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Characterization of advanced cyanate ester/epoxy insulation systems before and after reactor irradiation

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ABSTRACT

Insulation systems for fusion magnets have to operate in a harsh environment, especially also under intense radiation. Over the past years, cyanate ester (CE) resins have been playing an increasingly important role because of their enhanced temperature and radiation resistance compared to conventional epoxy resins. Blending CE with epoxy resins offers the possibility to manufacture radiation resistant insulations at a low price compared to pure CE materials. Therefore, it is of special interest to study the influence of the CE content and of the epoxy resin on the mechanical properties to find materials, which are suitable and economically reasonable for the specific demands of such magnets.

In this study R-glass fiber/Kapton reinforced cyanate ester/epoxy blends with different CE content were investigated. Each material was exposed to conditions matching those expected for the ITER TF coil insulation as closely as possible. In order to characterize the mechanical properties, short-beam shear and static tensile tests were carried out at 77 K prior to and after irradiation to fast neutron fluences of up to 5×10^{22} m^{-2} ($E > 0.1$ MeV), in the TRIGA reactor (Vienna) at ambient temperature (340 K). In addition, tension–tension fatigue measurements were performed in the load-controlled mode to simulate the pulsed operation conditions of ITER.

1. Introduction

Fiber reinforced plastics are employed as insulating materials for superconducting coils as well as for power generators. For applications in a radiation environment, the insulation of the superconducting coils is affected by a combination of fast neutrons and γ-radiation as well as by mechanical stresses at the magnet location. Because of the neutrons, the composite should consist of boron-free glass fibers embedded in organic matrix materials (resins). In addition, multiple electrical barriers, e.g. Kapton foils, have to be added to the reinforcement in order to guarantee the electrical performance over the entire lifetime of the device. Apart from the radiation resistance, the pot-life of the resin is an important factor. The resin has to remain liquid for a sufficient time to allow homogeneous impregnation.

Over the past years extensive work has been done to characterize various insulation systems under ITER relevant conditions. Materials consisting of different types of resins were supplied by various companies from all over the world. The results will be briefly summarized in the following.

Both DGEBA-based insulation systems of the toroidal field model coil (TFMC) fabricated by Ansaldo (Italy) and Alstom-MSA (France) showed significant radiation induced damage after exposure to the ITER design fluence of 1×10^{22} m^{-2} ($E > 0.1$ MeV), especially under interlaminar shear load. A reduction of the interlaminar shear strength by up to 50% was found [1–5]. In addition, Ansaldo used an adhesive to fix the Kapton foil to the glass fiber tape, which led to the formation of bubbles after irradiation. Therefore, it is highly desirable to find alternative materials.

The Japanese ITER Home Team suggested a TGDDM-DDS (tetraglycidyl diamino diphenyl methane-diamino diphenyl sulfone) epoxy pre-preg manufactured by Mitsubishi (Japan). Even at a fast neutron fluence of 2×10^{22} m^{-2} ($E > 0.1$ MeV) it demonstrated good stability against radiation damage [4,6,7]. The interlaminar shear strength dropped by 20%, while no significant influence on the tensile fatigue behavior was observed. However, this system is not suitable for the vacuum pressure impregnation (VPI) process, which is foreseen for the TF coils due to their complexity.

Compared to epoxy resins, cyanate esters (CEs) offer enhanced temperature and radiation resistance as well as high mechanical strength [8]. In addition, no technological changes in the coil fabrication are needed since CE resins can be treated like epoxies and are compatible with the VPI process. The higher costs (~10 times of epoxy) and the higher reactivity which may lead into an exothermic reaction, when the resin is not properly treated are the main disadvantages. In order to overcome these difficulties blending with

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epoxy resins is a proper solution. Furthermore, blending offers a broader range of properties and allows adapting the systems to specific application demands.

