Mechanical Analysis and Material Tests  
of the Twisted WENDELSTEIN VII-AS Coils

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Abstract

Design feature of the W VII-AS device is the use of vacuum impregnated non-planar coils. The magnetic and thermal forces acting at a coil leads to stress combinations which are approaching the limit of the necessary copper/glass/resin compound material. In this paper results of finite element stress calculations and of material tests for the stranded copper wires, the chosen insulation systems and for beams with original coil cross section will be shown. As limiting constituent of such a coil the insulation system is found.

1. Introduction

Modularity of the Advanced Stellarator WENDELSTEIN VII-AS is achieved by the use of forty-five nonplanar coils with an average coil radius of 0.5 m. They are distributed along a torus of approximately 2 m radius, the coil design is shown in fig. 1. The generated toroidal field on axis will be B<3 T (winding current 37 kA) for a pulse time of 5 seconds. Glass texture insulated wires are wound into a mould and impregnated with epoxy-resin. In a hardening process, the mechanical rigidity is achieved.

A coil consists of two pancakes with 8 turns each, a turn consists of 9 stranded Ag-alloyed flexible copper wires and 3 water cooled hollow copper conductors. The performance of the W VII-AS-device depends mainly on the mechanical and electrical reliability of these coils. A more detailed description of the experiment device is given elsewhere at this conference /1/.

Finite element calculations are necessary to determine critical stress combinations and critical parts in such a twisted coil. This analysis must be done for the maximum generated magnetic field and thus for maximum mechanical stresses.

To ensure the reliability of the materials used static and dynamic tests of samples and of large scale members have to be performed. The specimen should be produced using normal coil manufacturing techniques.

2. Mechanical stress analysis

The effective mechanical stress in the nonplanar coils was computed with the three-dimensional SAP V(2)-code for the end of the flat top time including a thermal component due to a temperature rise of 55 K and the magnetic forces. These forces are calculated using EFFL. The FE-model applied was presented in the last SMIRT Conference /2, 3/ and consists of the coil, the padding and the casing which are modelizing the real support regions. Measurements of the most important and calculation of the remaining coefficients of Hook's matrix (tab. 1) permit an improved orthotropic stress analysis. The necessary material tests were done with a straight beam and original cross section (temperature 80°C), loaded under compression, bending and combined bending-torsion conditions (fig. 2). Similar tests were carried out with individual
impregnated stranded copper wires. The limiting stress combinations for the coil 1 as resulting from these FEA calculations are shown in tab. 2. Finally, the subdivision of stress tensor for the two main components of the "composite material" coil, stranded copper wire and insulation system, are done approximately considering the inside compatibility and equilibrium condition of the coil. Inside the copper wires an additional shear due to the stranding angle is active.

3. Testing of the stranded copper wire and of the insulation system.

3.1. Copper wire
Static and dynamic material tests with individual vacuum pressure impregnated stranded copper wires (stranding angle 10°) have been carried out using a combined tension-torsion testing machine. The results are summarized on the Wöhler diagram of fig. 3.

As failure criterion damage of the copper wires occur, no delamination of the copper-resin interface is visible. Thus in the above mentioned fig. 3, the maximum equivalent (v. Mises) stresses in the stranded wire are plotted against the load numbers. These stresses are calculated not taking into account the copper space factor of the individual stranded wire (>83%).

In tension and combined tension/torsion fatigue tests the copper wires were undamaged after the foreseen lifetime of the device (5*10^5 cycles) with v. Mises stress values ε ≤ 180 N/mm². There is no significant difference in the lifetime of samples when changing the test temperature between 20°C and 80°C, the (dynamic) elongation and twisting amplitude is a little bit higher for the elevated temperatures. Contrary to this, the permanent twisting after the end of testing is at least 3 times higher at 80°C. This is due to the elevated creep rate of the epoxy-resin at this temperature.

