JET–P(99)57

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Analysis and Tests of TF Magnet Insulation Samples for the JET Upgrade to 4 Tesla

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Preprint of a Paper to be submitted for publication in the proceedings of
MT16, Talahassee, Florida, September 1999.

January 2000

ABSTRACT

The JET Toroidal Field (TF) coils were originally designed for operation at 3.4 tesla. In order to upgrade the field to 4 tesla and thus improve the performance of the JET machine, new mechanical tests and analysis were carried out on the insulation of TF coil samples. They were aimed at investigating the mechanical properties and the status of the insulation in order to set allowable stresses and force limits.

In particular since the shear stress in the insulation is strongly affected by the shear modulus of elasticity G, it is important to measure this parameter. A method for the measurement of G in glass–resin composites, the V-notched beam method (Iosipescu method), was applied. The particular shape of the rectangular Iosipescu V-notched sample and the particular modality of force application produce pure shear stress for a reliable measurement of the G value and of the shear strength of the insulation. The effect of temperature on these mechanical properties was also investigated. Results show higher average shear strength with lower scatter compared with previous tests on conventional rectangular samples, thus confirming the reliability of the method. Micrographic analysis of the insulation and comparison between the straight and curved regions of the magnet, where the highest stress occurs, confirm the good quality of the impregnation of the coil. Glass–resin content, void content, micros and TG measurements have been performed on different samples and correlation between the different properties of the insulation investigated. Moreover fatigue tests at different temperatures were performed and data analyzed with the cumulative damage technique, which allows for an extrapolation of the fatigue curve with less samples than the standard method.

I. INTRODUCTION

The JET toroidal field (TF) magnet system, Fig.1, comprises 32 D-shaped coils originally designed to produce a field of 3.45 T at 2.96 m radius. Water-cooled and lately freon-cooled copper conductors and glass fibres-epoxy resin insulation are the main components of the coils. Electromagnetic in-plane and out-of-plane forces increase with the toroidal magnetic field B. In order to assess the condition of the TF coils for the implementation of the upgrade of the JET machine to 4 T operation, new analyses and tests have been made. The obtained data give the basis for the review of allowable stress and force limits.

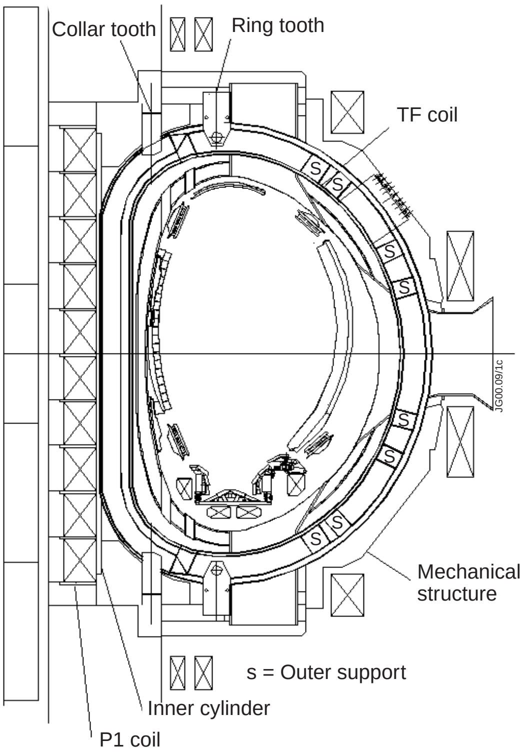

Fig.1: Cross section of the JET machine showing a TF coil with its supports.

II. MECHANICAL ANALYSIS OF THE TF COILS

The mechanical load of the TF coils is assessed for any operational scenario of the JET machine. The 2D finite element plasma equilibrium code MAXFEA (Maxwell Finite Element Analysis) calculates the poloidal field (PF) and a 3D Biot Savart magnetic code the toroidal field, given the input parameters defining a particular scenario. The plasma parameters and TF and PF coil currents are the input data for the calculation of the in-plane and out-of-plane force distribution in the TF coils. Thereafter the stress distribution is computed by finite elements codes which are based on 2 models, the beam model [1] and the hybrid model [2].