Composite Technology Development, Colorado, USA invested a lot of effort in developing cyanate ester (CE)-based composites for various applications. Cyanate esters (CEs) are well known for their mechanical strength, low moisture absorption and thermal resistance. In addition, CE resins can be blended with other components like additives or other resins, which offers a broader range of properties. Fabian et al. [9] investigated the compressive strength of novel glass fiber reinforced composites based on pure CE resin and mixtures of CE/polyimide/bismaleimide/epoxy resins before and after irradiation to fast neutron fluences of up to $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV). Also the interlaminar shear strength and the ultimate tensile strength were addressed prior to and after irradiation to the ITER design fluence and beyond [10–12]. The results demonstrated their reduced radiation sensitivity compared to traditional epoxy resins. Especially at the ITER fluence level these materials are hardly affected by neutron irradiation.

Based on these promising results a low viscosity CE (AroCy-L10) monomer was proposed by European industry (Huntsman, Switzerland) as an innovative resin system suitable for the VPI process. For blending the CE, a single component purified DGEBF epoxy resin (PY306) was suggested. The present paper summarizes the results obtained on the European materials. The CE content was varied between 20 and 100%, in order to study the influence of the CE content on the mechanical properties as well as on the radiation resistance. Also the bonding properties between the interleaving Kapton layers and the resin were investigated.

Besides the CE/epoxy systems, the “Orlitherm” epoxy resin showed increased radiation resistance compared to the TFMC insulation systems during initial screening tests [13]. For this reason, the PY306 epoxy resin was replaced by the “Orlitherm” resin to form another CE blend, and to investigate the enhancement of the radiation resistance by the admixture of CE. Two CE/Orlitherm blends were fabricated containing 20 and 30% CE, respectively. Compared to the previously investigated CE/PY306 blends, the chemistry of the new system is different. While PY306 is a purified single component resin, the “Orlitherm” system consists of a basic resin, a hardener and an additive, but the components and the chemical structure are undisclosed. First screening tests [13] showed that these blends were characterized by severe inhomogeneities, which increased with increasing CE content. The desired improvement of the mechanical properties was not achieved with these blends, mainly due to the multi-component epoxy resin. For this reason, these CE/Orlitherm blends were not further investigated.

All materials were characterized under static and dynamic tensile and interlaminar shear load at 77 K prior to and after irradiation to fast neutron fluences of up to $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV).

2. Materials and test procedures

Several materials were fabricated by Marti-Supratec Corporation, Switzerland, using the vacuum pressure impregnation (VPI) technique. The reinforcement consists of one R-glass fiber layer (0.25 mm × 40 mm) and seven layers of glass fiber/Kapton 200 HN tape (0.05 mm × 36 mm) sandwiches wrapped half-overlapped around an aluminium plate as would be done for insulating the ITER TF coils. The wrapped plates were dried under vacuum at ∼100 °C to remove moisture which may be absorbed during storing and wrapping. Afterwards they were impregnated with pure CE and CE/epoxy mixtures. After a well-defined curing schedule according to the recommendations of the resin supplier as well as the needs of ITER, test specimens were cut from the final material plates with a thickness of about 4 mm. In order to eliminate differences in the wrapping, test specimen were only cut from one wrapped plate (front and back plate) and used for all tests.

All static and dynamic tests were carried out at 77 K using a servo-hydraulic MTS 810 testing device, which was modified for measurements in a liquid nitrogen environment. The ultimate tensile strength (UTS) was measured on five samples according to the DIN 53455 and the ASTM D638 standards [14]. Dog-bone shaped samples of 70 mm length were cut from the sample plates [15]. This reduced size is necessary in order to carry out the irradiation experiments in a reasonable way. It was shown in many scaling experiments that the smaller size does not significantly influence the material properties under static and dynamic load [15,16]. The UTS of the smaller samples lies within a standard deviation of 10% of the standard sample sizes.

In addition, an extensometer suitable for cryogenic temperatures was used to record the sample elongation during the tensile test, which allows conclusions on the quality of the matrix reinforcement. However, due to the dog-bone shape the measured elongation is different from the real strain and cannot be used to determine the elastic modulus.

The interlaminar shear strength (ILSS) was assessed by the short-beam shear (SBS) test according to the ASTM D2344 standard (23 mm × 6.4 mm × 4 mm sample size). Span-to-thickness ratios between 4:1 and 5:1 were used in order to obtain interlaminar fracture. Only samples which showed interlaminar fracture were taken for the ILSS determination, others which showed a combination of tension and shear failure were rejected.

