CFETR Nb$_3$Sn coil in heat treatment deformation analysis and fixture designing

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Abstract. According to the research, it is found that the Hybrid Magnet coils, JT-60SA, ITER and CSMC coils are fixed by coils during heat treatment in order to prevent the coils deforming due to the release of residual stress. Since the penultimate process step of CFETR CSMC Nb$_3$Sn coil manufacturing process is the final assembly of the coil, the theoretical value of the initial unilateral gap between Nb$_3$Sn inner and outer coils is 27.4mm, and the theoretical value of the initial unilateral gap between Nb$_3$Sn outer coil and NbTi coil is 50mm. This gap will be reduced in each process of coil manufacturing process. In order to successfully assemble the coil, it is of great significance to analyze and develop a set of tooling to reduce coil deformation in heat treatment process.

1. Introduction

CFETR CSMC manufacturing is a connecting project that absorbs the manufacturing experience of domestic EAST and foreign ITER coils, and has accumulated valuable technical experience for the manufacturing of superconducting tokamak magnets in the future $^{[1]}$. There are generally two forms of Nb$_3$Sn superconducting magnet manufacturing process: "wind-and-react" and "react-and-wind". Due to its poor mechanical properties, strain has a serious impact on the properties of Nb$_3$Sn superconducting wire, and the residual stress generated in the winding process will affect its properties $^{[2]}$. The key manufacturing technology of the model coil consists of several important components: high-precision coil winding manufacturing technology, high current superconducting joint manufacturing technology, Nb$_3$Sn coil heat treatment technology, insulation wrapping technology, VPI, coil assembly and testing. Nb$_3$Sn coil heat treatment technology is of great significance as a connecting process step. Firstly, the coil and connector terminal have superconducting properties. Secondly, the residual stress in the armor in the coil winding process is eliminated to lay the foundation for the subsequent coil winding insulation.

2. Assembly gap analysis

According to CFETR CSMC Nb$_3$Sn coil manufacturing process, there are: 1. Coil winding process ; 2. Heat treatment process; 3. Coil turn and ground insulation wrapping process; 4. VPI process;The four process will change the assembly gap between Nb$_3$Sn inner and outer coils , between Nb$_3$Sn outer coil and NbTi coil.

At present, two Nb$_3$Sn coils and three NbTi coil windings of CFETR CSMC have been fully formed. After the coil is wound, it is scanned by the laser tracker, as shown in Figure 1.
As can be seen from Fig. 1 (a), the outer diameter of Nb3Sn inner coil is 1897.6 (+ 1.04, - 2.13) mm, and the inner diameter of Nb3Sn outer coil in Fig. 2 (a) is 1952.4 (+ 1.78, - 1.99) mm, all of which meet the tolerance requirements of winding process ± 2mm. According to the measurement results, the gap between the inner and outer coils of Nb3Sn is 2.2mm at most.

As can be seen from Figure 2 that the outer diameter of Nb3Sn outer coil is 2360 (+ 0.9, -1.89) mm, and the inner diameter of NbTi coil is 2460 (+ 2.688, - 0.832) mm. According to the measurement results, the gap between the inner and outer coils of Nb3Sn is 2.7mm at most [3].

The insulation wrapping process will also affect the assembly gap. The process has not been completed, so we can only analyze it according to the technical requirements of its design.
The thickness of conductor is 1.3mm and the thickness of ground insulation is 3.1mm as shown in Fig. 3. Because the insulation wrapped by glass ribbon and it has certain elasticity, there is no tolerance requirement in this process.

After the insulation wrapped process, the manufacturing process has entered into the VPI process, it can be seen from Fig. 4. The thickness of the insulating layer is 3.4mm after the VPI process. Therefore, the whole insulation process will reduce the assembly gap between the inner and outer coils of Nb3Sn by 6.8mm.

During the assembly of Nb3Sn inner and outer coils, the sling needs to be used. The weight of Nb3Sn outer coil is about 20t, and the four-point lifting is adopted. The bearing capacity of a single sling should be 8-10t. Refer to JBT8521.1-2007, the safety factor is 6, and the width and thickness of a single sling are 100mm and 7.5mm. For the sake of hoisting safety, a gap of at least 5mm shall be reserved during hoisting. Therefore, a gap of at least 12.5mm shall be reserved during final assembly.