The beam model gives the distribution along the coil of the mechanical stresses related to the particular operational scenario. The model consists of 136 beam elements, with smeared properties calculated across the section and support and load conditions as for the actual configuration. This represents a quick tool for the assessment of the averaged stresses in the section of the coil, according to the classical beam theory.

The hybrid model, Fig.2, was created to investigate on the level of peak shear stress in the insulation itself in one of the most critical area of the coil, the third interturn at the collar tooth support area. Fig.3 shows a typical cross section of the TF coil, made up of 2 adjacent pancakes with 12 turns each. The insulation is divided in interturn, interpancake, key and ground insulation. The hybrid model consists of a 3D detailed model with brick elements in the area of interest and a beam model of the remaining coil. Following the explicit modeling of the copper conductors and the glass-resin insulation in the section, extra safety margin was found. Moreover key efficiency and delamination analysis was performed, which gives a trend of a crack non-propagation effect. Sensitivity analysis of the shear stress in the insulation with the shear modulus of elasticity G was carried out, which imposed the necessity to measure the actual value of the above mentioned parameter. A new correlation between the reaction force at the collar tooth support and the related peak shear stress in the insulation was therefore set up for the measured G.

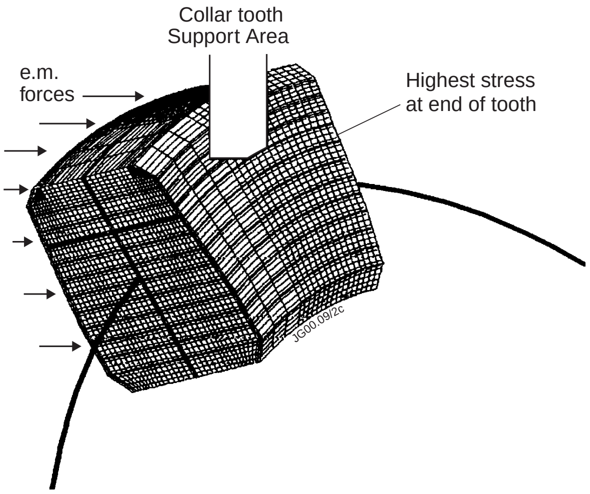

Fig.2: The hybrid model.

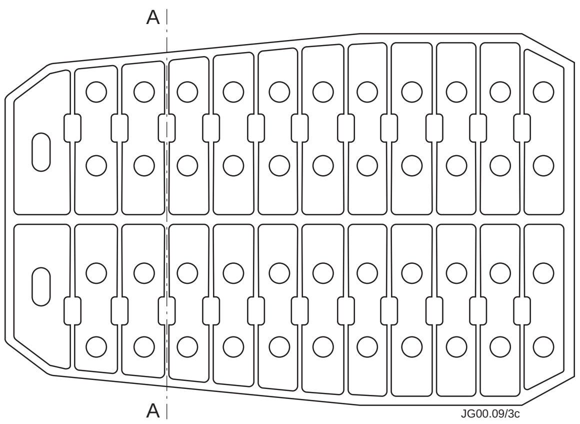

Fig.3: A cross section of the TF coil.

III. TESTS AND ANALYSIS ON THE COIL INSULATION

Optical examination and mechanical tests were carried out to investigate the mechanical properties and condition of the coil insulation, in particular the interturn insulation. Its constituents are glass fibres vacuum impregnated with epoxy resin. The resin composition is Araldite CY205 – Hardener HY906 – Flexibilizer DY040. Samples were cut from slices of the first faulty coil at various positions, so as to increase the statistics of the results.

