Study on inner insulation tube for ITER axial insulation breaks

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Abstract. Inner insulation tube as a key component of ITER insulation break, its fabrication process was designed, and the specimen type was designed and made. Fibres and void content was tested, and thermal coefficient was measured. The results showed that it is reasonable to use R glass fibres in filament wet winding as inner tube for ITER IB because the thermal shrinking measure of this composite fabricated by this process technology is so close to the one of stainless steel 316L that it is good to reduce the thermal stress in the insulation structure of IB.

1. Introduction
Low-temperature high-pressure Helium tightness axial composite insulation breaks are key components of ITER (International Thermal nuclear fusion Experimental Reactor) magnet systems [1-4]. During the assembly and operation of the apparatus the cold shrink generated thermal stress, due to the large superconducting magnet and the return temperature of the cooling process, and the electromagnetic interaction generated tensile stress during charging and discharging, then causing damage hermetic insulation, which led to the cryogenic liquid into the vacuum system, prone to PASCHEN discharge, the entire apparatus will have a devastating damage [5-7].

Inner insulation tube as a key component of ITER axial insulation break, its fabrication process was optimized and analyzed [8-10]. These same inner insulation tubes have been fabricated in ASIPP and test in technical institute of physics and chemistry, Chinese academy of sciences. These test results will be applied in mechanical and electrical analysis for IBs.

Seven types of specimens whose inner dimension is the same with ITER IB specification was designed, by using different glass fiber and process. This document includes the specimen type design, fiber content test and thermal coefficient test for the selected insulation materials to be used in the ITER axial insulation breaks [11-13].

2. Insulation tube materials
Glass fiber reinforced plastic will be used as the insulation structure materials of ITER IB. Two types of E and R glass fibers are compared.

DWZ cryogenic epoxy resin system is chosen for insulation structure adhesive that is EAST patent. This type of epoxy resin system is composed of two components, one is DGEBA epoxy resin, the other is curing agent that is a mixture of GY051 and DDM. The percentage of these two components in weight is 4:1 in which the curing agent is 1 weight. Results in Table 1 imply that the shear strength of this type of epoxy resin at different temperature. It is apparent that modified epoxy resin is
toughening structure that has good resistance to crack propagation. Results in Table 2 imply that the tension strength and impact strength of this epoxy resin.

Table 1. The shear strength of DWZ epoxy resin at different temperature.

| Type  | Shear strength (MPa) | Glass transition temperature Tg (K) | Thermal coefficient (1/K) |
|-------|----------------------|-----------------------------------|--------------------------|
|       | 4.2 K 77K 300K 333K 373K | 120.2 | 3.88×10⁻⁵ |
| DWZ   | 19.76 19.49 20.45 18.96 10.53 |                   |                           |

Table 2. Tension strength and impact strength of DWZ resin at different temperature.

| Type | Temperature (K) | Tension strength (MPa) | Impact strength (MPa) |
|------|-----------------|------------------------|-----------------------|
| DWZ  | 77              | 112.36                 | 19.22                 |
|      | 300             | 57.84                  | 14.21                 |

3. GFRP inner tube fabrication
Glass tows and glass tapes were wound on mold by wet winding process. The mold was fixed on the winding machine. Different samples had been fabricated with same tension by changing different winding angle and different types of fibers. Figure 1 shows the cross-section of mold for inner tube fabrication. Figure 2 shows the real inner tubes by different process.

The same cure schedule was applied for all insulation tubes because the same type of epoxy resin DWZ was used. Seven types of insulation tubes had been fabricated as shown below. Results in Table 3 imply that the specification of insulation tube specimens.

1) Insulation tube L1
   E glass fiber in filament winding, the fiber winding angle is 30°~45°, tow tex is 500.
2) Insulation tube L2
   R glass fiber in filament winding, the fiber winding angle is 20°~30°, tow tex is 500.
3) Insulation tube L3
   E glass fiber tape (width 20mm, thickness 0.1mm) half-lapped, the winding angle is 30°~45°.
4) Insulation tube L4
   E glass fiber in filament winding, the fiber winding angle is 30°~45°, tow tex is 500.
5) Insulation tube L5
   R glass fiber in filament winding, the fiber winding angle is 30°~45°, tow tex is 500.
6) Insulation tube L6
   E glass fiber tape (width 10mm, thickness 0.1mm) half-lapped, the winding angle is 40°~45°.
7) Insulation tube L7
   E glass fiber tape (width 10mm, thickness 0.1mm) half-lapped, the winding angle is 40°~45°.
Table 3. The specifications of insulation tube specimens.

