ASIPP

High strength CICC jacket with YS>1500MPa at 4.2 K for future magnetic confinement fusion

Weijun Wang[1], Jinggang Qin[1], Chuanjun Huang[2], Laifeng Li[2], Jiangang Li[1]

[1]Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)

[2]Technical Institute of Physics & Chemistry, Chinese Academy of Sciences (TIPC, CAS)

July. 24th, 2024

"CHN01" Cryogenic Structural Steel

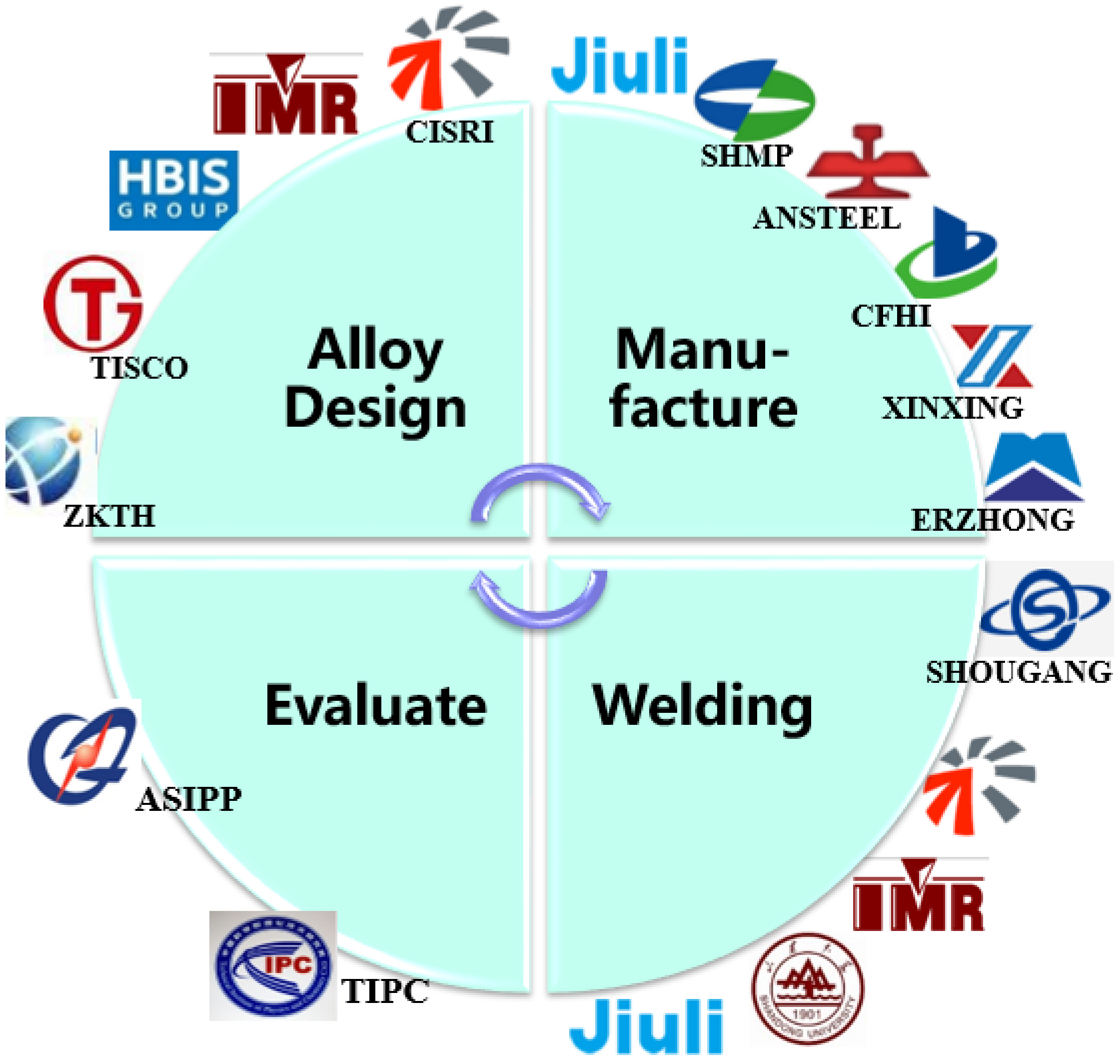
CHN01: Chinese High Nitrogen cryogenic structural steel 01

2015, Sponsored by Prof. L.F. Li (TIPC) for MCF and Space applications;

2019, Trial manufacture by IMR(Institute of Metal Research, CAS)&TIPC;

2020, Research alliance by ASIPP(End-user for MCF)&TIPC; Directed by Prof. Li

2022, To be used as jacket material and TF case of MCF.



