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The CFETR CSMC Nb_3Sn coil heat treatment process research

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1. Introduction

The central solenoid (CS) model coil is being developed to verify the large-scalar superconducting coil manufacture technology for China Fusion Engineering Test Reactor (CFETR) in ASIPP (Institute of Plasma Physics). The CSMC are major components of CFETR to generate the magnetic field for Simulating the Central Solenoid coil manufacturing process.Several trials were performed to qualify and optimize the heat treatment procedure of the Central Solenoid coil. In the trials, gas replacement, temperature controlling, protective gas flow controlling, coil fixture, and assembling procedure were performed to resolve some technical issues and to demonstrate the fabrication procedure. Major requirements are: the radius increase of the conductor must be less than 4.1mm in the reaction heat-treatment when the residual stress relax; the temperature ramp rate limited to 5℃/hr; the temperature uniformity need to be satisfied ± 5℃ at the same time in whole of the furnace; The gas ,which is exhaust from the furnace and conductor ,its' impurity content must be less than 10ppm;

2. Parameters for CSMC Heat treatment

The Nb_3Sn CICC will be used for the internal high magnetic field (12T) winding, and it must be heated treatment

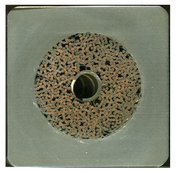


Figure 1 Cross section of Nb_3Sn CICC

Figure 2 Nb_3Sn inner and outer coil

Table 1 Nb_3Sn inner and outer coil parameters

	Nb_3Sn Coil	
	Inner	Outer
Conductor size / (mm)	49×49	
Cable diameter (mm)	32.6	
Inner radius /(mm)	745	981.2
Outer radius /(mm)	948.8	1180
Height /(mm)	3410	
Conductor length /(m)	745	850
Conductor weight /(t)	12	14

Table 2 Temperature uniformity requirement

	requirement	temperature range
1	/	Room temperature~210℃
2	±15℃	210℃
3	/	210℃~340℃
4	±15℃	340℃
5	/	340℃~450℃
6	±10℃	450℃
7	±10℃	450℃~575℃
8	±5℃	575℃
9	±10℃	575℃~650℃
10	±5℃	650℃

Table 3 The impurity in protection gas requirement

	O_2(ppm)	CH(ppm)	H_2O(ppm)
Inner coil	<10	<1	<10
Outer coil	<30	/	<30

The assembling single side gap is only 32.4mm between Nb_3Sn inner and outer coil in the coil assembly process(Fig 2&Table 1). Each process(Nb_3Sn coil manufacturing process) will reduce the gap which is single side between Nb_3Sn inner coil and outer coil(Figure 3). The residual stress in the bending process and the thermal stress in the heat treatment process will cause the deformation of the coil. Therefore, it need to control the coil deformation in heat treatment process.The coil deformation is less than 9.1mm as showing in the table 4.

In the coil heat treatment time, inner and outer coil will reacted the impurity gas, then designed the prctection gas subsystem（Figure 4） and the parameters(table 3&5).

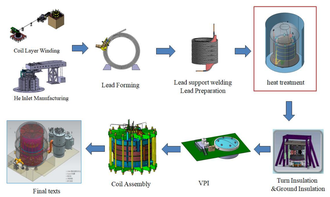


Figure 3 Nb_3Sn coil manufacturing process

Table 4 The gap is on the single side between Nb3Sn inner coil and outer coil after each process

Process	gap's value （mm）	coil size increment （mm）	tolerance （mm）
theoretical value	32.4	/	/
Bending	30.4	/	±2
Heat treatment	30.4-x	x	/
Tune insulation	27.8-x	1.3	/
Groud insulation	21.6-x	3.1	/
VPI	19.1-x	0.5	±2
assmeble	19.1-x≥10	/	/

