STATUS OF WINDING & FORMING TECHNOLOGY DEVELOPMENT FOR CFETR CSMC

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The central solenoid model coil (CSMC) for China Fusion Engineering Test Reactor (CFETR) is being developed in ASIPP (Institute of Plasma Physics, Chinese Academy of Sciences). The coil winding & forming is one of the crucial manufacture technologies for CSMC.

1. Parameters and Structural for CSMC Windings

CSMC is a hybrid superconducting magnet of 12T maximum magnetic field and 1.5 T/s changing rate composed of Nb_3Sn coils and NbTi coils in high and low magnetic field respectively.

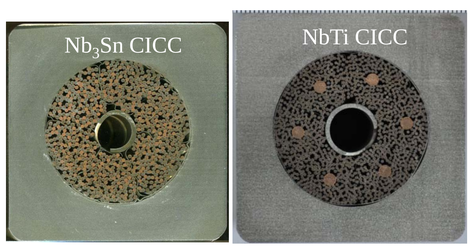


Figure 1 Cross section of CICC for CFETR CSMC

Table 1 The specification of Nb_3Sn and NbTi CICC

Items	Nb_3Sn CICC	NbTi CICC
Jacket material	316LN stainless steel	316L stainless steel
External Dimension /(mm)	49 × 49	51.9 × 51.9
Dia. of inner bore /(mm)	32.6	35.3
Cabling pattern	(2sc + 1) ×3 × 4 × 4 × 6	(3sc×4 × 4 × 4) + 1Cucore
Cable twist pitches	First Stage: 20±5mm Second Stage: 45±8mm Third Stage: 80±10mm Fourth Stage: 150±15mm Fifth Stage: 450±20mm	First Stage: 45±5mm Second Stage: 85±8mm Third Stage: 145±10mm Fourth Stage: 250±15mm Fifth Stage: 450±20mm
Petal wrap	0.1 mm thick, 70% cover	0.05 mm thick, 50% cover
Cable wrap	0.1 mm thick, 40% overlap	0.10 mm thick, 40% overlap
Core pattern	n/a	Cu strand: 0.73mm Cu core 3: 2.85mm
Number of sc strand	576	1152
Void fraction	32.5%	34.1%
Central spiral	7 × 9 mm	10 × 12 mm

There are five windings, two Nb_3Sn windings (inner and outer) for internal high magnetic field and three NbTi windings (upper, middle and lower) for external low magnetic field.