From the FE-calculation of coil 1 the maximum resulting equivalent stresses in the stranded wire at maximum field values and coil working temperature are ~105 MPa. This value takes into account the additional shear due to tensile stresses in the stranded wire. The available safety factor for maximum magnetic field values and the foreseen lifetime of the device (5*10^5 pulses) is ~ 1.7.

3.2. Insulation system
The chosen vacuum impregnated epoxi insulation system (Urlitherm OH 67-UM) is about the same as used for the JET Poloidal Coils /4, 5/. After drawing (without using grease), the surface of single wires are oxide free. An immediate subsequent treatment with an aliphatic polyamide primer (DD 80 from Ciba) prevents oxidation and improves the adhesion between copper and resin. Reinforcing strengthener is Silan sized glass fabric.

In the insulation system of the coils the most limiting stress seems to be shear. Hence shear tests were carried out using test samples as shown in fig. 4. The shear stress distribution along the test planes isn't linear, the peak value is approximately 1.6 times higher than the mean value. Additional tension/compression stresses perpendicular to the insulation system cause a decrease/increase of the shear strength. The selected shear test device is a 3 by 3 arrangement of
- 9 stranded copper wires only
- 9 solid (water cooled) wires only
- 8 stranded copper wires with one solid wire in the middle.

First static tests where performed using samples of copper wires glass fiber taped only and additional with preimpregnated glass fabric in some planes (at plane X, see Fig. 4). The critical shear stress value in the chosen design for the coil is first reached in the insulation layer between stranded copper wires without winding or pancake insulation (tab. 3).
Fatigue tests using the same test device and samples with the above found mechanical limiting insulation system starts up with "JET-resin". Variation of impregnation and hardening conditions as well as variation of glass tapes, primer hardening conditions and resin system, combination lift the available values for mean shear stresses after $5 \times 10^6$ loadcycles up from 15 MPa to 20 MPa (fig. 5).

This maximum save working stress-taking also into account nonlinear shape of stress curve and additional normal stresses have to be compared with stresses resulting from calculations (see tab. 2). The difference between existing and permissible stress in the insulation system are smaller than that one for the stranded copper wires.

4. Beam test

Two fatigue tests of straight beams with original coil cross section were carried out to confirm the results found with sample tests. The combination of critical stresses found in FE-calculations and material tests where simulated by loading a beam with combined bending and torsion (fig. 2). Test temperature was 80° C, test frequency 0.25 Hz (sin). For impregnation the "JET"-resin was used.

In a first test the stresses applied where in the range of the calculated values for coil 1 - the maximum shear was 16 MPa and maximum tension/compression in the copper wires 150 MPa. For $5 \times 10^6$ loadcycles the beam endured this stress combinations without failure.

The damage mechanism of the composite material coil and its behaviour was studied at elevated loads ($\sigma_{\text{max}} = 27.8 \text{ N/mm}^2$, $\varepsilon_{\text{max}} = 150 \text{ N/mm}^2$) (fig. 2). The delamination occurred in the insulation layer between the wires (not within the winding insulation). Failure starts to be visible after approximately 1 300 loadcycles. At the present stage the safety factor of the coil at $5 \times 10^6$ loadcycles with full load is near 1. It can be increased by using the optimized resin system.

5. Conclusion

The reliability against mechanical and hence against electrical breakdown of the coils depends upon the difference between existing and permissible mechanical stress combinations.

Both beam and sample fatigue tests with stress combinations similar to nominal load foreseen for coil 1 of the W VII-AS device showed that the limiting constituent is the insulation system. In the stranded copper wires the available safety factor is satisfactory. For support of the test results and for improving the safety factor it is intended to carry out furthermore material tests.

When starting FE-calculations the limiting quantity for mechanical reliability of the coils thought to be the stress combinations inside the stranded copper wires causing fracture or delamination. In comparison with the insulation additional shear stresses due to stranding of the wires and heavily increased circumferential tensile/compression stresses are active there. First computations of the five geometric different nonplanar coils of the W VII-AS test device shows that maximum v. Mises stresses occur in coil 1. A more detailed FE-analysis of this coil load to stress combinations as shown in this report. Mechanical tests based upon these results demonstrate that delamination inside the insulation system will be the most probable coil fracture mechanism. So additional finite element computations taking into account these recent informations are in work to estimate the safety of the coils against fatigue damage. With this knowledge it will also be possible to optimize the supporting system of the coils.