ASIPP

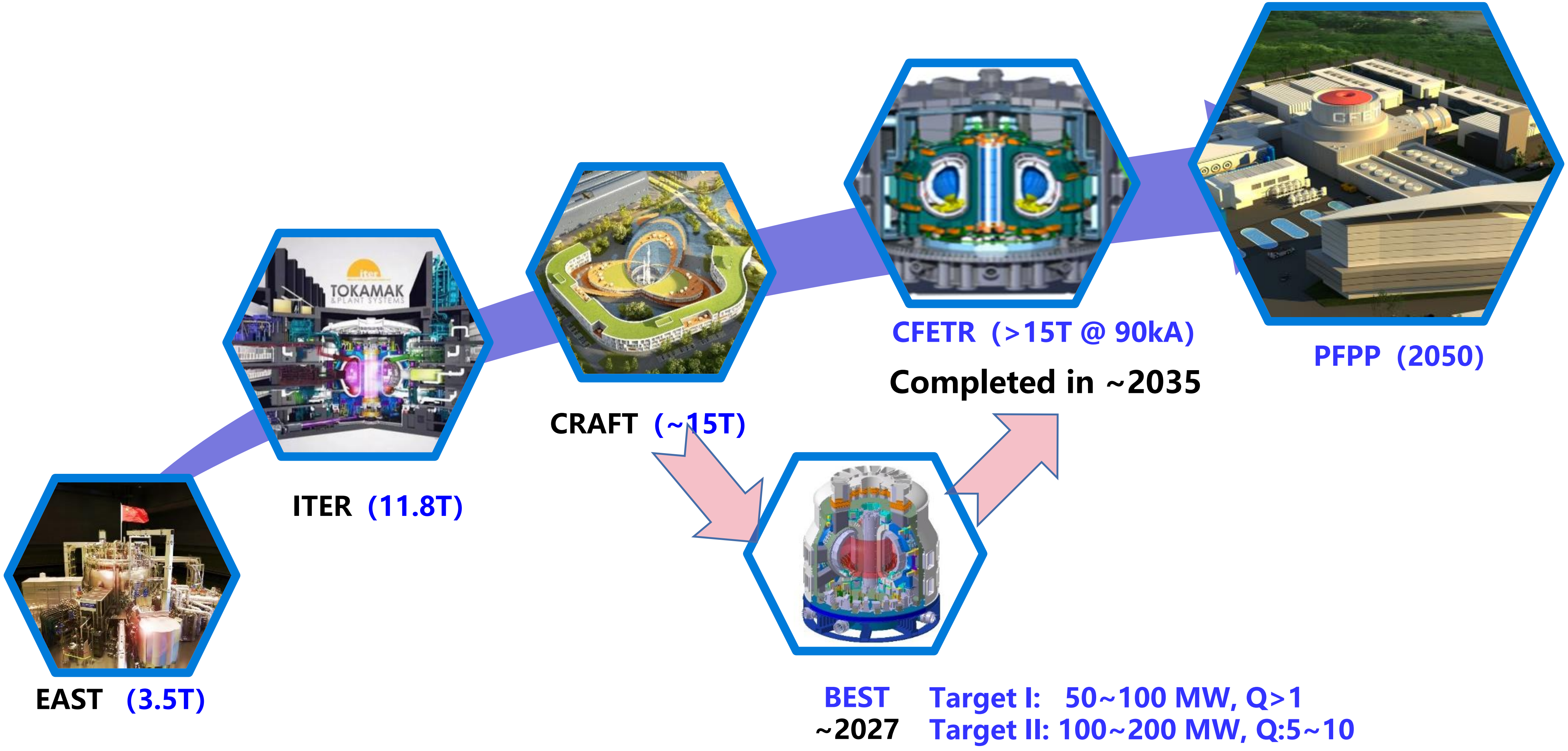
Contents

Part 1

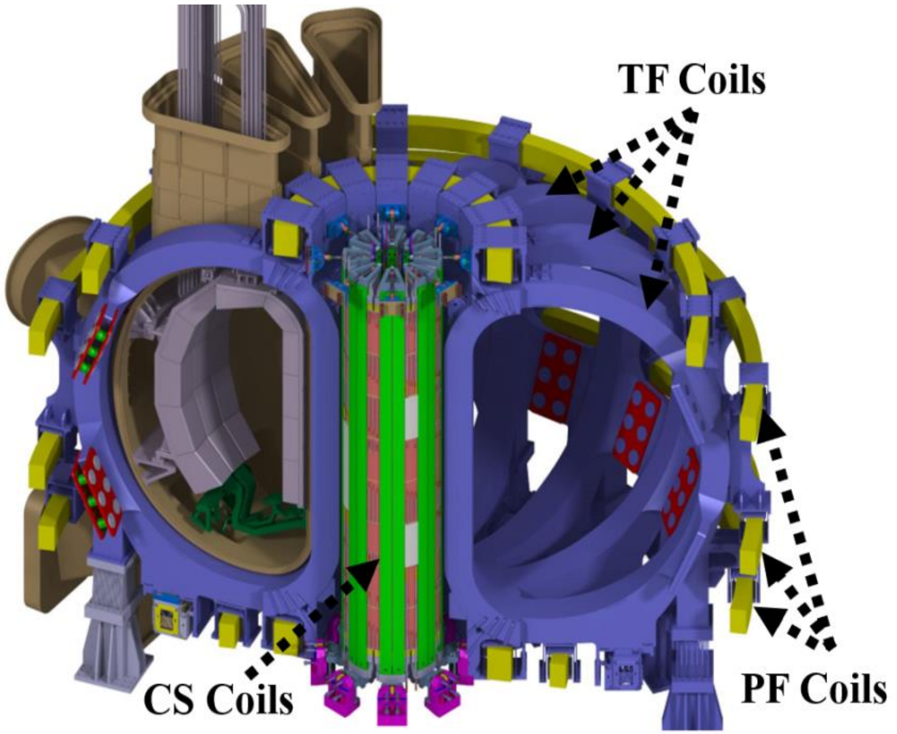
Introduction

Introduction

Fusion energy development strategy roadmap in China



SC Magnets of CFETR



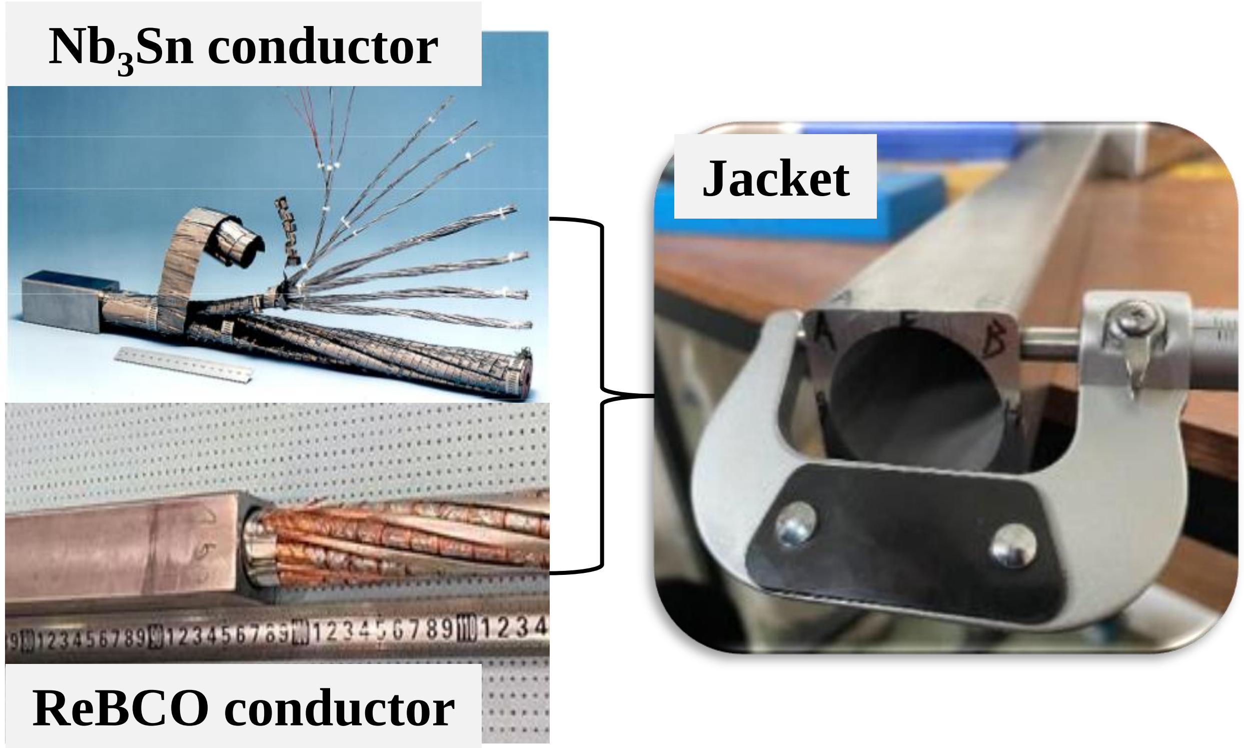
16 TF coils, 8 CS coils, 6 PF coils

(1) ReBCO CICC: CS

(2) Nb_3Sn CICC：TF、CS、PF1/7

(3) NbTi CICC：PF2-6

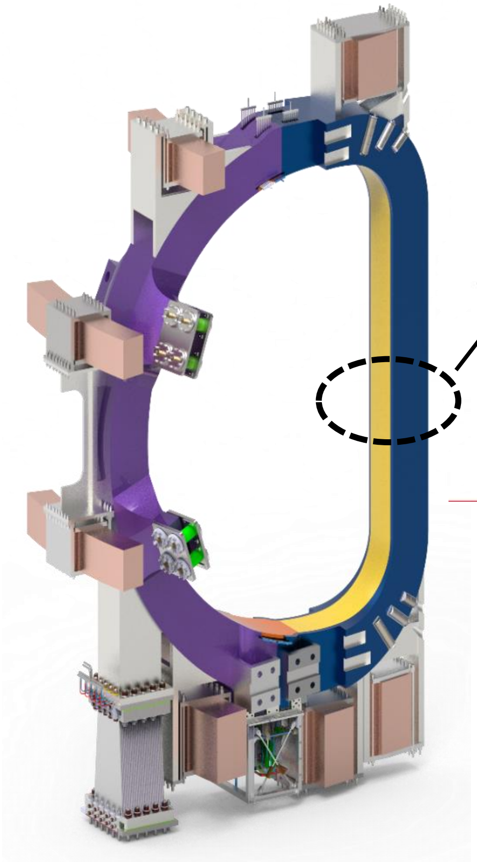
Cable-in-conduit conductors (CICC)

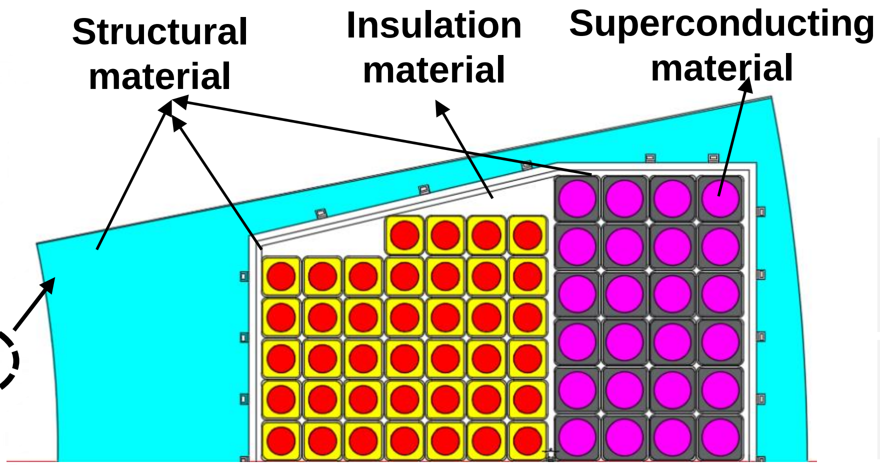


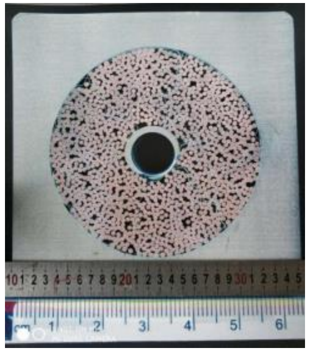
The jacket in the CICC is the bearing component for the electromagnetic force, which is required to have high strength and toughness at 4.2 K.

Introduction

Increase in magnetic field intensity in limited space is an effective strategy to improve fusion power. ($P \propto B^4$)
Increase in magnetic field ⟶ Huge Lorenz forces ⟶ High strength and toughness cryogenic structural steel.