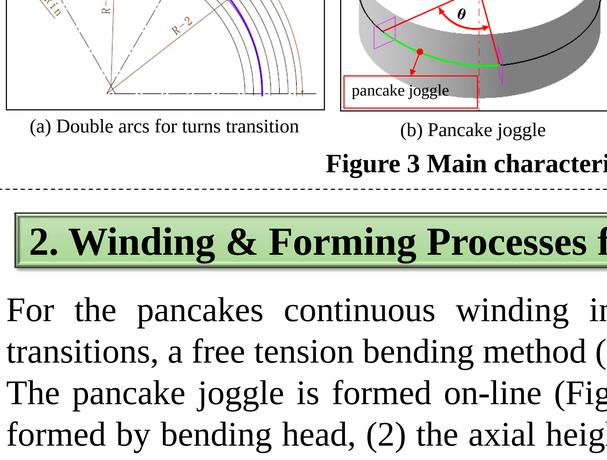


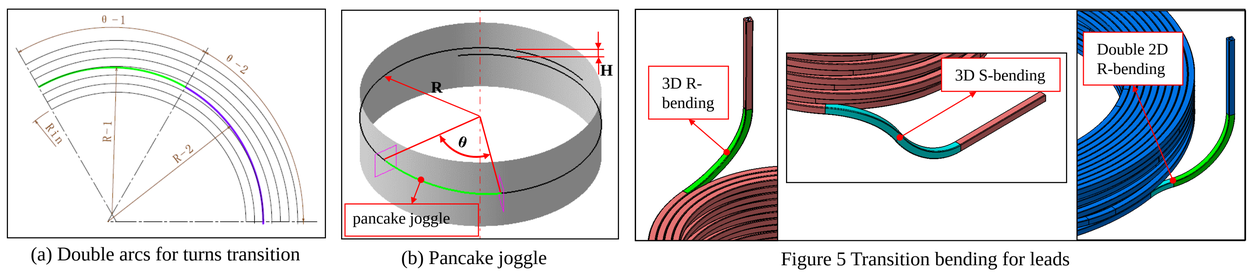
Figure 2 CFETR CSMC windings

Table 2 Parameters for CSMC windings

Items	Nb_3Sn Coil		NbTi Coil		
	Inner winding	Outer winding	Upper winding	Middle winding	Lower winding
Winding type	Pancake	Pancake	Pancake		
CICC dimensions /(mm)	49×49 - Φ32.6		51.9 × 51.9 - Φ35.3		
Turn / pancake insulation thickness /(mm)	2.6/2.6	2.6/2.6	2.6/2.6		
Ground insulation thickness /(mm)	3.1	3.1	3.1		
Clearance between windings /(mm)	22.4		50		
Num. of radial turns	4	4	10		
Num. of axial turns	30	30	8		
Total Num. of turns	120	120	80		
Inner radius /(mm)	750	976.2	1230		
Outer radius /(mm)	953.8	1180	1772.4		
Height of main winding excluding insulation/(mm)	1545.4	1545.4	433.4		
Operating current /(kA)	47.65				
Maximum magnetic field /(T)	12	8.42	6.10		

Each of five windings all is pancake coil wound one-in-hand by CICC. The innermost radius is 750 mm, the outmost radius is 1772.4 mm, the maximum axial height for main pancakes is 1545.4 mm. The turn / pancake insulation thickness all is 2.6mm.

Double arc segments are designed to realize the concentric circles turns transition (Figure 3 (a)). Pancakes are connected by joggles positioned on the innermost and outermost turns (Figure 3 (b)). And 3D R-bending, 3D-S bending and double 2D R-bending are designed to guide the leads (Figure 3 (c)).



(a) Double arcs for turns transition (b) Pancake joggle Figure 5 Transition bending for leads

Figure 3 Main characteristic bending segments

2. Winding & Forming Processes for CSMC

For the pancakes continuous winding including concentric circular turns and turns transitions, a free tension bending method (Figure 4) is applied.

The pancake joggle is formed on-line (Figure 5) in three steps, (1) the circular shape is formed by bending head, (2) the axial height is gotten by the stretch bending tooling, and (3) the circular shape is reshaped by a three-points bending tooling.

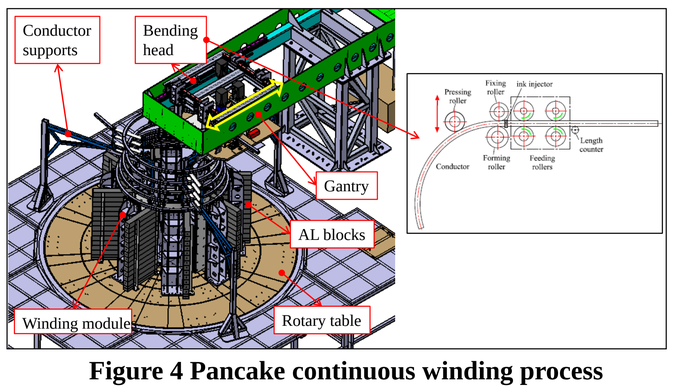


Figure 4 Pancake continuous winding process

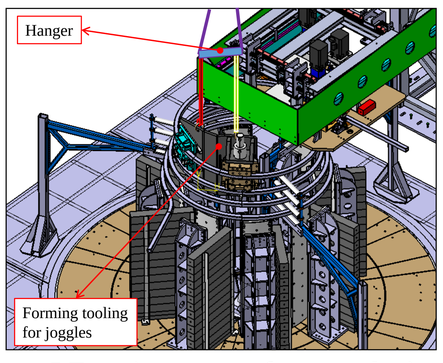
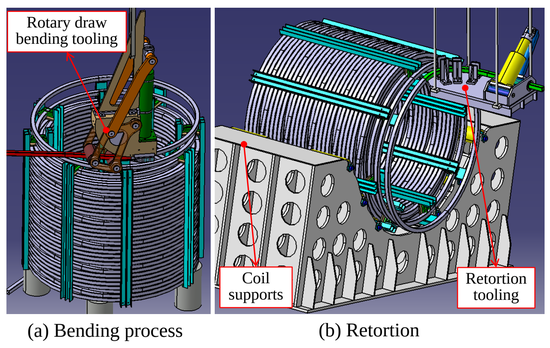
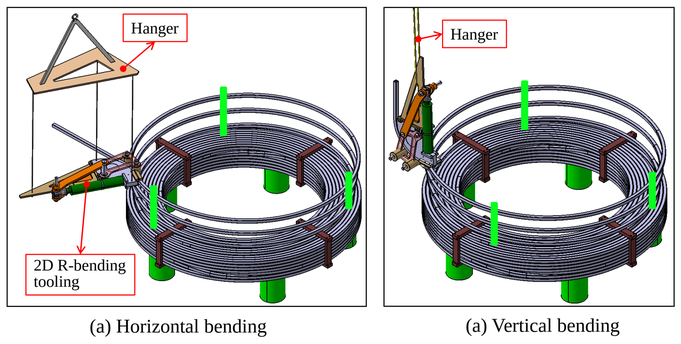