During the assembly of NbTi coil and Nb3Sn outer coil, it should be noted that there is a helium inlet outside the Nb3Sn outer coil, as shown in Figure 5. The height of helium inlet coil in radial direction is 30 ± 0.6mm. Therefore, the assembly gap between coils in this process can be reduced by 35.6mm at most. Due to the existence of helium inlet, the thickness of sling does not need to be considered.

In conclusion, considering the winding accuracy:
(1) Assembly gap of Nb3Sn inner and outer coils: 970.8-953.2-x-y-12.5 > 0, x + y < 5.1mm;
(2) The inner diameter of NbTi coil is 1226.4-1185.2-z-35.6 > 0, z < 5.6mm.
Therefore, the maximum unilateral deformation of a single coil after and before heat treatment shall not exceed 2.5mm.

| Process          | Gap between inner and outer Nb3Sn coil(mm) | Gap between outer Nb3Sn coil and NbTi coil(mm) |
|------------------|--------------------------------------------|-----------------------------------------------|
| Theoretical value| 27.4                                       | 50                                            |
| Heat treatment   | 27.4-w                                     | 50-u                                          |
| Insulation       | 20.6-w                                     | 43.2-u                                        |
| Assembly         | 8.1-w                                      | 7.6-u                                         |

Without considering the winding accuracy, table 2 describes the gap between Nb3Sn inner and outer coils and the gap change between Nb3Sn outer coil and NbTi coil. "w" (in the table 2) is the sum of the maximum increment of Nb3Sn inner coil outer diameter and the maximum negative increment of Nb3Sn outer coil inner diameter compared with the theoretical model after heat treatment; "u" (in the table 2) is the maximum increment of Nb3Sn outer coil outer diameter. w < 8.1mm; u < 7.6mm.
Therefore, compared with the theoretical model, after the heat treatment period, the radial deformation of Nb3Sn inner coil increases greatly, the radial deformation of Nb3Sn outer coil decreases by no more than 8.1mm, and the maximum increase of Nb3Sn outer coil outer diameter cannot exceed 7.6mm.

Summary, the deformation increment of Nb3Sn inner coil or outer coil must less than 2.5mm after heat treatment (compared with the theoretical model)

3. Mechanical analysis of conceptual design

Before designing the coil clamp, its radial deformation can be roughly estimated. According to the deformation of the same type of superconducting coil after heat treatment, the influence of heat treatment on the radial size of winding can be analyzed quantitatively. Because the winding conductor materials of ITER TF coil winding and Nb3Sn coil winding are the same, and the heat treatment system is basically the same; Therefore, the change trend of radial size of Nb3Sn coil after heat treatment can be quantitatively analyzed by referring to the elongation of conductor after heat treatment of ITER TF coil [4]. After heat treatment, the conductor of TF coil shows an elongation trend, the average elongation is 0.035%, and the overall outline of the coil increases. The overall shape of Nb3Sn coil is circular. If considering only the direction of gap change, it is necessary to estimate the change of the outer diameter of Nb3Sn inner coil and the inner and outer diameter of Nb3Sn outer coil. The deformation is estimated by formula (1), and the results are shown in Table 3.

\[ D' = D \left(1 + 0.035\% \right) \]  

Table 3 The deformation evaluation after Nb3Sn coil heat treatment

| Nb3Sn inner coil outer diameter (mm) | Nb3Sn outer coil inner diameter (mm) | Nb3Sn outer coil outer diameter (mm) |
|-----------------------------------|------------------------------------|------------------------------------|
| Value                             | 0.33                               | 0.34                               | 0.41                               |

According to the previous investigation and the estimation of coil deformation, the preliminary design of coil fixture is carried out. The conceptual design is shown in Figure 6. The basic design parameters are shown in Table 3.

According to the estimated coil deformation in Table 3, the radial preload is estimated through the formula. Since the estimated deformation is less than the theoretical allowable coil deformation limit, the limit deformation value is brought into the calculation. The conductor with internal stress caused by deformation is simplified as the stress problem of double-sided supported arch beam in material mechanics.

The outward tension of single turn coil deformation can be calculated according to formula (2) [5].

\[ F = \frac{4Ehl_t}{R^2} \]  

Fig.6 Design of fixture
Where $I$ is the moment of inertia of the conductor section, and its calculation formula is $I = A^4 / 12 - \pi D^4 / 64$; $E=158 \times 10^9$ Pa; Considering that the fixture will compact the deviation during winding when clamping the coil, and add the maximum allowable deformation, $u=7.17$ mm into the calculation, so the tension of single-layer coil is $f = 977$ N. The outward tension of 32 turn coil is 31264.7 N. Considering that there are 8 radial pre tightening bolts, each bolt needs to provide a pre tightening force of 4000 N, so each bolt needs to apply a force of 5000 N.