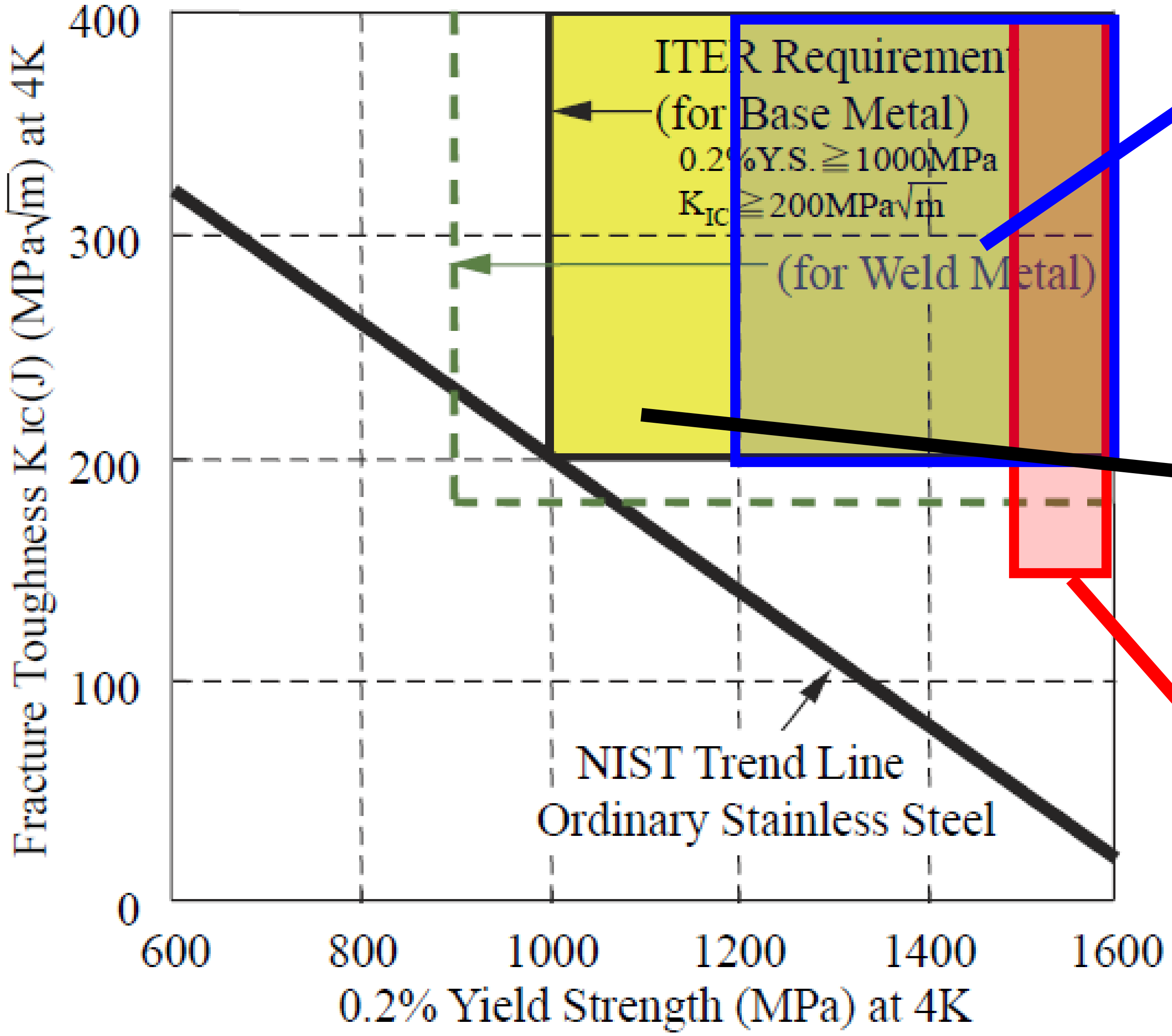


Mechanical requirements of CFETR jacket

Temp. K	YS MPa	UTS MPa	EL %	K_{IC} $MPa \cdot m^{1/2}$
4.2	≥1500	≥1800	≥25	≥150

- High strength and toughness
- Excellent fatigue resistance
- Good weldability
- Non-magnetic
- corrosion-resistant

JAERI Box



JAERI Target (1982)

(1)YS≥1200 MPa

(2)K_{Ic}≥200MPa.m$^{1/2}$

(3)Non-magnetic

(4)Rust resistance

(5)Good workability & weldability

ITER requirements

(1)YS≥1000 MPa

(2)K_{Ic}≥200 MPa.m$^{1/2}$

…

CFETR requirements

(1)YS≥1500 MPa

(2)K_{Ic}≥150 MPa.m$^{1/2}$

…

Status of cryogenic structural materials for MCF

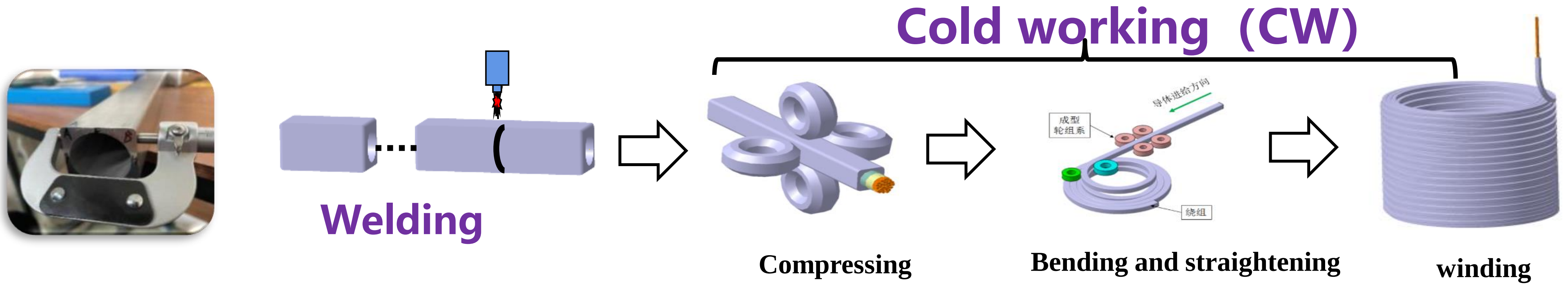
Materials	YS (MPa)	UTS (MPa)	EL (%)	K_{Ic}（MPa√m）	Application
316L	~800	~1550	~44	~200	ITER PF/CC jacket
316LN	~1078	~1535	~35	~200	ITER TF jacket
JK2LB	~1076	~1450	~43	~209	ITER CS jacket
Incoloy 908	~1115	~1660	~24	~200	KSTAR jacket
CHN01（N50）	≥1500	≥1800	≥25	≥150	CFETR jacket

The 316LN and JK2LB jackets developed by ITER do not meet the requirements.

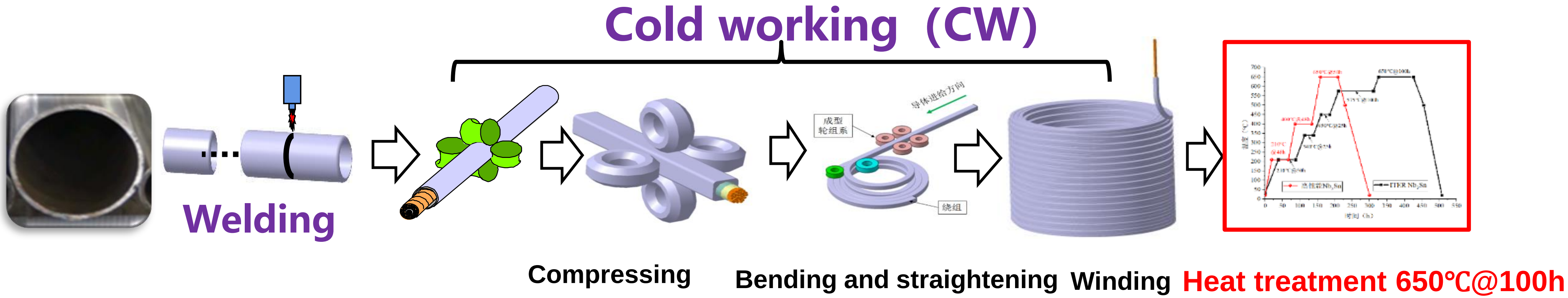
The development of cryogenic structural steel with high strength and high toughness has become one of the challenges in the application of the CFETR.

Two type of jacket (ReBCO-/Nb_3Sn- CICC jacket) in CFETR

Cold Working (ReBCO-CICC jacket)



Cold Working + Heat Treatment (Nb_3Sn-CICC jacket)



Part 2

R&D of CHN01 jacket

Chemical composition of CHN01

Fe-22%Cr-14%Ni-5%Mn-2%Mo-0.15%V-0.15%Nb-(0.2-0.4)%N-0.01%C

Element	C	Si	Mn	P
Nitronic@50/XM-19	≤0.06	1.0	4-6	≤0.04
CHN01	≤0.01	≤0.3	4.5-6.0	≤0.06
Element	Cr	S	Ni	N
Nitronic@50/XM-19	20.5-23.5	≤0.03	11.5-13.5	0.2-0.4
CHN01	20.5-22.0	≤0.005	13.5-15.5	0.2-0.4

1. For Nb_3Sn-CICC, heat treatment (HT, 650 ^{o}C/100h) leads to decrease in ductility due to formation of carbide ($M_{23}C_6$, thus low Carbon, <0.01 wt.%).

2. Increasing the Nickel content is beneficial to eliminate the δ ferrite phase and to increase the cryogenic toughness.

R&D Progress

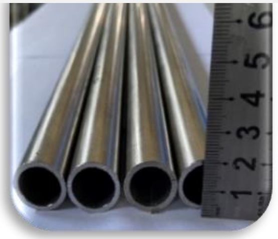
Since 2020, it took two year to complete 5 batches of jacket material.

Mass production and performance verification were completed in 2023.

2020.11: 1st batch (billet) @4.2K
YS~1249MPa
EL~21.16%

80kg

2021.07: 2nd batch (jacket) @4.2K
CW+HT
YS~1640MPa
EL~12%



φ20*2mm
80kg

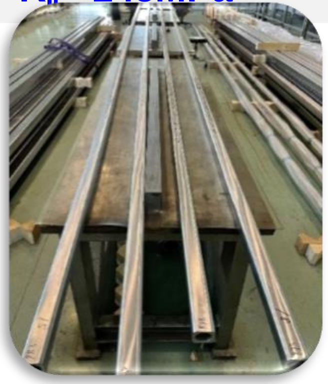
2022.02: 3rd batch (jacket) @4.2K
CW
YS~1640MPa
EL~27%
K_{IC}~170MPa·$^{1/2}$

1 t

2022.09: 4th batch (jacket) @4.2K
CW+HT
YS~1500MPa
EL~28%
K_{IC}~145MPa·$^{1/2}$

φ43*3mm
200 kg

2024.05: 5th batch (jacket) @4.2K
CW+HT
YS~1550MPa
EL~30%
K_{IC}~245MPa·$^{1/2}$

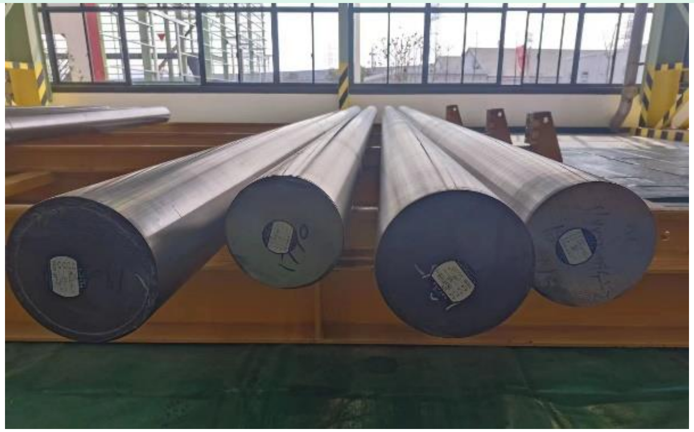


30 t

Mass production

In 2023, 30 tons CHN01 steel were prepared.

