 MPa, unirradiated) and of 0.15 UTS (119 MPa, irradiated) is found for 10^4 cycles and more (life endurance limit).

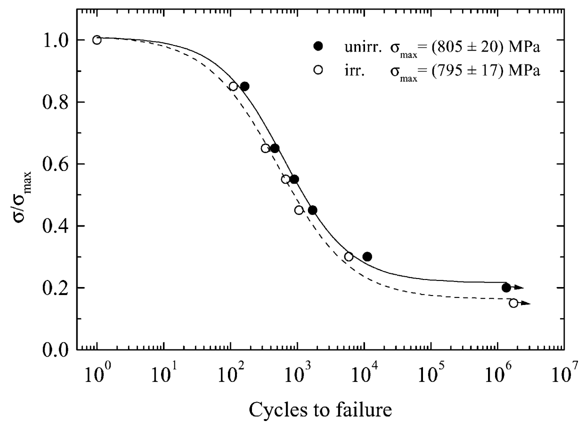

Fig. 4. Tension–tension stress-lifetime diagrams of the laminate before and after reactor irradiation to a fast neutron fluence of 2×10^{22} m^{-2} ($E > 0.1$ MeV) measured at 77 K. Each curve is normalized by the static UTS. The measurements were stopped manually above 10^6 cycles, as indicated by the arrows.

To explain this decrease, the influence of the Kapton film is considered. Hartwig et al. [11] compared the fatigue behavior of various fiber-reinforced composites at 77 K. They found that the interface between the glass ply and the film is an important parameter for the fatigue behavior of the laminates. A similar influence could prevail in our prepreg system. If several rows of a glass ply fail, the missing strength has to be taken over by the neighboring glass plies. Therefore, the load within the composite has to be transferred by the shear forces of the epoxy matrix. However, this transfer will only succeed between good fiber-matrix bonds and as long as an interrupting barrier material, like a Kapton film, is absent. Otherwise, the shear transfer fails and the fibers are not able to support the compound anymore. An additional degradation of the shear strength of the matrix due to the resulting stress concentration may lead to an early failure during the fatigue cycles.

4. Summary

The insulation system of the ITER coils requires a good mechanical performance. Because of the pulsed operation (3×10^4 cycles) of ITER, the material properties have to be assessed under static and dynamic loads. Therefore, tension–tension fatigue tests and static tensile and SBS tests were carried out at 77 K before and after irradiation to neutron fluences of 5×10^{21}, 1×10^{22} and 2×10^{22} m^{-2} ($E > 0.1$ MeV). Furthermore, the swelling of the laminate was determined prior to the mechanical test.

The main results can be summarized as follows:

- The ILSS decreases by up to $\simeq 20\%$ after irradiation to a fast neutron fluence of 2×10^{22} m^{-2} ($E > 0.1$ MeV). Therefore, the results of the SBS test demonstrate a good mechanical stability of the insulating system against radiation damage.
- Swelling in the through-thickness direction is low, but increases to 0.86% after reactor irradiation to the highest dose level.
- No significant influence of the irradiation on the tensile fatigue behavior is observed at a neutron fluence of 2×10^{22} m^{-2} ($E > 0.1$ MeV). The small degradation ($\simeq 2\%$) of the UTS indicates a high radiation resistance of the composite in agreement with the above results on the ILSS and with previous work on the shear-compression behavior [8]. However, the fatigue behavior of the composite is poor, i.e. the maximum stress levels are 0.2 UTS before and 0.15 UTS after irradiation. The fatigue behavior is presumably strongly influenced by the addition of the Kapton films.

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References

[1] R. Aymar, ITER R&D, Fus. Eng. Des. 55 (2001) 107.
[2] H. Tsuji, S. Egorov, J. Minervini, M. Martovetsky, K. Okuno, Y. Takahashi, R.J. Thome, ITER R&D, Fus. Eng. Des. 55 (2001) 153.
[3] N. Mitchell, E. Salpietro, ITER R&D, Fus. Eng. Des. 55 (2001) 171.
[4] H.W. Weber, E. Tschegg, Adv. Cryog. Eng. (Mater.) 36 (1990) 869.
[5] S.M. Spiessberger, K. Humer, H.W. Weber, E.K. Tschegg, H. Gerstenberg, A. Udagawa, Adv. Cryog. Eng. (Mater.) 44 (1998) 191.
[6] K. Humer, P. Rosenkranz, H.W. Weber, P.E. Fabian, J.A. Rice, J. Nucl. Mater. 283–287 (2000) 973.
[7] K. Humer, H.W. Weber, R. Hastik, H. Hauser, H. Gerstenberg, Cryogenics 40 (2000) 295.
[8] H.Fillunger, H. Gerstenberg, K. Humer, R.K. Maix, K. Okuno, P. Rosenkranz, H.W. Weber, N. Wiegner, Fus. Eng. Des. 58–59 (2001) 135.
[9] R.P. Reed, P.E. Fabian, J.B. Schutz, Adv. Cryog. Eng. (Mater.) 44 (1998) 175.
[10] K. Humer, S. Spiessberger, H.W. Weber, E.K. Tschegg, H. Gerstenberg, Cryogenics 36 (1996) 611.
[11] G. Hartwig, R. Hübner, S. Knaak, Adv. Cryog. Eng. 42 (1996) 75.