For the simulation of the pulsed ITER operation, tension–tension fatigue measurements (ASTM D 3479) were done at a frequency of 10 Hz applying a sinusoidal load function up to 10^6 cycles at minimum-to-peak stress ratios (R-ratio) of 0.1. Each data point refers to 4 or more samples.

The materials have anisotropic properties because of the manufacturing process. Therefore, test specimens were cut parallel (0°) and perpendicular (90°) to the winding direction of the reinforcing glass fiber tapes. For tensile tests only the 90° direction was investigated, because the UTS in 0° direction is mostly dominated by the strength of the glass fibers and the influence of the irradiation is much smaller than for 90° samples.

The neutron irradiation was performed in the TRIGA reactor (Vienna) at ambient temperature (∼340 K) to fast neutron fluences of 1, 2, 4, and $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV), which corresponds to a total absorbed dose of up to 250 MGy [17,18]. Calculations to determine the absorbed dose [18] show that the neutron contribution is in the range of 30% depending on the chemical composition of the resin. The reactor operates at a γ-dose rate of 1×10^6 Gy/h, a fast neutron flux density of $7.6 \times 10^{16}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$ ($E > 0.1$ MeV), and a total neutron flux density of $2.1 \times 10^{17}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$, respectively.

3. Results

We present in the following results obtained on insulation systems based on mixtures of the CE AroCy-L10 and the epoxy PY306 resin. To initialize the polymerization a Mn-catalyst was added, which acts on the CE monomers and the epoxy monomers will be embedded in the CE network. By changing the amount or the metal ions of the catalyst the pot-life of the resin can be adjusted. The pot-life (time where the viscosity remains below 100 mPa s) is in the range of 6–8 h. The two main reasons for choosing these components were the technological experience with this mixture as well as the chemical nature of the epoxy resin. Since PY306 is a purified single component system, the formation of the network is more homogeneous. In total, the CE content was reduced to 20%, which – according to the resin supplier – is close to the expected

Table 1
Overview of the CE/PY306 insulation systems.

Type	Cyanate ester	DGEBF
Resin	AroCy-L10	PY306
Hardener	–	–
Additives	Mn Acetylacetonate in nonylphenol	
Reinforcement	R-glass/Kapton	
Curing temp.	4 h at 100 °C 5 h at 160 °C	

Insulation system	CE/epoxy ratio
T1 (100)	100:0
T2 (40)	40:60
T8 (30)	30:70
T10 (20)	20:80

limit, where the network formation fails [19]. An overview of the investigated materials is given in Table 1.

3.1. Bonding between Kapton and CE

The radiation resistance should not be influenced by the presence of Kapton, since its strength is not affected at these fluence levels. However, the mechanical strength of the composite is determined by the reinforcement/matrix interface which may be weakened. It turned out that the bonding properties of a pure CE composite was weak as can be seen from the stress–strain relation shown in Fig. 1. At a relatively low strain level of ~0.7%, the material starts to delaminate but it does not break. While the sample is strained further, the applied stress remains between 180 and 250 MPa up to 3% strain. Also the delamination continues, indicated by the serrated curve. Then the mechanical strength drops until the sample is completely destroyed at 4–5% strain. This stepwise delamination was also observed acoustically during the measurement. In addition, the samples were investigated in a microscope after the test. Fig. 2 shows parts of the specimen in through-thickness direction. It becomes obvious that material failure mainly occurs at the location of the Kapton foils. Further, one break was found in an overlapping fiber area together with an accumulation of resin. In general, no evidence for glass fiber breakage was found, which leads to the assumption that the resin/Kapton interface is the weak link in this composite. Contrary to this, only the breakage of the glass fibers as well as of the Kapton foils is found for all the CE/epoxy blends. Also parts of the resin are still attached to the Kapton surface, which indicates excellent bonding properties. However, another set of sample plates, produced with an identical lay-up, were accidentally cured at 210 °C. Tensile tests on this material showed a slightly different behavior. As can be seen from Fig. 1 this composite also delaminates, but less pronounced. Fiber breakage and ruptured Kapton foils were also seen (cf. Fig. 2).