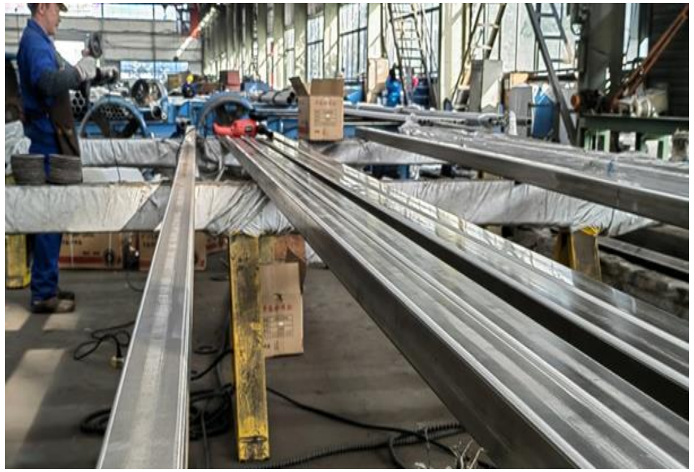
In 2023, the production of circle-in-square jackets with a total length of 5000 m was completed.



Two suppliers:

Jiuli

新兴铸管股份有限公司
XINXING DUCTILE IRON PIPES CO.,LTD.



Main Parameters of CHN01 Jacket Tube

Item	Requirements	Results
Dimensional accuracy	± 0.2 mm	± 0.15 mm
Grain size	Grain size number is larger than 5	7-9
Ferrite Content	No ferrite traces	satisfy
Carbide	No $M_{23}C_6$	satisfy
Magnetic permeability	$\mu < 1.03$	1.001-1.003

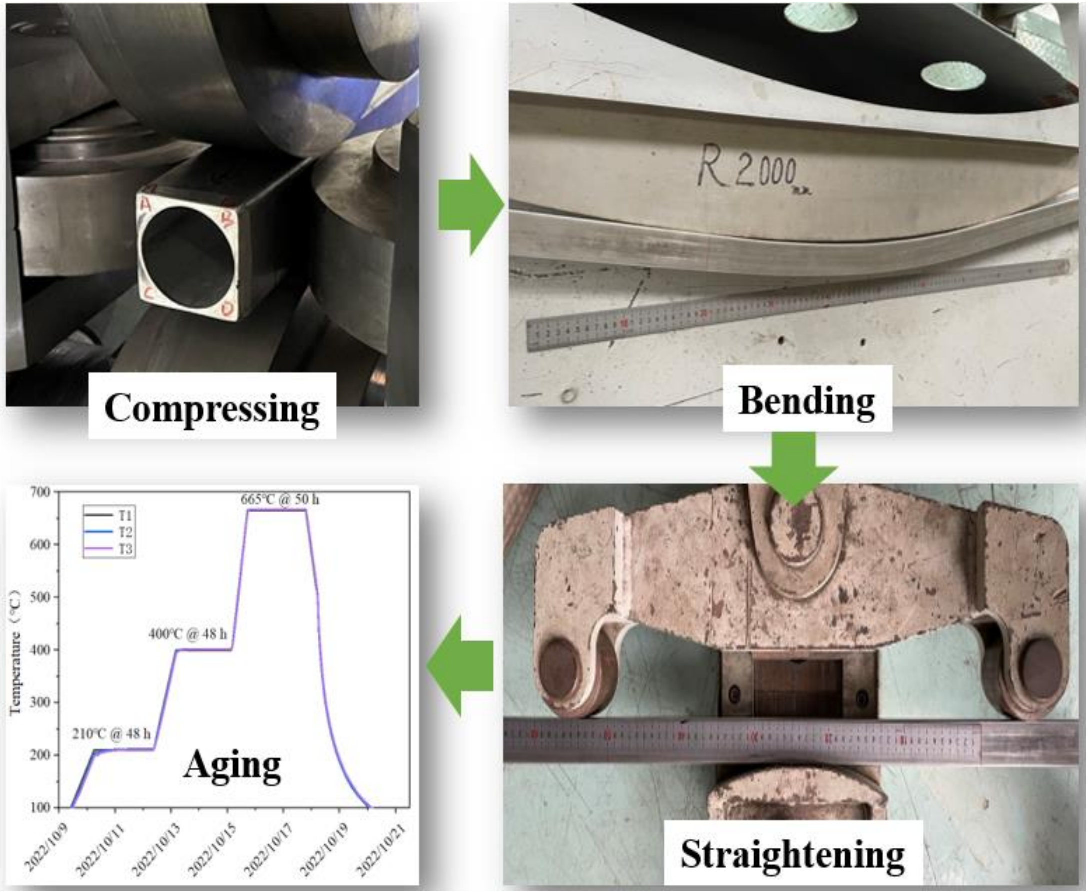
The success rate of pipe preparation is higher than 90%.

Mechanical Properties Evaluation

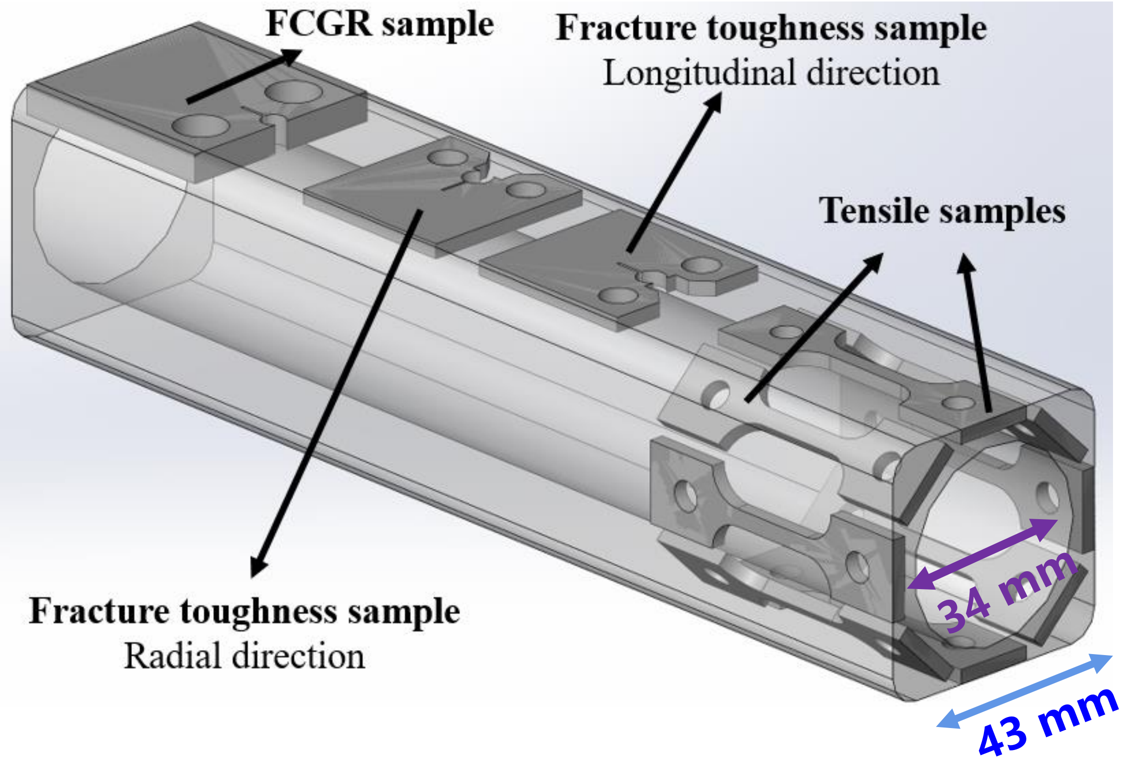
Jacket Type:

ReBCO-CICC Jacket (4%CW)

Nb_3Sn-CICC Jacket (4%CW + HT)



Specimens Geometry:

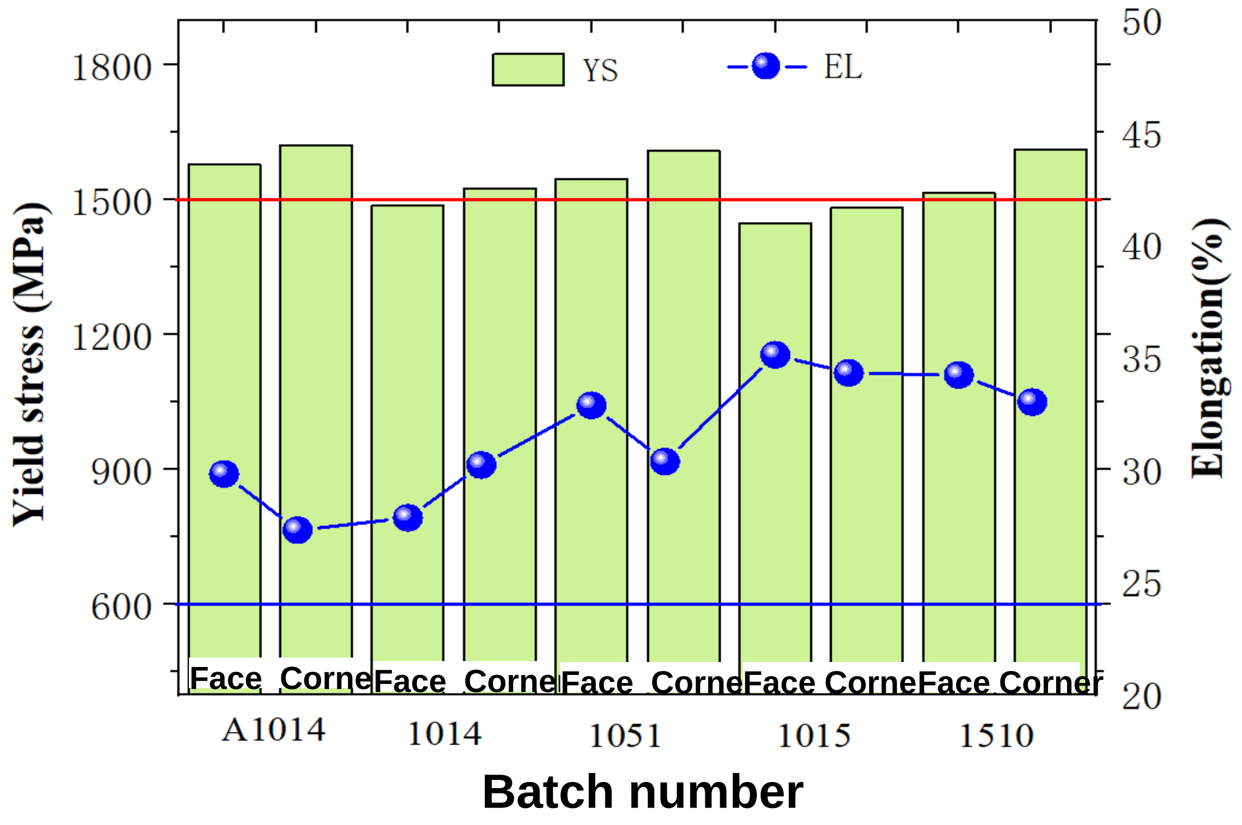


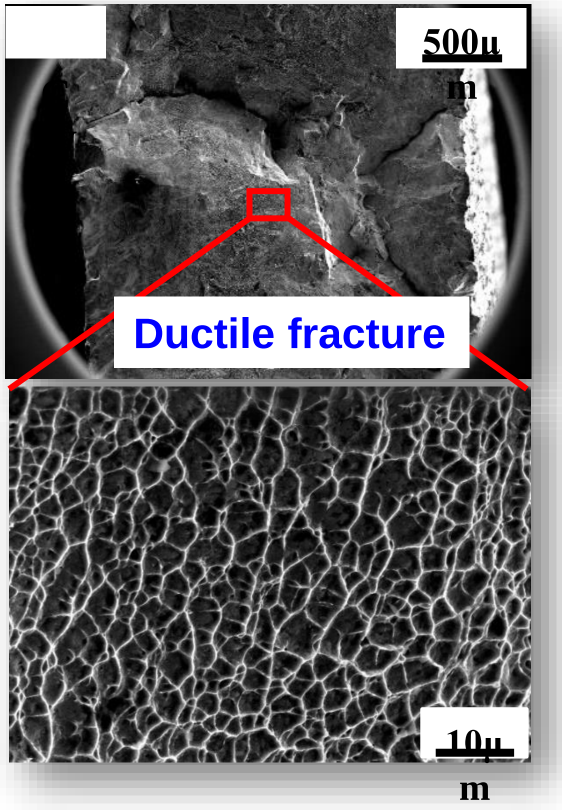
Tensile test according to the ASTM E1450
FT test according to the JIS Z 2284
FCGR tests according to the ASTM E647
All tests have been performed at the TIPC

ReBCO-CICC jacket

Tensile test results at 4.2 K (5 batches, 10% sampling rate).

The average UTS, YS, and EL are 1815 MPa, 1532 MPa and 32%. respectively.





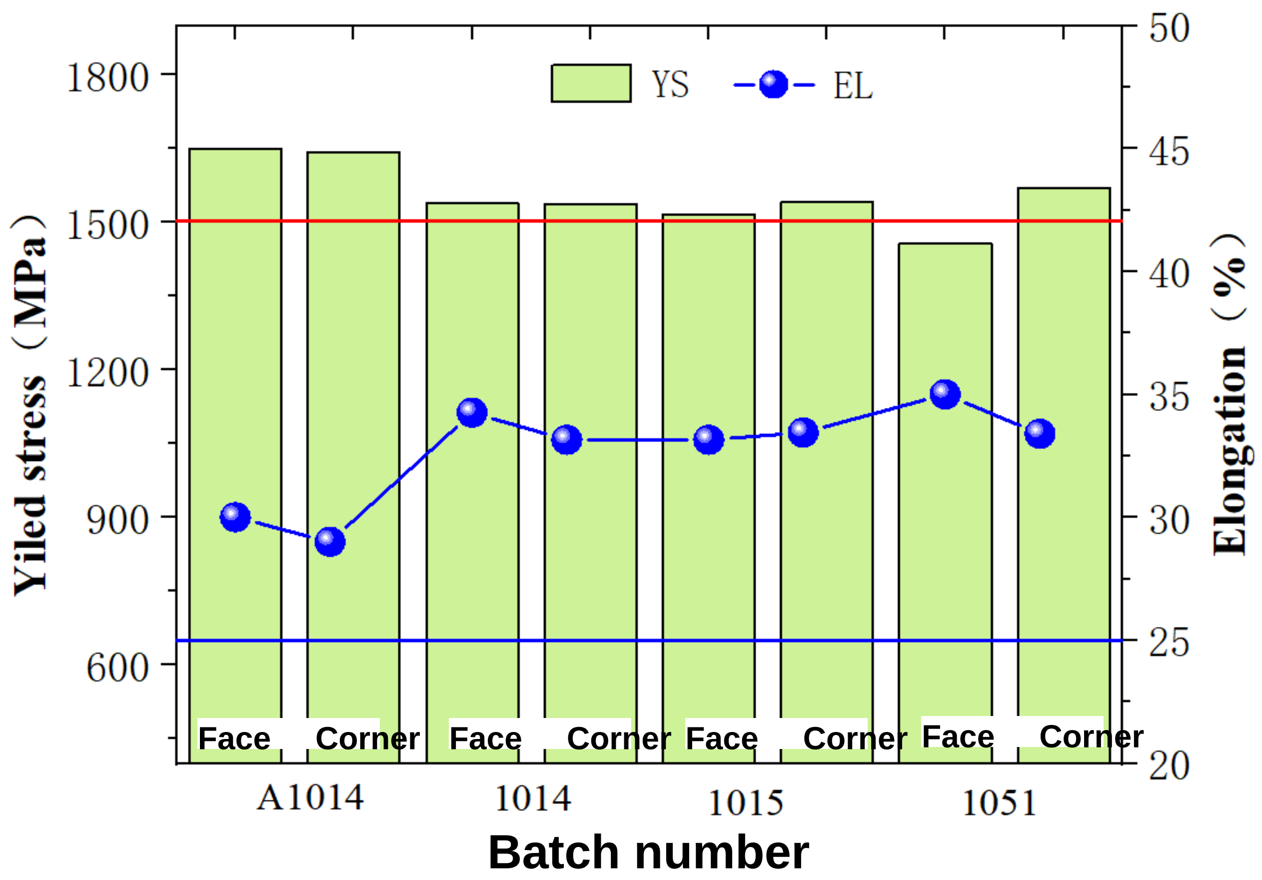
Nb_3Sn-CICC jacket

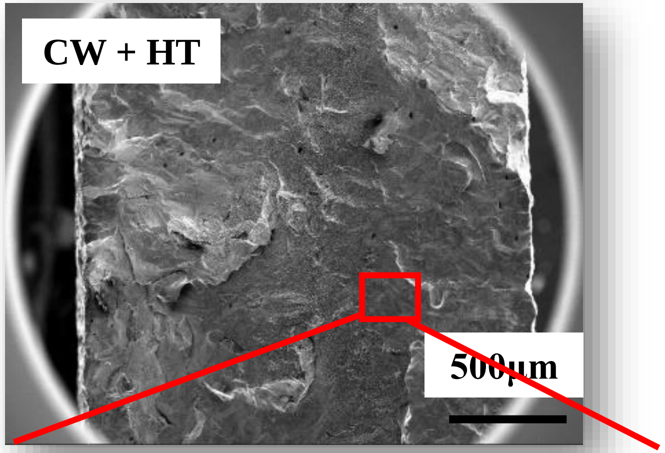
ASIPP

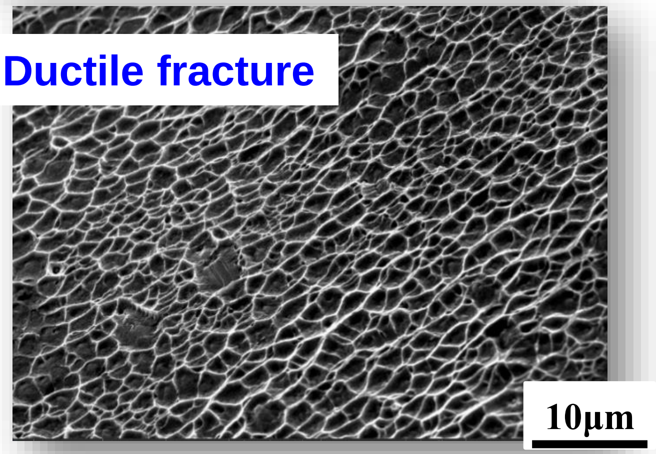
IPC

Tensile test results at 4.2 K (4 batches, 10% sampling rate)

The average UTS, YS and EL are 1813 MPa, 1553 MPa and 33%, respectively.