A. Measurement of G with Iosipescu Method

The shear stress in the insulation is strongly affected by G, therefore it is of the utmost interest to measure this parameter. Since cylindrical samples for standard measurement of shear properties could not be machined out of the available material of the coil, the Iosipescu method for the measurement of G on rectangular samples was implemented [3]. This is a standard method designed to produce shear property data of composite materials. A rectangular sample with symmetrical centrally located V-notches is loaded in a mechanical testing machine by a special fixture designed to produce pure shear stress. The notches improve uniformity of the shear strain distribution along the loading direction. Any twisting of the sample is corrected through the readings from strain gauges on both sides of the sample. 18 samples were tested according to the standard and the τ-γ curve recorded up to failure. The effect of temperature was also investigated. For our measured ultimate shear strain capability the G value is derived from the chord in the shear strain range 1000 ÷ 6000 $\mu\varepsilon$.

$$G = \frac{\Delta\tau}{\Delta\gamma}$$

Preload test up to maximum 5 MPa at the 3 different temperatures T=20^{0}C, T=70^{0}C and T=90^{0}C and failure test at the chosen temperature were performed on each sample. The averaged G drastically decreases with temperature from 3700 MPa at room temperature down to about 2600 MPa at 70^{0}C and 1400 MPa at 90^{0}C, Fig. 4. The preload test gives the possibility to compare the G value of the same sample at the 3 different temperatures. Results from these tests give a constant G at low temperature, while G drastically decreases with the shear load increase at high temperature.

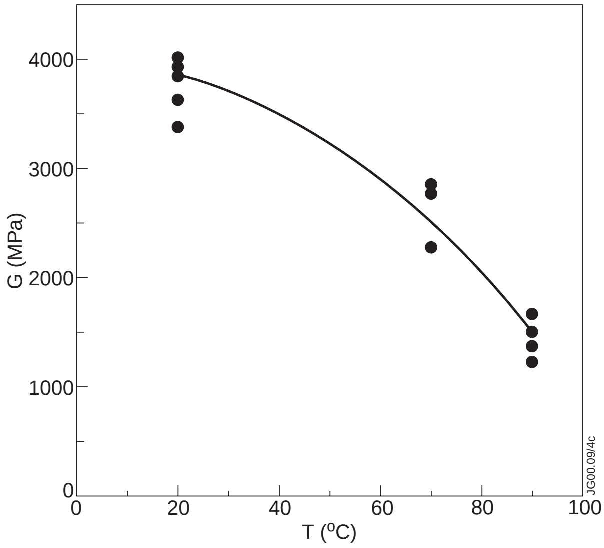

Fig.4: Variability of G with temperature (Iosipescu samples).

Preliminary calibration was carried out on a sample with well known G, which confirm reliability of the method within few percent.

Moreover finite elements analysis was carried out to check the stress field and sensitivity of G with the glass-resin content. A maximum 15% uncertainty was found between the computed and the measured G for the same glass-resin composition. This gave confidence for computing the G value of the key insulation, knowing its composition.

B. Shear Strength with Iosipescu Method

The obtained data allow also for investigation of the shear strength capability of the insulation and its sensitivity with temperature, Fig. 5. Results show higher average with lower scatter compared with previous tests on conventional small rectangular samples, Fig. 6, and on double shear samples [1], thus improving confidence in the result. Fig. 7 shows the geometry of the different samples.

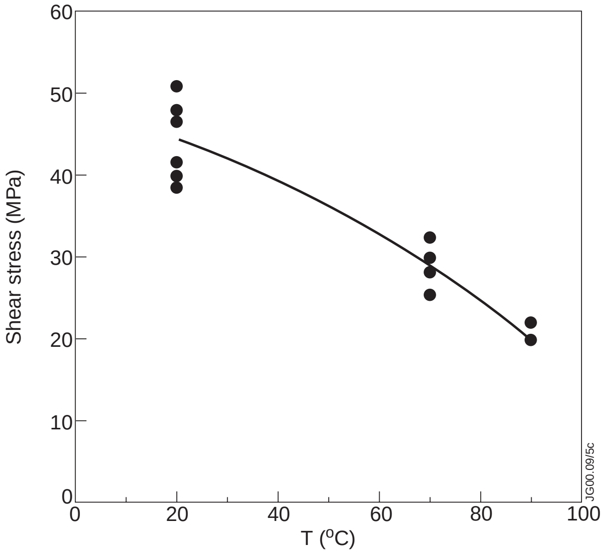

Fig.5: Shear strength versus temperature (Iosipescu samples).