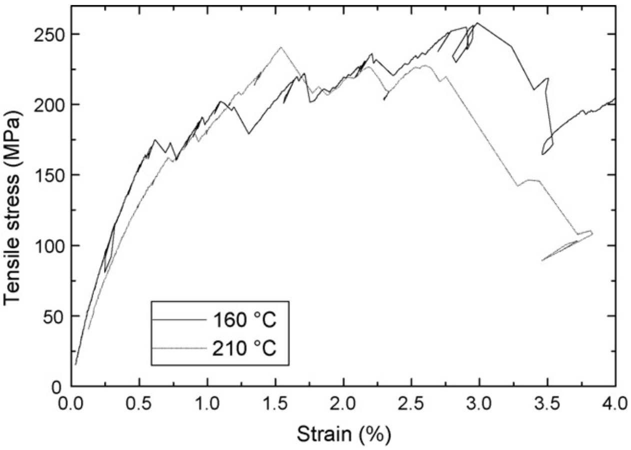

Fig. 1. Stress–strain curves at 77 K of pure CE materials cured at different temperatures.

Contrary to these results, Hooker et al. recently reported that no difference between a pure CE and a CE blend was observable and that both systems had excellent bonding properties to Kapton [20].

These results might indicate that the bonding between the CE resin and Kapton is affected by the curing temperature, since a higher curing temperature improved the bonding properties. Both temperatures do not represent the optimum curing conditions which possibly caused the different bonding properties compared to optimally cured samples. According to the supplier, the CE resin AroCy-L10 should be cured at 178 °C. For the sample fabrication 160 °C was chosen, because the final curing temperature for the TF insulation will be between 150 and 170 °C.

3.2. Influence of the CE content on the mechanical properties

Regarding the UTS, all results lie in the range from 250 to 270 MPa, where the lowest UTS is found for the pure CE material,

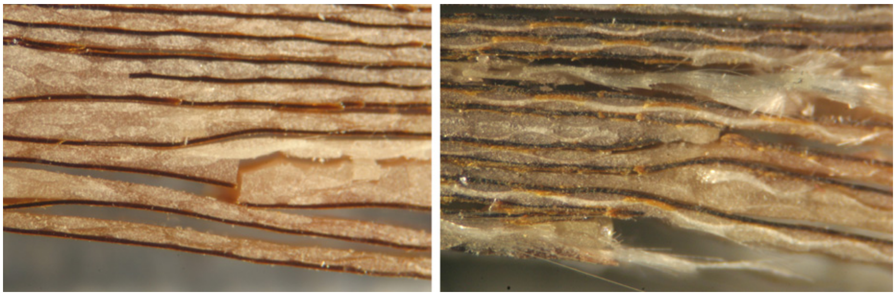

Fig. 2. Different fracture behavior of CE samples cured at 160 °C (left) and at 210 °C (right) after tensile test (magnification 9:1).

Table 2
Ultimate tensile strength (UTS) measured at 77 K before and after irradiation to fast neutron fluences of up to 5 × 10^{22} m^{-2} ($E > 0.1$ MeV).

Insulation system	T1 (100)UTS 90° (MPa)	T2 (40)UTS 90° (MPa)	T8 (30)UTS 90° (MPa)	T10 (20)UTS 90° (MPa)
Unirradiated	250 ± 19	313 ± 18	269 ± 19	265 ± 16
1×10^{22} m^{-2}	250 ± 22	296 ± 10	274 ± 6	243 ± 12
2×10^{22} m^{-2}	228 ± 13	253 ± 16	260 ± 7	218 ± 8
5×10^{22} m^{-2}	193 ± 6			

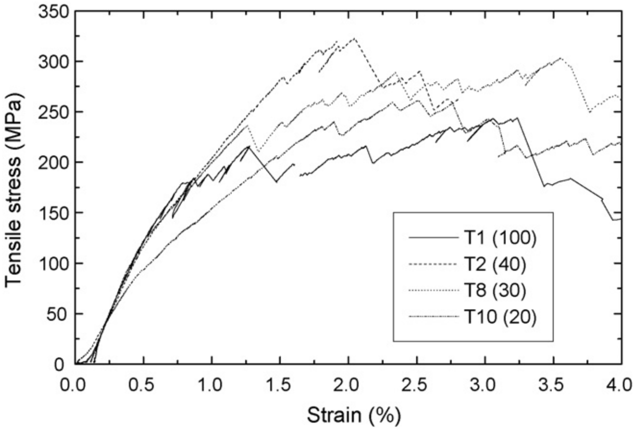

Fig. 3. Stress–strain curves at 77 K of various CE/PY306 blends loaded in 90° direction.