According to formula (3), the torque required for radial and axial pre tightening bolts can be calculated.

$$M = \frac{K F D}{3}$$

$M$——bolt applied torque
$F$——preload
$D$——nominal diameter of bolt
$K$——torque coefficient

The value of metric stainless steel bolt $K$ is between 0.17 and 0.2, so the applied torque of radial pre tightening bolt is $20N\cdot M$.

Check the strength of the coil clamp according to the above calculation parameters. ANSYS software is used for modeling, and the material properties of 316L are shown in Table 4.

The loading method is shown in Figure 7. Apply an outward force $F = 5000$ N to 8 bolt holes on one side, and select the material property at 650 °C. The simulation results are shown in figures 8 and 9.

| temperature (°C) | yield strength(MPa) | Elastic modulus(GPa) | density(kg/m³) | Poisson's ratio |
|------------------|---------------------|----------------------|----------------|----------------|
| 20               | 282                 | 193                  |                |                |
| 100              | 253.8               | /                    |                |                |
| 200              | 230                 | /                    |                |                |
| 410              | 220.8               | /                    |                |                |
| 470              | 206.8               | /                    | 7980           | 0.3            |
| 530              | 200                 | /                    |                |                |
| 590              | 195                 | /                    |                |                |
| 620              | 195                 | /                    |                |                |
| 650              | 183.3               | 158                  |                |                |

It can be seen from the simulation results that the maximum deformation is located at the contact position between the axial downward preloading plate and the radial preloading plate, and its value is 43 Mpa. As a result, due to the contact setting problem, the stress at other positions is less than 144mpa. The maximum deformation of the clamp is located in the middle of the height direction, and
its value is 3.7 mm, which has exceeded the allowable deformation of the coil by 2.5 mm. Therefore, considering to add the stiffener for strengthening the clamp, as shown in Figure 10. Simulation again, and the results are shown in Figure 11. The deformation is evenly distributed, and the maximum value is 0.5 mm.

After the Nb$_3$Sn coil heat treatment process, measuring the deformation of the coil. The result is showing in the fig 12 and fig 13.

![Fig.10 New model](image1)
![Fig.11 New deformation](image2)

![Fig.12 Outer diameter of Nb$_3$Sn inner coil measuring after heat treatment](image3)
As shown in Fig. 12, compared with the theoretical model, the maximum positive deformation of the outer diameter profile of the inner coil after heat treatment is 1.24 mm (< 2.5 mm), and the maximum negative deformation of the inner diameter profile of the outer coil is -1.15 mm (< 2.5 mm). Therefore, through the coil winding and heat treatment process, the assembly gap between the inner and outer coils of Nb$_3$Sn is reduced by 2.39 (1.15 + 1.24) mm (less than 5 mm).

As shown in Figure 13, compared with the theoretical model, the maximum positive deformation of the outer diameter profile is 1.25 mm (< 2.5 mm). The assembly gap between Nb$_3$Sn outer coil and NbTi coil is reduced to 1.25 mm (less than 5 mm), so the coil deformation during coil heat treatment meets the design requirements. The final value of assembly gap between inner and outer coils of Nb$_3$Sn is 27.4 - 2.39 - 6.8 - 7.5 = 10.7 mm; The assembly gap between Nb$_3$Sn outer coil and NbTi coil is 50 - 1.25 - 6.8 - 30.6 = 11.35 mm.

4. Conclusion

The relationship between the coil gap and the manufacturing process of CFETR CSMC Nb$_3$Sn coil is calculated by the inverse method, and the maximum allowable deformation of the coil is finally confirmed. According to the size and deformation trend of the coil, the fixture is designed, the preload required by the fixture is calculated through the maximum deformation, and the strength of the fixture is checked. After the heat treatment, the outer profile of the coil is measured, and the final value of the assembly gap between the inner and outer coils of Nb$_3$Sn is 10.7 mm; the assembly gap between Nb$_3$Sn outer coil and NbTi coil is 11.35 mm. Therefore, the designed fixture meets the requirements (Assembly gap ≥ 5 mm).

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