| Serial number | Glass fiber | Fiber gauge | Fiber angle(°) | Process | Tension(Kg) |
|---------------|-------------|-------------|----------------|---------|-------------|
| L1            | E glass     | Tex 500     | 30-45          | Wet     | 2           |
| L2            | R glass     | Tex 500     | 20-30          | Wet     | 2           |
| L3            | E glass     | Tape: Width=20mm, thickness=0.1mm | 30-45 | Wet | 2 |
| L4            | E glass     | Tex 500     | 30-45          | Wet     | 2           |
| L5            | R glass     | Tex 500     | 30-40          | Wet     | 2           |
| L6            | E glass     | Tape: Width=10mm, thickness=0.1mm | 40-45 | Wet | 2 |
| L7            | E glass     | Tape: Width=10 mm, thickness=0.1 mm | 40-45 | Wet | 2 |

4. Inner Glass Fibre Reinforced Plastic (GFRP) insulation tube
First, the mold fixed on the winding machine was half-lapped with Teflon tape as non-stick and slide materials. Then, Glass tows with DWZ resin were winded on mold by wet winding process. The fiber winding angle was about 20°-45° to radial direction, tow tex was 500, tension was 2kg and fiber speed was less than 6mm per second. At last, the silicone tapes are wrapped on the outer of inner tube to keep DWZ not flow out. Wet winding process method was chosen, process in detail as follows:
1) Clean the mold using acetone or alcohol, dry, and store at drier before winding
2) Teflon tape is wrapped on the surface which diameter is 15mm
3) R glass fiber wet winding: Tow should be transparent from eye after dipping DWZ epoxy resin, tow speed is less than 6 mm/s
4) Half-lapped silicone tape on the outer of glass tow after glass fiber winding finished to keep DWZ glue not flow out
5) Gel while winding machine rotating at room temperature 1 hour and cure in stove
6) Fabricate according to design dimension
7) Clean using acetone or alcohol, dry and store in a drier

5. Glass fiber content test
Resin and void content of GFRP inner tubes were tested according to GB/T 2577-2005. It was necessary to confirm that all insulation is of the same quality.
1) Resin mass and volume content percent:
   \[ M_t = \frac{M_2 - M_3}{M_2 - M_1} \times 100 \]  
   \[ V_t = \frac{M \times \rho_c}{\rho_t} \times 100 \]  
   \[ M_t: \text{Resin mass content}, \ M_1: \text{mass of pot}, \ M_2: \text{mass of pot and sample before roasting}, \ M_3: \text{mass of pot and remaining fiber after roasting}, \ V_t: \text{resin volume content}, \ \rho_c: \text{Density of GFRP composite sample}, \ \rho_t: \text{Density of resin adhesive}. \]
2) Fiber mass and volume content
\[ M_g = \frac{M_4}{M_2 - M_1} \times 100 \]  
(3)

\[ V_g = \frac{M_g \times \rho_c}{\rho_g} \times 100 \]  
(4)

\( M_4 \): Mass of remaining fiber after roasting, \( M_g \): Glass fiber volume content, \( V_g \): Fiber volume content, \( \rho_c \): Density of GFRP composite sample, \( \rho_g \): Density of glass fiber.

3) Void volume content:

\[ M_f = \frac{M_3 - M_4 - M_1}{M_2 - M_1} \times 100 \]  
(5)

\[ V_f = (1 - V_i - V_g) \times 100 \]  
(6)

\( M_f \): Void mass content, \( V_g \): Void volume content, \( \rho_c \): Density of GFRP composite sample.

Figure 3. Mass measurement for fiber content test.  
Figure 4. Oven for roasting.

Figure 3 and Figure 4 show the equipments of glass fiber and void volume test. Test steps were shown as follow:

1) Cleaning the specimens
2) Measuring mass of pots and specimens before roasting
3) Roasting for 4 hours in oven at 600°C
4) Measuring mass of pots and specimens after roasting
5) Calculating mass and volume content of fiber and resin

Table 4. Glass fiber content measurement of GFRP composite by roasting method.