mainly because of the weak bonding between Kapton and CE (cf. Table 2). Only for the system with a CE content of 40% (T2) the UTS is slightly higher, 313 MPa. This is in good agreement with expectations expressed by the resin supplier, who pointed out that, from a chemical point of view, the best properties of the resin mixture should be reached at 40% CE [19]. All further information is proprietory. However, the UTS is only higher by ~15% than for the other two CE/epoxy blends. A more pronounced effect of the blend ratio is found in the stress–strain relation. As shown in Fig. 3, the highest Young's modulus is found for the pure CE material T1 (100). This material does not show a distinct plastic–elastic transition point (kink), contrary to the CE/blends. No differences were found between the 40% and the 30% CE material up to a stress level of 225 MPa. For higher loads only small serrations can be observed, especially above a strain of 1% until the final fracture takes place. These small load drops indicate minor fractures of glass fibers and rovings. The Young's modulus of the composite correlates with the amount of CE resin, which is explained by the higher cross-linked structure of the CE network compared to the epoxy. In general, by reducing the CE content the material becomes less stiff. Especially the 20% CE system T10 (20) is more elastic and differs strongly from the behavior of the other materials (cf. Fig. 3).

In order to simulate the pulsed operation of ITER, tension–tension fatigue measurements were also carried out. The results are shown in Fig. 4. The Wöhler curves of all CE/epoxy blends are characterized by a slow and continuous decrease up to 10^6 load cycles. Only the pure CE system (T1) shows a pronounced life endurance limit σ_D at 0.5 UTS (=125 MPa).

The slight variations at high load levels are mainly related to differences in the initial strength, as can be seen from the normalized curves. All four curves are nearly identical with two exceptions. Apart from the previously mentioned life endurance limit of T1 (100), T8 (30) deviates from the behavior of the other materials at a load of $\sigma = 0.85$ UTS. At this point the number of survived cycles is higher by a factor of 15. Additional measurements were carried out at this load level, but they confirmed the previous result. The reason is presently unknown.

For ITER, where 30,000 load cycles are expected, the impact of the varying CE content is even smaller. The residual strength of

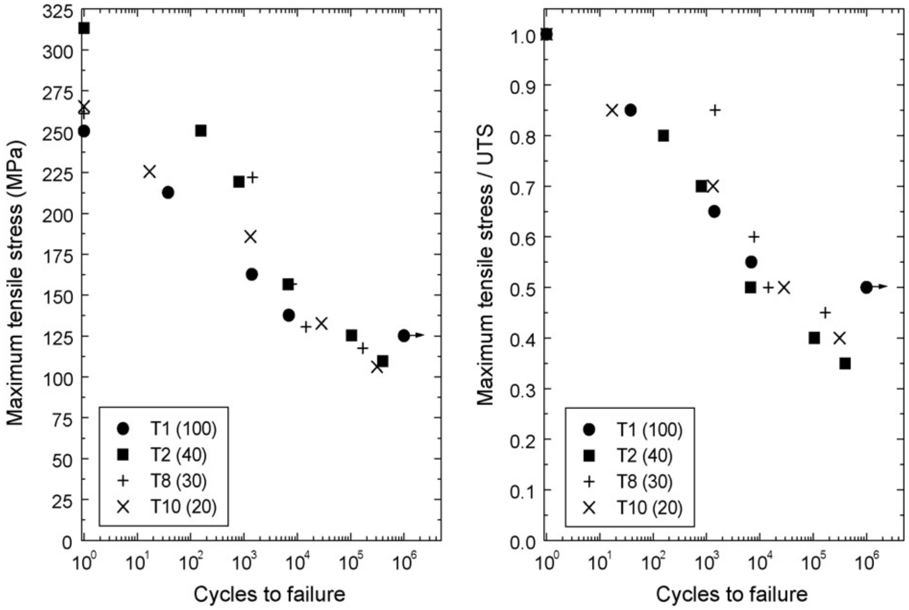

Fig. 4. Absolute (left) and normalized (right) tension–tension stress-lifetime diagrams before irradiation measured at 77 K. All measurements were stopped manually above 10^6 cycles, as indicated by the arrows.