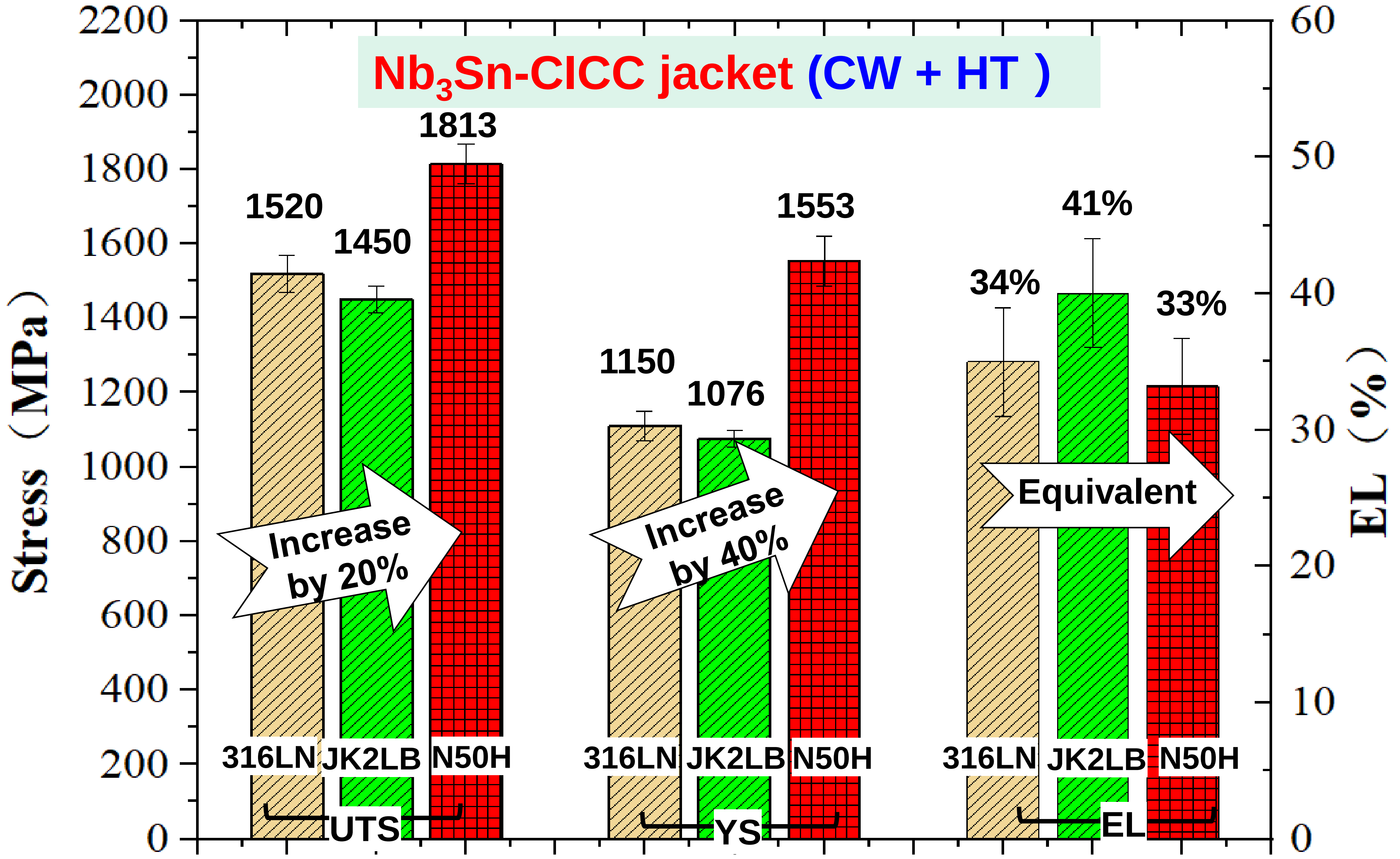




Fracture toughness at 4.2 K

	Status	$K_{Ic}(J)$/ MPa·m^{½}
Requirements		≥150
ReBCO jacket	CW(4%)	279
	CW(4%)	293
Nb_3Sn jacket	CW(4%)+HT(650^{o}C/100h)	262
	CW(4%)+HT(650^{o}C/100h)	267

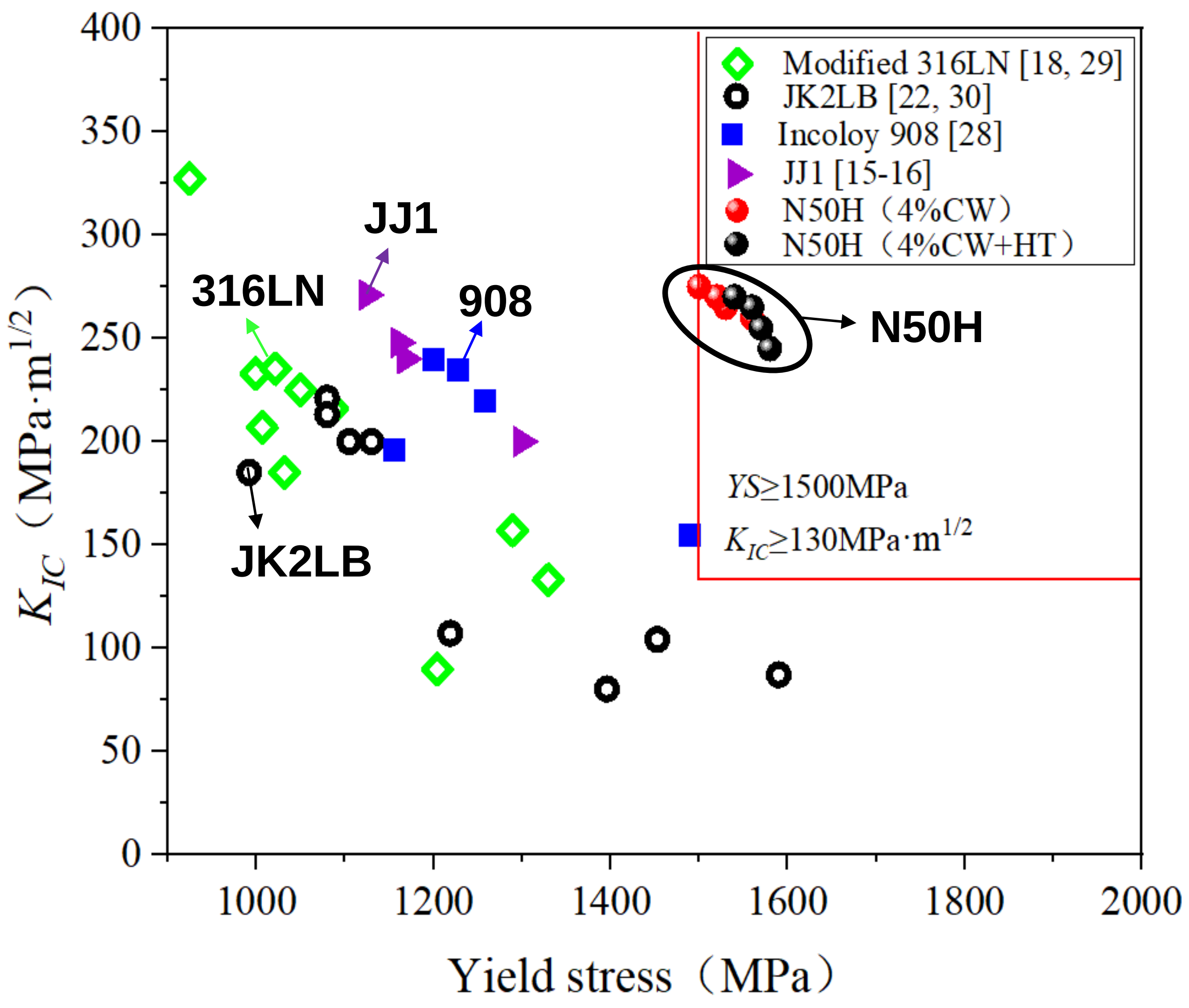
CHN01 *vs.* ITER 316LN/JK2LB



[1] Weijun Wang, et al., *Nuclear Materials and Energy*, Volume 36, 2023, 101474.