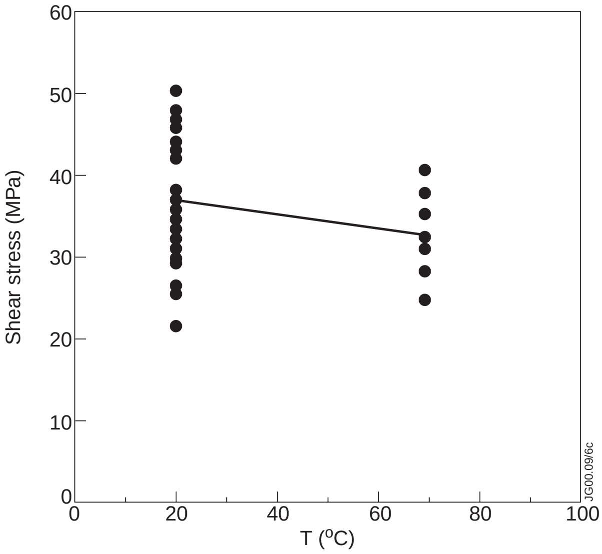

Fig.6: Shear strength versus temperature (small samples).

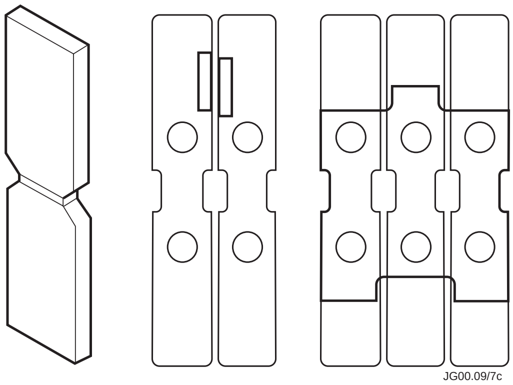

Fig.7: Iosipescu, small and double shear samples.

The contact failure is defined as the percentage lack of resin over the total area. The void content is a volumetric measurement of voids, therefore it is a quantitative measurement of the percentage lack of resin in the sample volume. The qualitative information on the shape, concentration and topology of the voids is given by the contact failure. The contact failure may explain the spread of shear strength in the measurements. Fig. 8 shows the correlation between contact failure and shear strength obtained by microscopic analysis in the failed area of the broken sample at room temperature for both Iosipescu and small samples. From the failure mode analysis 2 main failure mechanisms were observed, at the pre-preg layer in the center of the insulation and at the copper/insulation interface. The number of samples which break at the pre-preg layer is higher, thus confirming that the weakest point of the coil is related to the technological choices of the manufacturing cycle more than on the quality of the impregnation.

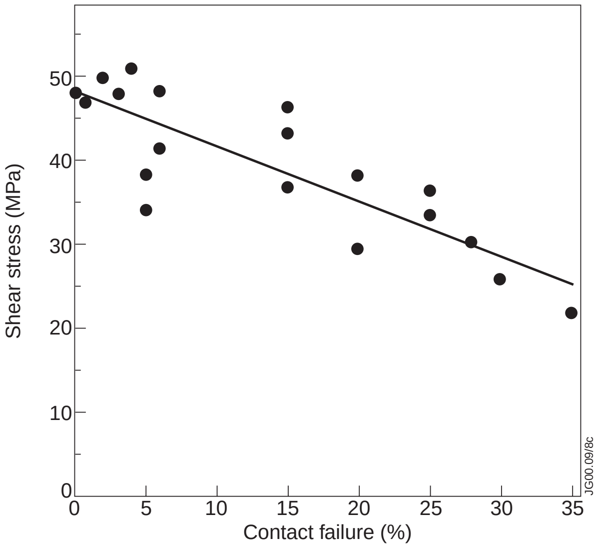

Fig.8: Shear strength against contact failure at room temperature (Iosipescu and small samples).