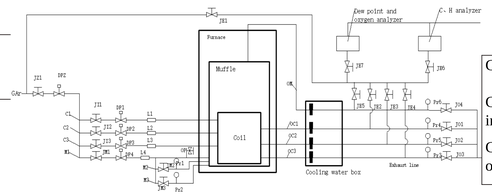


Figure 4 Argon protection subsystem

Table 5 Technical parameter of argon protection subsystem

Gas pressure	≥0.5MPa
Gas flow inner coil	≤10L/min
Gas flow outer coil	≤60L/min

3. Nb_3Sn coil heat treatment process research

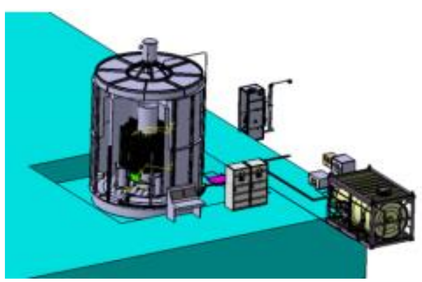


Figure 5 Heat treatment systems

Figure 6 Nb_3Sn inner coil assembled

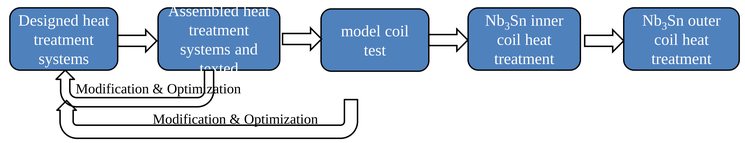


Figure 7 Nb_3Sn coil heat treatment process research

Design heat treatment systems according to technical requirements is showing in the figure 5 .

Experiment process

① Used the coil fixture to fix the coil for preventing deformation.Measuring coil inner and outer profile.

② Assembled the thermocouple(for Monitoring temperature on coil) and sample(for estimating coil function after heat treatment)(figure 6)

③ Assembled the other systems and beginning heat treatment

④ Keep the parameters of the temperature on coil and the impurity in protection gas meeting the requirement in the coil heat treatment time.

⑤ Texted the sample function after the coil heat treatment.

4. Results and Conclusions

Compeleted the Nb_3Sn inner coil heat treatment by now.

-Compared the figure 8 with table 1,the temperature on the coil (in the heat treatment time),it is meeting the requirement.

-From the figure 8 the impurity out of the coil is meeting the requirement ,but the impurity (H_2O) inner coil over the requirement 22 hours(figure 9).

-The outer profile of coil is 1897.6（-2.13, 1.04）before heat treatment, The outer profile of coil is 1897.6（-1.89, 1.24）after heat treatment.The max variation is 0.24mm.The inner profile of coil is 1490（-0.71, 1.77）before heat treatment, The inner profile of coil is 1490（-0.65, 2.05）after heat treatment.The max deformation of Nb_3Sn inner coil is 0.28mm less than 9.1mm.

- The variety range of the sample is （+3.6%，-2.5%).

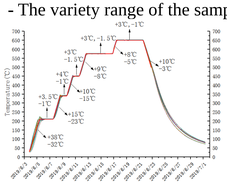


Figure 8 Temperature measurement results

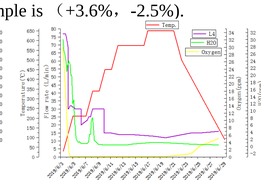


Figure 9 Gas flow and the impurity in protection gas out of the coil

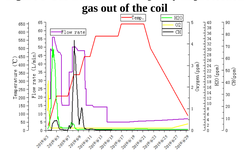
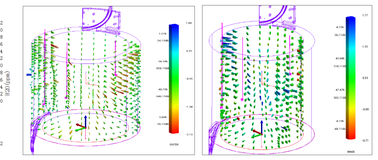
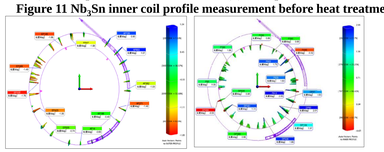


Figure 10 Gas flow and the impurity in protection gas inner coil



(a)Outer profile (b)inner profile

Figure 11 Nb_3Sn inner coil profile measurement before heat treatment



(a)Outer profile (b)inner profile

Figure 12 Nb_3Sn inner coil profile measurement after heat treatment

Table 6 The sample properties

NO	Before heat treatment IC（A）	After heat treatment IC（A）	tolerance
SU1	263.1	256.4	-2.5%
SM1	263.1	263	-0.04%
SJ1	263.1	262.1	-0.4%
SU2	263.1	261.1	-0.76%
SM2	263.1	264.6	+0.57%
SD1	263.1	263	-0.04%
SD2	263.1	267.8	+1.8%
SJ2	263.1	262. 1	-0.4%
SSOB	263.1	272.6	+3.6%