Table 3
Interlaminar shear strength (ILSS) for both directions measured at 77 K before and after irradiation to fast neutron fluences of up to 5×10^{22} m^{-2} ($E > 0.1$ MeV).

Insulation system	T1 (100)		T2 (40)		T8 (30)		T10 (20)	
	0°	90°	0°	90°	0°	90°	0°	90°
Unirradiated	59 ± 8	42 ± 10	77 ± 4	57 ± 3	74 ± 4	63 ± 9	62 ± 6	48 ± 9
1×10^{22} m^{-2}	68 ± 4	48 ± 5	66 ± 5	58 ± 3	69 ± 8	58 ± 7	65 ± 4	48 ± 5
2×10^{22} m^{-2}	50 ± 2	46 ± 1	61 ± 2	52 ± 3	62 ± 3	51 ± 3	53 ± 6	48 ± 3
4×10^{22} m^{-2}	46 ± 2	37 ± 2	52 ± 2	45 ± 6	43 ± 3	37 ± 5	36 ± 4	26 ± 4
5×10^{22} m^{-2}	48 ± 8	33 ± 5	50 ± 4	37 ± 2				

all four materials is ~130 MPa, which is more than adequate for ITER.

The results obtained under interlaminar shear load confirm the trend of the tensile tests (cf. Table 3). The ILSS in 0° direction lies between about 60 and 80 MPa, whereas in 90° direction the ILSS is lower by approximately 10–15 MPa. As expected from the tensile tests, the system with 40% CE shows slightly higher values, but in general the CE content does not have a big influence neither on the UTS nor on the ILSS.

Comparing the ILSS of these three blends with those of the materials fabricated by CTD, the ILSS of the US materials was higher, where values of up to 95 MPa were found [21]. This difference results from the reinforcement, because stacked glass fiber fabrics were used by CTD instead of wrapped tapes, but they are not suitable for the TF coil insulation.

3.3. *Influence of the CE content on the radiation resistance*

After irradiation to the ITER design fluence of $1 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV), no reduction of the UTS is found. The differences lie within the standard deviation. Even a reduction of the CE content to 20% does not lead to a significant reduction of the UTS after irradiation (cf. Table 2).

After doubling the fluence, minor radiation effects are observed. However, these changes of the mechanical strength are not significant. The UTS is reduced by less than 20%, the standard deviation lies between 5 and 10%. The pure CE composite (T1) was further exposed to $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV), but even at this fluence it maintained ~75% of its mechanical strength compared to the unirradiated state.

As an example for the stress–strain relation of the CE/epoxy blends, the results on T2 (40) are presented in Fig. 5. Over a wide range of strain, the shape of the stress–strain curve is hardly affected by irradiation. However, with increasing dose, an earlier onset of the load drop is observed, which indicates initiation and propagation of cracks along the Kapton–matrix interfaces. After exposure to $2 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV) the shape of the stress–strain relation is no more affected at low strain levels. However, obvious damage inside the composite is found at tensile stresses above 200 MPa. A similar behavior was found for the other two CE/epoxy blends.

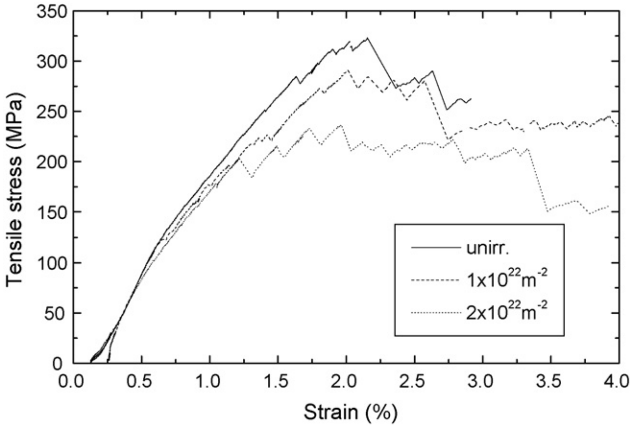

Fig. 5. Stress–strain behavior of T2 (40) before and after irradiation to fast neutron fluences of up to $2 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV).