C. Fatigue Tests

Fatigue tests were performed on conventional small samples with the cumulative damage technique. This allows for the determination of the S-N curve using less samples than the standard fatigue test method. The same sample is cycled for a chosen number of cycles, i.e. 20000 as it demonstrates double the required life, with a frequency F=0.83 Hz, at different stress levels with constant stress steps up to failure. The effect of the previous cycling is allowed for by cumulative damage calculations. 7 samples were tested at T=20^{0}C and 6 at T=90^{0}C, Fig. 9.

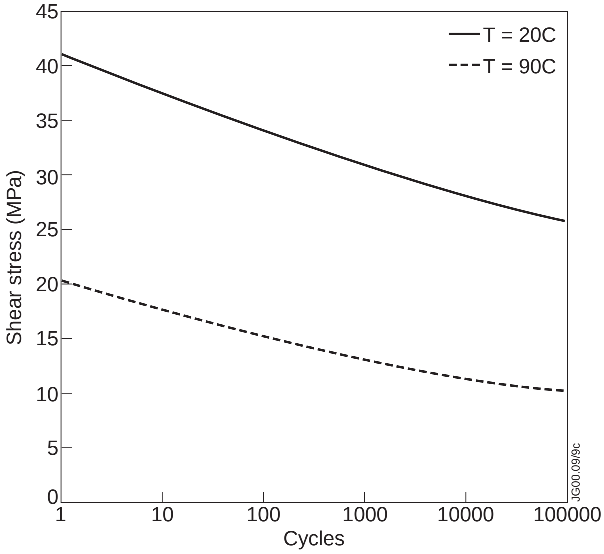

Fig.9: Fatigue curves at temperature 20°C and 90°C (small samples).

Other fatigue tests were performed on double shear samples at the different temperatures T=20^{0}C, T=70^{0}C and T=90^{0}C, Fig.10. The curves at room temperature are very similar, while they are different at high temperature. In particular the double shear samples give higher strength at high temperature: this is mainly due to the test frequency which is a factor 10 higher. Preliminary creep tests show a clear creep effect already at temperature T=70^{0}C, which implies that the total time at maximum load affects the fatigue behavior at temperature. Fig. 11 shows the fatigue curve at room temperature obtained with Iosipescu samples and the standard fatigue method. The 3 curves at room temperature are very similar, thus increasing confidence on the result.

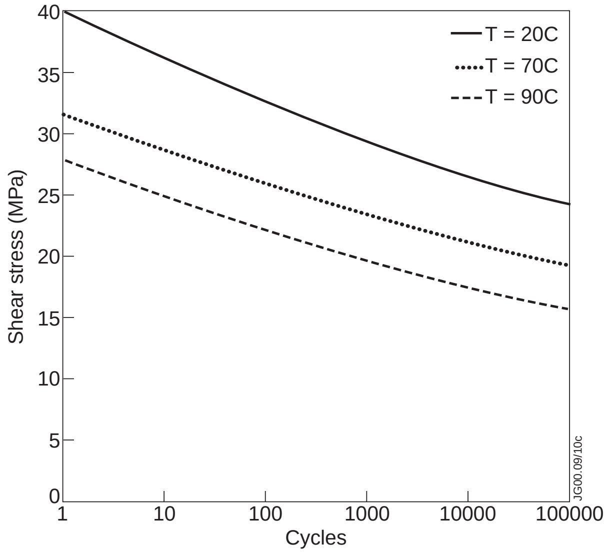

Fig.10: Fatigue curves at 20, 70 and 90^{0}C (double shear samples).