Figure 5 Forming process for pancake joggles



(a) Bending process (b) Retortion

Figure 6 Forming method for 3D R-bending



(a) Horizontal bending (a) Vertical bending

Figure 7 Forming method for double 2D R-bending

The bending head can translate along the gantry to reach defined positions. For pancakes winding & forming of Nb_3Sn and NbTi coils, one layer AL blocks are removed and the pancakes wound are fallen down about two pancakes height when each two pancakes have been formed. The pancakes winding and the joggles forming all are conducted on-line. After the pancakes wound finished, the transition bending segments for leads are formed below the production line.

3. Key tests

Subsystems of the winding production line has been designed and fabricated from April 2015 to August 2016, furthermore, the installation and stand-alone debugging for all subsystems are finished in November 2016. From December 2016 to March 2017, the 154m 316LN hollow circle-in-square jacket fabricated is used for the integration debugging of production line and the winding & forming trials.

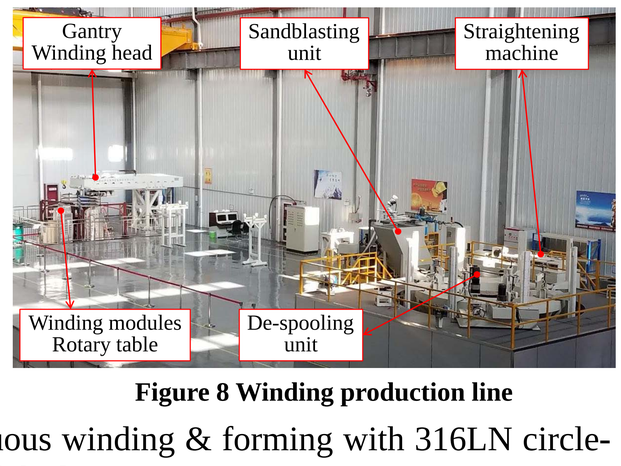
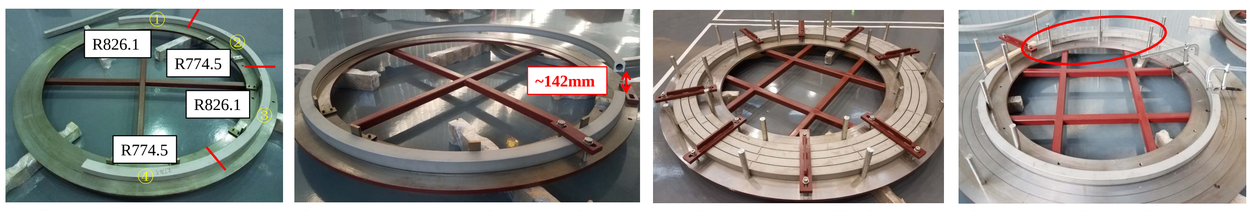


Figure 8 Winding production line

Thereinto, key trials for the pancakes continuous winding & forming with 316LN circle-in-square jacket have been conducted and qualified.



(a) Double arc segments for the concentric circular turns transiting is verified. (b) An anti-torsion machinery is added to solve the vertical plastic deformation is solved (c) One pancake of Nb_3Sn inner coil has been successfully wound & formed continuously . (d) Inner joggle of Nb_3Sn inner coil has been conducted on-line and qualified.

Figure 9 Key trials used of 316LN circle-in-square jacket

The former bending trials with hollow circle-in-square jacket show the maximum keystoning reach to 1mm of the minimum bending radius 750mm, and then short 316LN hollow reverse-trapezidal jacket has been trial-fabricated and used for the bending trials, which the results illustrate the keystoning being decreased to 0.75mm.