[2] *G. Romano et al., IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, pp. 1-4*

CHN01 *vs.* ITER jacket

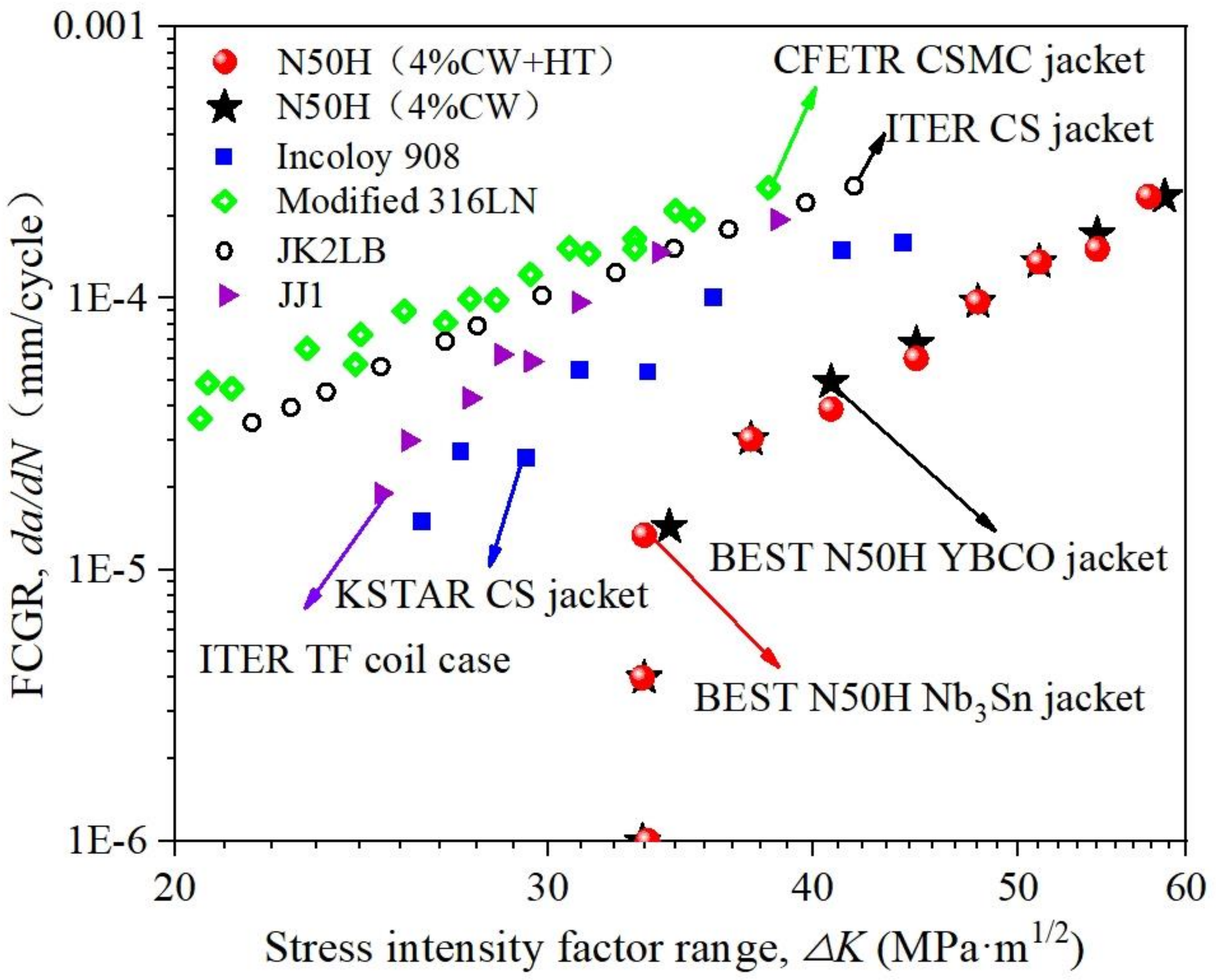


The toughness of modified 316LN, JK2LB, Incoloy 908, and JJ1 declines sharply after the strength increases (K_{Ic}(J) < 100 MPa·m$^{1/2}$ @ YS~1500 MPa)

The CHN01 jacket has the same fracture toughness as the ITER jacket, but the strength is higher.

[15] M. L. Saucedo-Muñoz, et al., *Cryogenics* 41.10 (2001): 713-719.
[16] K. Hamada, et al., *Fusion Eng. Des.* 82.5-14 (2007): 1481-1486.
[18] A. Nishimura, et al., Nucl. Mater. Energy. 30 (2022) 101125.
[22] H. Ozeki, et al., Physics Procedia 67 (2015): 1010-1015.
[28] L. S. Toma, et al., Incoloy alloy 908 data handbook,PFC/RR-94-2.
[29] J. H. Kim, et al., AIP Conf. Proc. 986 (2008): 92-99.
[30] K. Hamada, et al, IEEE Trans. Appl. Supercond. 16.2 (2006): 787-790.

CHN01 vs. ITER jacket



The FCGR of the CHN01 jacket is lower than those of the modified 316LN, JK2LB, JJ1, and Incoloy 908 materials.

There is no obvious degradation of the CHN01 jacket after aging.

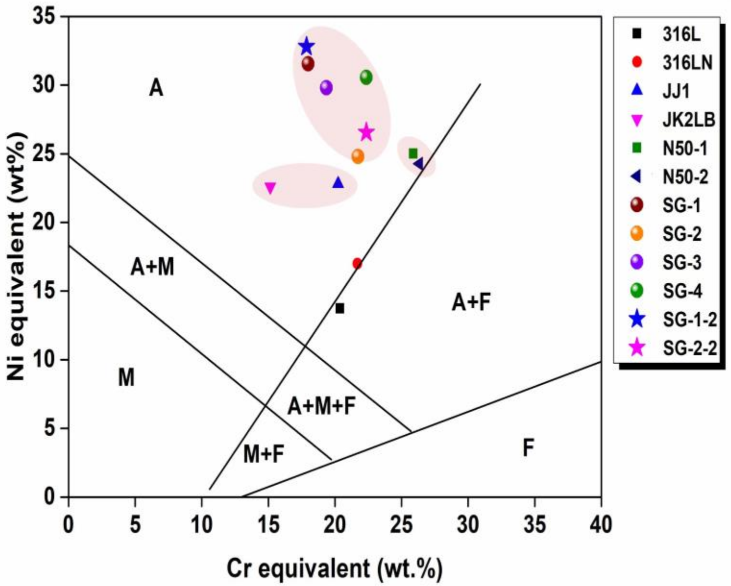
[1] Weijun Wang, et al., Nuclear Materials and Energy,Volume 36,2023,101474.
[2] S. Sgobba, et al., Fusion Eng. Des. 88.9-10 (2013): 2484-2487.
[3] K. Hamada, et al., Fusion Eng. Des. 82.5-14 (2007): 1481-1486.
[4] H. Jin, et al., Fusion Sci. Technol. 74.3 (2018): 211-218.
[5] L. S. Toma, et al., Incoloy alloy 908 data handbook,PFC/RR-94-2.

Jacket Welding

Mechanical properties of the welding joints are required to be the same as those of the jacket;

In a CW+HT condition, producing sound welds is particularly difficult;

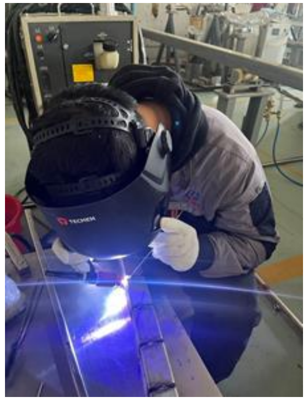
Novel filler material was developed by the Shougang Research Institute of Technology .