6. Acknowledgement

Thanks to BBC-Company (Mannheim, W. Germany), MPA (Darmstadt, W.G.) and Iabg (Ottobrunn, W.G.).
References

/1/ Mathis, R.; Sapper, J.; Schoenewolf, I.: "Engineering Problems of the Wendelstein VII-AS Experiment" Proc. of the 8th in. Conf. on Structural Mechanics in Reactor Technology, Brussels, Belgium (1985), Paper N1/4


Table 1: Orthotropic material data of the coil.

<table>
<thead>
<tr>
<th></th>
<th>$E_x$</th>
<th>$E_y$</th>
<th>$E_z$</th>
<th>$G_{xy}$</th>
<th>$G_{xz}$</th>
<th>$G_{yz}$</th>
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<td>coil</td>
<td>40.000</td>
<td>40.000</td>
<td>65.000</td>
<td>11.5000*</td>
<td>12.500</td>
<td>12.500</td>
</tr>
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<td>impregnated stranded copper wire</td>
<td>52.000*</td>
<td>52.000*</td>
<td>88.000</td>
<td>12.000*</td>
<td>14.000</td>
<td>14.000</td>
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<td>glassfiber reinforced epoxy resin (from /6/)</td>
<td>$E_4$</td>
<td>$E_4$</td>
<td></td>
<td></td>
<td>$G_{44}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28.000</td>
<td>13.000</td>
<td></td>
<td></td>
<td>4.500</td>
<td>13.000</td>
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|| parallel to the (2D) reinforcement
| perpendicular to the (2D) reinforcement
| * calculated

Table 2: Calculated maximum stress combinations of coil 1.

<table>
<thead>
<tr>
<th>N/mm$^2$</th>
<th>$\sigma_L$</th>
<th>$\sigma_4$</th>
<th>$\tau$</th>
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<td>Insulation</td>
<td>12</td>
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<td>2</td>
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<td></td>
<td>-2</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>24</td>
<td>14</td>
</tr>
<tr>
<td>stranded copper wire</td>
<td>12</td>
<td>55</td>
<td>14*</td>
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<tr>
<td></td>
<td>-7</td>
<td>98</td>
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<td></td>
<td>-9</td>
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<tr>
<td></td>
<td>30</td>
<td>-1</td>
<td>14</td>
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* Including internal shear due to stranding
| perpendicular to reinforcement (copper wire/glass fabric)
|| parallel to reinforcement
= critical combinations

Table 3: Static shear fracture stresses for the possible combination of wires and insulation systems /Mpa/.

<table>
<thead>
<tr>
<th>3 by 3 arrangement with:</th>
<th>JET-resin 20°C</th>
<th>JET-resin 80°C</th>
<th>IPP-resin 80°C</th>
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</thead>
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<tr>
<td>stranded copper wires only</td>
<td>53</td>
<td>32.5</td>
<td>40</td>
</tr>
<tr>
<td>solid cooling wires only</td>
<td>61</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>solid cooling wire in the middle</td>
<td>56</td>
<td>---</td>
<td>41</td>
</tr>
<tr>
<td>stranded copper wires only and winding insulation*</td>
<td>56.5</td>
<td>---</td>
<td>---</td>
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<tr>
<td>solid cooling wire in the middle, winding insulation*</td>
<td>67.5</td>
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* Winding insulation at one plane only
Fig. 1: Coil design (schematic)

Fig. 2: Beam (fatigue) test arrangement, resulting stress combination and failure behaviour.

Fig. 3: Fatigue tests of impregnated stranded copper wires.
Fig. 4: Shear test arrangement.

Fig. 5: Fatigue tests of the insulation system.