In case of dynamic loading, no dramatic changes of the material performance are observed after irradiation to 1 or to $2 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV). The absolute and normalized Wöhler curves of T2 (40) are presented in Fig. 6. The other investigated materials showed the same tendency.

All curves are nearly identical as can be seen from the normalized curves. Especially at the ITER point (3×10^4 cycles) and above, the residual strength is not reduced by irradiation. As expected from the static tensile tests, the smallest effect is found for the pure CE system. However, for the material with the lowest CE content (T10 (20)) some differences were observed at $2 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV). Here the shape and the absolute values of the Wöhler curve were hardly affected, but the scatter of the data points increased, which indicates an enhancement of material inhomogeneities. At this fluence level the radiation damage starts to become more severe.

In addition, SBS samples were irradiated to fast neutron fluences of up to $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV) (cf. Table 3). In good agreement with the tensile tests, radiation damage starts to degrade the mechanical properties at $2 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV). In 0° direction the ILSS is in the range between 50 and 62 MPa, whereas in 90° direction the ILSS is lower by about 5–10 MPa. After irradiation

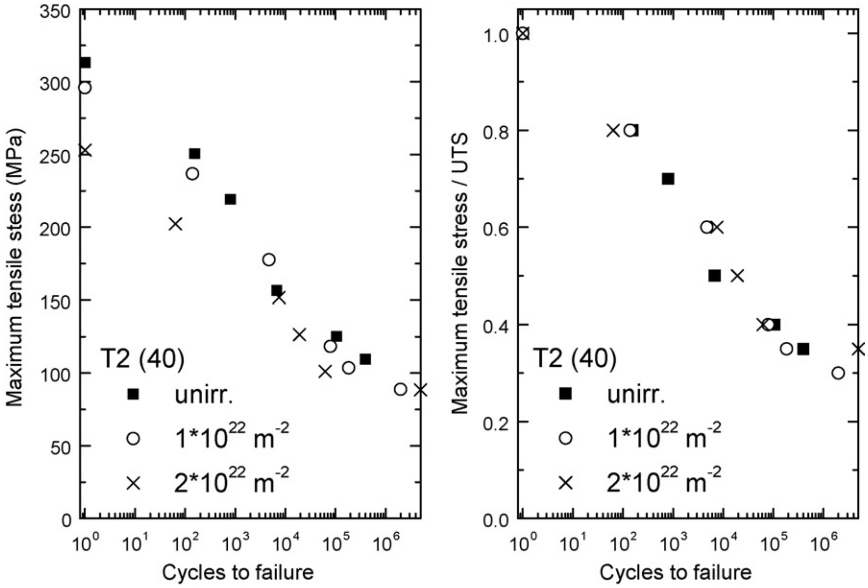

Fig. 6. Absolute (left) and normalized (right) tension–tension stress-lifetime diagrams of T2 (40) before and after irradiation to fast neutron fluences of up to $2 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1$ MeV) measured at 77 K.

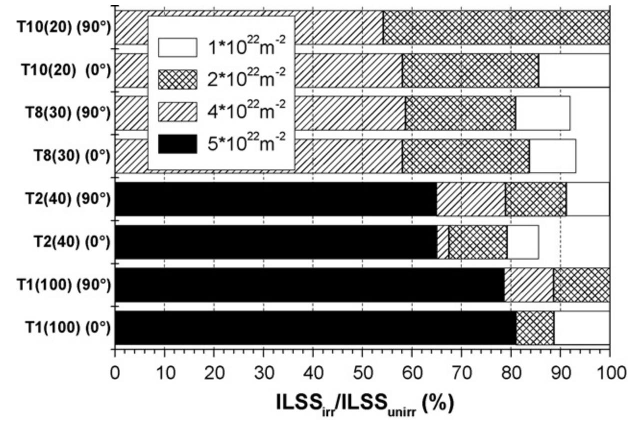

Fig. 7. Normalized interlaminar shear strength after irradiation to fast neutron fluences of up to $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$).