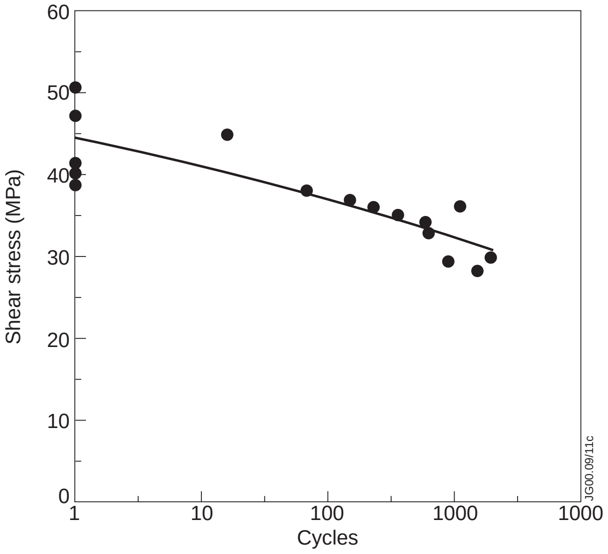

Fig.11: Fatigue curve at 20°C (Iosipescu samples).

D. Micrographic Examination

To investigate the condition of the insulation, micrographic analysis of samples taken at different positions in the section of the coil and comparison between the straight and curved region were carried out.

7 plus 7 interturn samples at correspondent positions in the 2 sections were chosen for the analysis taking into account also the sample position of the previous tests, in order to study possible correlation between the different parameters.

Void content [4] and glass-resin content [5] was performed through calcination of a sample. Moreover micrographic analysis of the 2 sections adjacent to the sample was carried out to study the morphology of the defects.

The average void content is 0.66%, in particular 0.64% in the straight region and 0.68% in the curved one. This confirms the good quality of the impregnation, since the limit reported in the standard is 1%. These voids are mainly due to the resin shrinkage, during the polymerization process and their main shape resembles a flattened sphere, which gives a lower overall weakening. The average glass content is 63.6% and the resin content 35.7% and are not significantly different in the 2 analyzed regions. The lowest measured G does not correspond to a sample with the lowest glass and highest void content as expected, which implies that the glass content and void content have no correlation with the G values. This confirms that within the observed variability of the measurements, the mechanical properties of the insulation are not affected from region to region. The voids observed by micros show the same pattern and comparable concentration in the 2 regions and are mainly due to little air bubbles trapped during the manufacturing cycle in the 2 layers of pre-preg positioned in the middle of the inter-turn insulation. The shape of these voids suggests that they kept their shape and dimension since then. As already mentioned no correlation was found between void content and shear strength, while a correlation exists between contact failure and shear strength, Fig. 8.

E. Second Order Glass Transition Temperature (GTT)

GTT measurement was performed on different samples by both the Differential Scanning Calorimetry and the Differential Thermal Analysis [6]. The averaged GTT is 109^0C, ranging from 105^0C to 115^0C. This level of temperatures explains the drastic fall of shear resistance observed in both static and fatigue tests performed at $T=90^0$C. From correlation analysis on correspondent samples , GTT increases with G at the same glass content.

IV. CONCLUSIONS

The results achieved confirm the good status of the coil insulation. It must be emphasized that the samples are cut from a real coil which has been operational in the JET machine for years, while normally new laboratory-made samples are used for the tests. This increases our confidence in the results. The Iosipescu method for the G measurement was extended to determine also the shear strength and the fatigue behavior.

The results obtained lead to the definition of allowables and fatigue limits. Fatigue tests with different samples give approximately the same fatigue curve at room temperature, which is the basis for the fatigue assessment of the TF coils. The result from this work is the basis for the reliability assessment of the JET machine and acceptance of its upgrade to 4 tesla operation for improved performance.

ACKNOWLEDGMENTS

Thanks are due to M Gasparotto, S Tosti and L Verdini for their contribution to this work.

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