| No. | M1 (g) | V (cm\(^3\)) | Ma (g) | Va (cm\(^3\)) | Mf (g) | Vf (cm\(^3\)) | Fiber content | Adhesive content | Void |
|-----|--------|--------------|--------|--------------|--------|--------------|---------------|----------------|-------|
|     |        |              |        |              |        |              | Mass%  Vol%   Mass%  Vol% |  Mass%  Vol% |
| 1   | 10.41  | 5.426        | 2.816  | 7.589        | 7.589  | 2.988        | 72.936 55.07 | 27.06 43.25 | 1.68 |
| 2   | 7.242  | 3.71         | 2.016  | 5.226        | 5.226  | 1.98         | 72.165 53.36 | 27.83 45.28 | 1.36 |
| 3   | 14.21  | 8.448        | 5.908  | 8.307        | 8.307  | 3.27         | 58.439 38.71 | 41.56 58.27 | 3.02 |
| 4   | 10.22  | 5.468        | 3.046  | 7.17         | 7.17   | 2.823        | 70.186 51.63 | 29.81 46.42 | 1.96 |
| 5   | 10.63  | 5.362        | 2.645  | 7.989        | 7.989  | 3.026        | 75.127 56.44 | 24.87 41.11 | 2.46 |
| 6   | 8.927  | 5.057        | 3.157  | 2.631        | 5.77   | 2.272        | 64.635 44.92 | 35.36 52.02 | 3.06 |
| 7   | 9.568  | 5.493        | 3.594  | 5.974        | 5.974  | 2.352        | 62.436 42.81 | 37.56 54.52 | 2.66 |
Notes: M1 and V is respectively total mass and total volume of specimen; Ma and Va is respectively mass and volume of adhesive in specimen; Mf and Vf is respectively mass and volume of glass fiber in specimen.

According to the density of E glass fiber and R glass is respectively 2.54 g/cm³ and 2.64 g/cm³. The density of adhesive is 1.2g/cm³, Results in Table 4 imply that the glass content test for inner tubes. This was a clear statement that mass of fiber of the insulation tube using glass fiber filament winding was 70-75% higher than 55-65% that using glass fiber tape winding. Volume of fiber of the insulation tube using glass fiber filament winding was almost 55% higher than 40% that using glass fiber tape winding. Void volume content using R glass fiber was lower than using E glass fiber under the same process conditions.

6. Thermal Expansion coefficient test
Thermal coefficient was measured in the axial, round, and radial directions. The measurements were made using a ‘Resistance Piece Dilatometer’. Resistance Piece Dilatometer transmitted the contraction of the sample at low temperature to a linear variable differential transformer (LVDT) operating at ambient temperature. Figure 5 illustrated the test apparatus.

\[ \frac{\Delta l}{l} = K, \frac{\Delta R}{R} \]

The test method was as follows:
1) Cleaning the samples
2) Assembling strain piece on the Sample
3) Jointing with the LVDT apparatus
4) Liquid helium was poured into the cryostat until the sample temperature was stable at 4.2K.
5) The samples were warmed up over a period of 24 hours while the temperature and LVDT voltage was recorded.

Figure 5. The specimen and strain instrument for thermal coefficient test.

Results in Table 5 imply that it was clear that thermal shrinking measure of insulation tube using glass fiber filament in radial direction is lower than that using glass fiber tape at 77K and at 4.2K temperature conditions.

| No. | R(axial) | R(round) | R(axial) | R(round) | R(axial) | R(round) | R(radial) | R(radial) |
|-----|----------|----------|----------|----------|----------|----------|-----------|-----------|
| 1   | 0.3840   | 0.2031   | 0.3695   | 0.4455   | 0.2659   | 0.4200   |           |           |
| 2   | 0.2114   | 0.0980   | 0.3540   | 0.3311   | 0.1062   | 0.3940   |           |           |
| 3   | 0.2635   | 0.2820   | 0.5458   | 0.3827   | 0.3934   | 0.6450   |           |           |
| 4   | 0.3415   | 0.1632   | 0.3730   | 0.4114   | 0.2319   | 0.4120   |           |           |
| 5   | 0.3109   | 0.1087   | 0.3573   | 0.3340   | 0.1630   | 0.3890   |           |           |
| 6   | no       | no       | no       | no       | no       | no       |           |           |
| 7   | 0.2718   | 0.2670   | 0.5740   | 0.3574   | 0.4046   | 0.6560   |           |           |
7. Conclusion
This was a clear statement that mass of fiber of the insulation tube using glass fiber filament winding is 70-75% higher than 55-65% that using glass fiber tape winding; volume of fiber of the insulation tube using glass fiber filament winding is almost 55% higher than 40% that using glass fiber tape winding. Void volume content using R glass fiber was lower than using E glass fiber under the same process conditions.

In filament winding, the fiber angle and fiber content strongly influence the thermal shrinking measure. This is clear that thermal shrinking measure of insulation tube using glass fiber filament in radial direction is lower than that using glass fiber tape.

Above all, it is reasonable to use R glass fiber in filament wet winding as inner tube for ITER IB because the thermal shrinking measure of this composite fabricated by this process technology is close to the one of stainless steel 316L that is good to reduce the thermal stress in the insulation structure of IB.

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