to $4 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$) a remarkably high ILSS is observed for materials with 40% CE content and above, i.e. about ~40 and ~50 MPa depending on the load direction. For the other two systems, T8 (30) and T10 (20), the ILSS in 90° direction drops to 26 MPa in the worst case. Further irradiation to $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$) shows increased radiation damage with decreasing CE content. However, the ILSS of the pure CE system is still remarkably high at 48 MPa (0°) and 33 MPa (90°), respectively.

In order to make the irradiation damage more obvious, Fig. 7 shows the relative ILSS compared to the unirradiated state. For all materials the observed degradation lies between 0 and 20% at $2 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$). No distinct correlation between radiation resistance and CE/epoxy ratio is found up to this dose level. The situation changes after irradiation to $4 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$), where the radiation damage increases with decreasing CE content, especially the 30% (T8) and the 20% CE systems (T10) are more severely affected than the others. The ILSS of the insulation system impregnated with pure CE (T1) is only reduced by approximately 20%. Also the 40% system (T2) shows quite a similar radiation resistance (−30%), whereas the ILSS of systems with a lower CE content (T8 (30) and T10 (20)) drops by 45%. At $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$), the pure CE composite T1 (100) remains slightly below 80%, the 40% material T2 drops to 65% of its initial strength. Compared to the results on conventional epoxy resins, such as the TFMC systems, the least radiation resistant blend (T10) has still better mechanical properties, even after exposure to a 4 times higher neutron fluence [4,10].

4. Summary

The mechanical properties of various cyanate ester/epoxy blends were studied at 77 K, in order to find radiation resistant materials for use as insulation systems for the ITER TF coils or for other superconducting coils exposed to radiation. The influence of the cyanate ester content was investigated prior to and after irradiation to fast neutron fluences of up to $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$). The results may be summarized as follows.

- An insulation system based on pure CE may suffer from some mechanical difficulties, if the reinforcement contains Kapton to enhance the dielectric properties. Delamination along the Kapton foils was observed. However, it may be related to a wrong curing temperature of the resin. Additional experiments should be carried out to clarify this aspect.
- The influence of the blend ratio on the mechanical properties is not very pronounced, the differences are only slightly above the standard deviation. The highest mechanical strength is obtained for a material, which contains 40% CE. However, a reduction of CE leads to a decrease of stiffness, especially for a system containing 20% CE.
- Tension-tension fatigue measurements showed that the dynamic performance of all materials was similar, especially at the ITER point of 30,000 cycles. Also the residual strength is adequate for ITER.
- Up to a fast neutron fluence of $2 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$) the reduction of the mechanical strength under tensile and interlaminar shear load is lower than 20%. Under dynamic load, the shape of the Wöhler curves is hardly affected by irradiation. Especially at the ITER point of 30,000 cycles and beyond, all CE/epoxy blends tend to have a slightly higher residual strength than the unirradiated material.
- CE/epoxy blends with a CE content of more than 40% show an acceptable ILSS after irradiation to a fast neutron fluence of $5 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$). The ILSS is even higher than that of the TFMC insulation system after exposure to $1 \times 10^{22}\,\mathrm{m}^{-2}$ ($E > 0.1\,\mathrm{MeV}$). The shear strength of the pure CE material drops by ~20%, whereas a reduction of 35% is found for the system containing 40% CE.

Finally, it should be pointed out that all cyanate ester/PY306 blends showed excellent mechanical properties. With respect to the radiation resistance needed for ITER, the pure as well as three CE/PY306 blends are suitable. The 40:60 blend is the best compromise regarding costs as well as additional safety margins for possible extension of the operation time or a removal of shielding materials.

However, the pot-life of the resin is too short for impregnating the TF coils. Most recently, the pot-life was extended to more than 100 h by exchanging the Mn-catalyst by a Co-catalyst. Several test programs are currently under way to investigate the effects of this change in catalyst on the mechanical properties. Initial screening tests show that the mechanical properties as well as the radiation resistance are not affected [22].

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