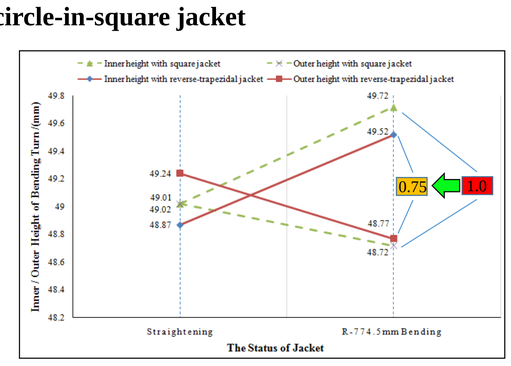
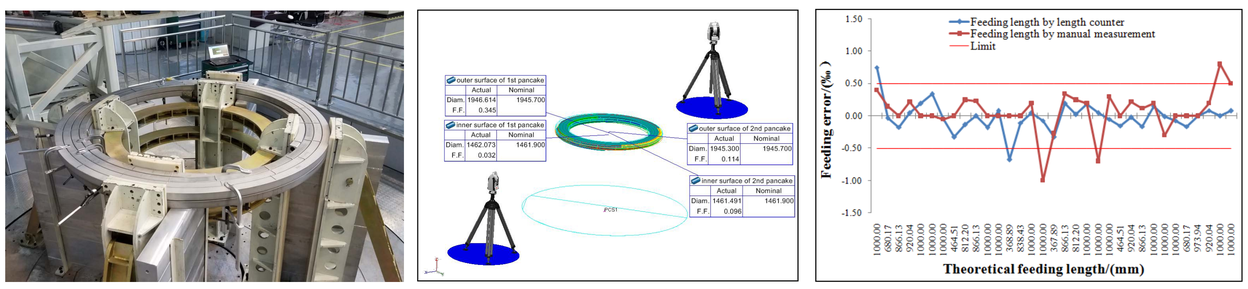


Figure 10 Reverse-trapezidal jacket bending trial

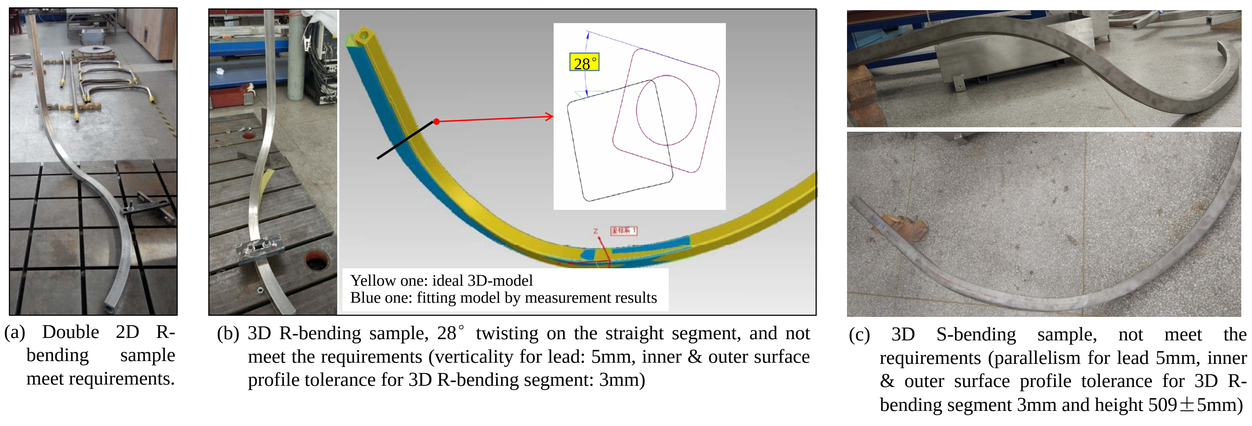
Furthermore, ~60m length 316LN hollow reverse-trapezidal jacket has been fabricated and used for continuously winding & forming the double pancakes of Nb_3Sn inner coil.



(a) Double pancakes wound (b) Inner and outer circular surface profile error < 1mm, meet requirement 2mm. (c) Some conductor feeding errors > 0.5‰L (requirement), all < 1‰L. ('L' is the feeding length of each bending segments)

Figure 11 Double pancakes trial continuous winding & forming

Forming trials of the transition bending segments for leads have been conducted.



(a) Double 2D R-bending sample meet requirements. (b) 3D R-bending sample, 28° twisting on the straight segment, and not meet the requirements (verticality for lead: 5mm, inner & outer surface profile tolerance for 3D R-bending segment: 3mm) (c) 3D S-bending sample, not meet the requirements (parallelism for lead 5mm, inner & outer surface profile tolerance for 3D R-bending segment 3mm and height 509±5mm)

Figure 12 Forming trials of the transition bending segments for leads

4. Summary

Based on the short sample bending experiments, the winding design and optimization have been completed. At present, the winding production line has been constructed and is being in debugging, furthermore, the forming tools for joggles & leads are being tested. Some technical problems during trials have been solved, such as the vertical plastic deformation of coil and the keystoning of conductor bended. The continuous winding & forming trial for double pancakes of Nb_3Sn inner coil has been conducted. However, more bending trials of complicated 3D bending segments for leads need to be carried out. In next step, a 4×4 mockup coil of Nb_3Sn inner coil is planned to be manufactured all processes with real CICC.

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