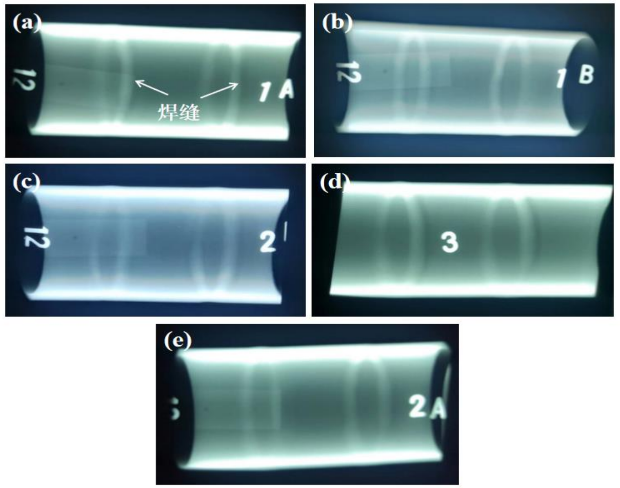


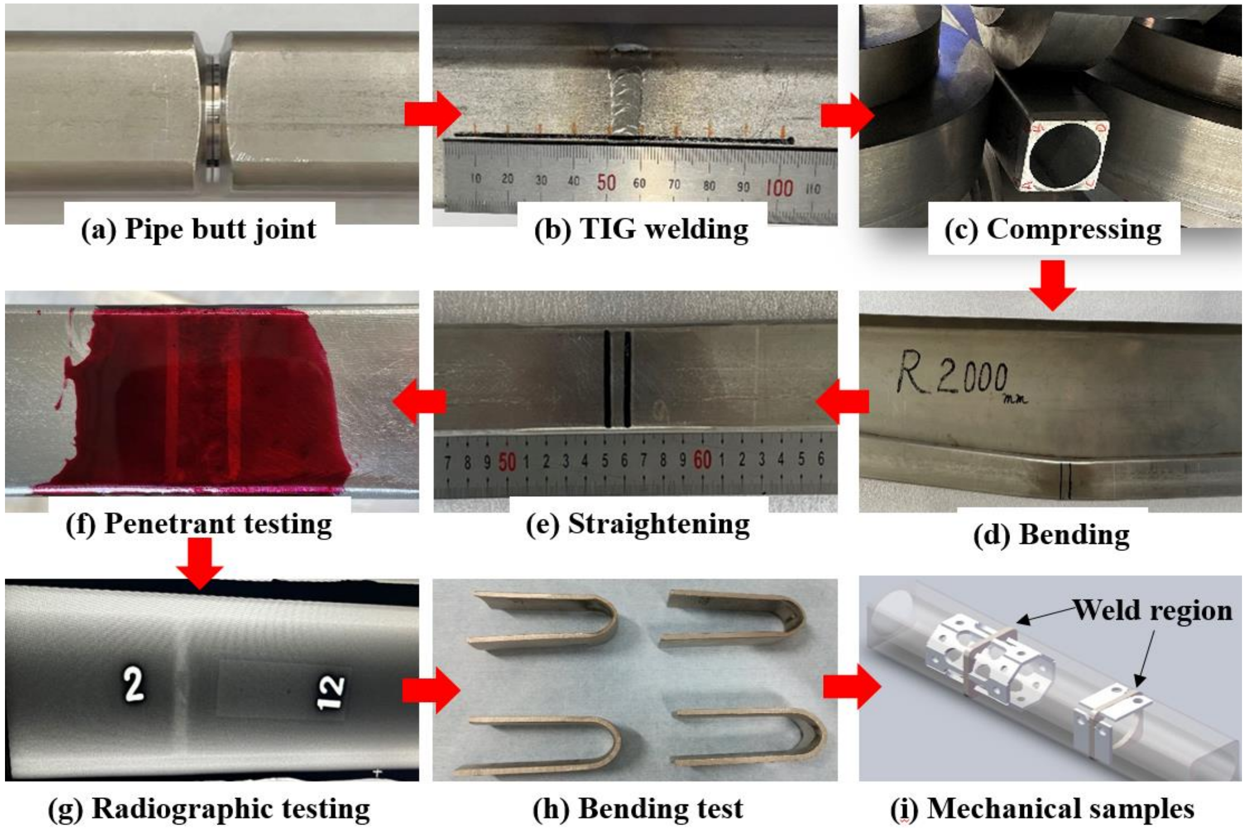
	C	Si	Mn	P	S	Cr	Ni	Mo	V	Nb	N	O
CHN01	0.008	0.30	5.18	0.005	0.002	22.3	14.6	2.1	0.19	0.09	0.31	0.0019
CHN01 filler	0.015	0.43	11.02	0.005	0.003	12.2	11.8	4.9	0.20	0.17	0.25	0.0016

Jacket welding

Reliable tungsten inert gas (TIG) welding technology has been developed
Welding joint without any defects observed.



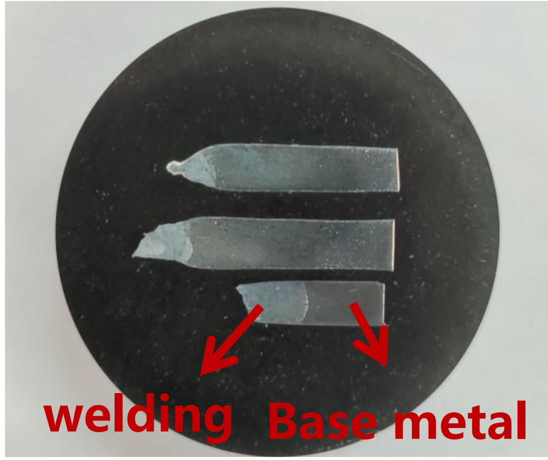


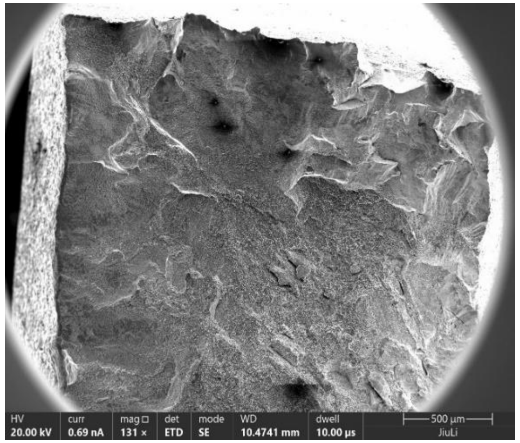


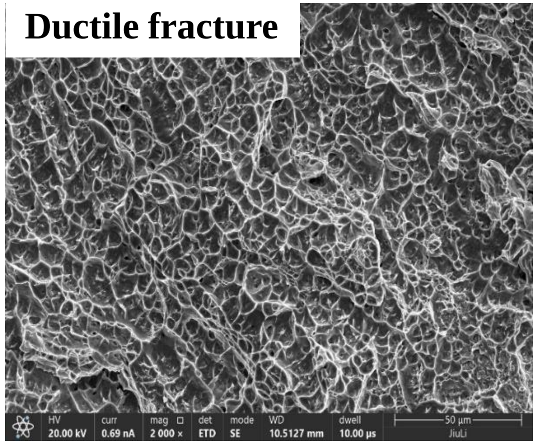
ReBCO-CICC Jacket welding

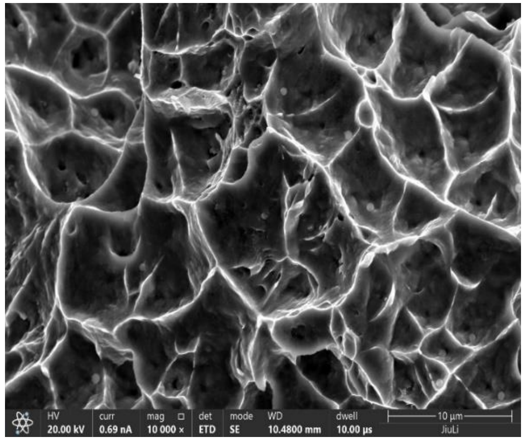
Tensile and FT results of ReBCO-CICC jacket welding joint at 4.2 K

Series	Explanation	YS（MPa)	EL（%)	K_{IC}（$MPa \cdot m^{1/2}$)
Requirements		≥1500	≥20	≥130
JFY-ASIPP1-C3.5H0-M1	CW, face	1506	32.9	260
JFY-ASIPP1-C3.5H0-JM1	CW, corner	1519	30.6	









Nb_3Sn-CICC jacket welding

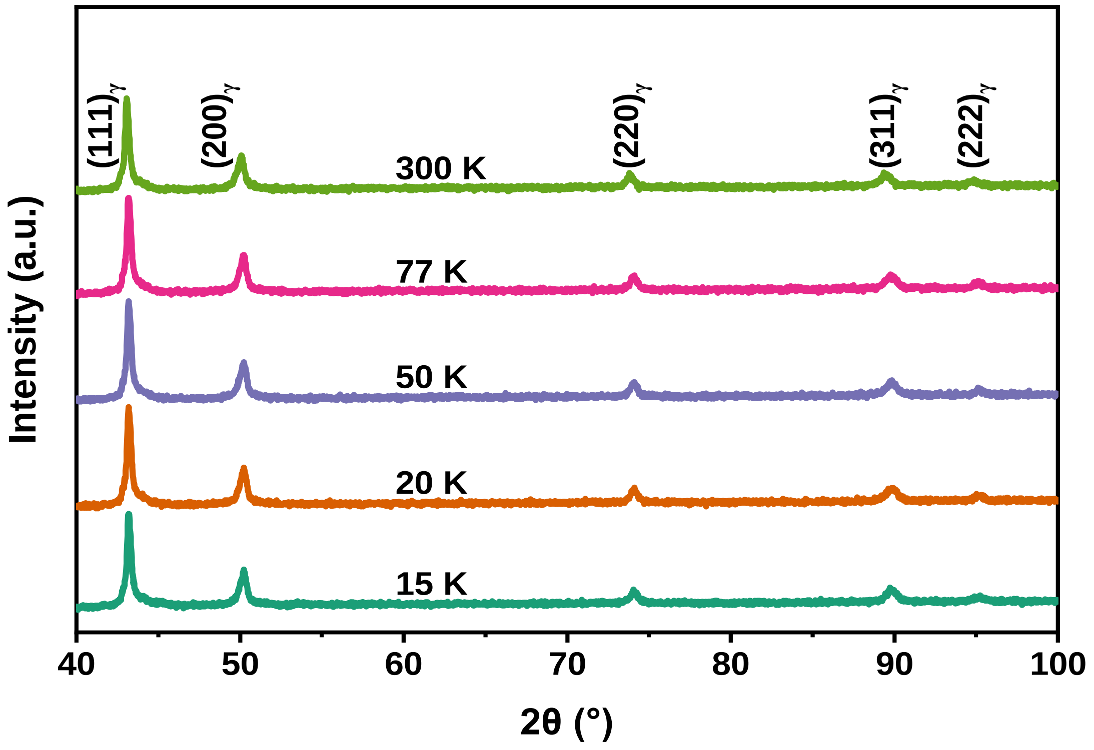
Tensile and FT results of Nb_3Sn-CICC jacket welding joint at 4.2 K

Series	Explanation	YS (MPa)	EL (%)	K_{IC} (MPa·m$^{1/2}$)
Requirements		≥1500	≥20	≥130
JFY-ASIPP1-C3.5HN-M1	CW+HT, face	1436	23.9	200
JFY-ASIPP1-C3.5HN-JM1	CW+HT, corner	1512	20.6	

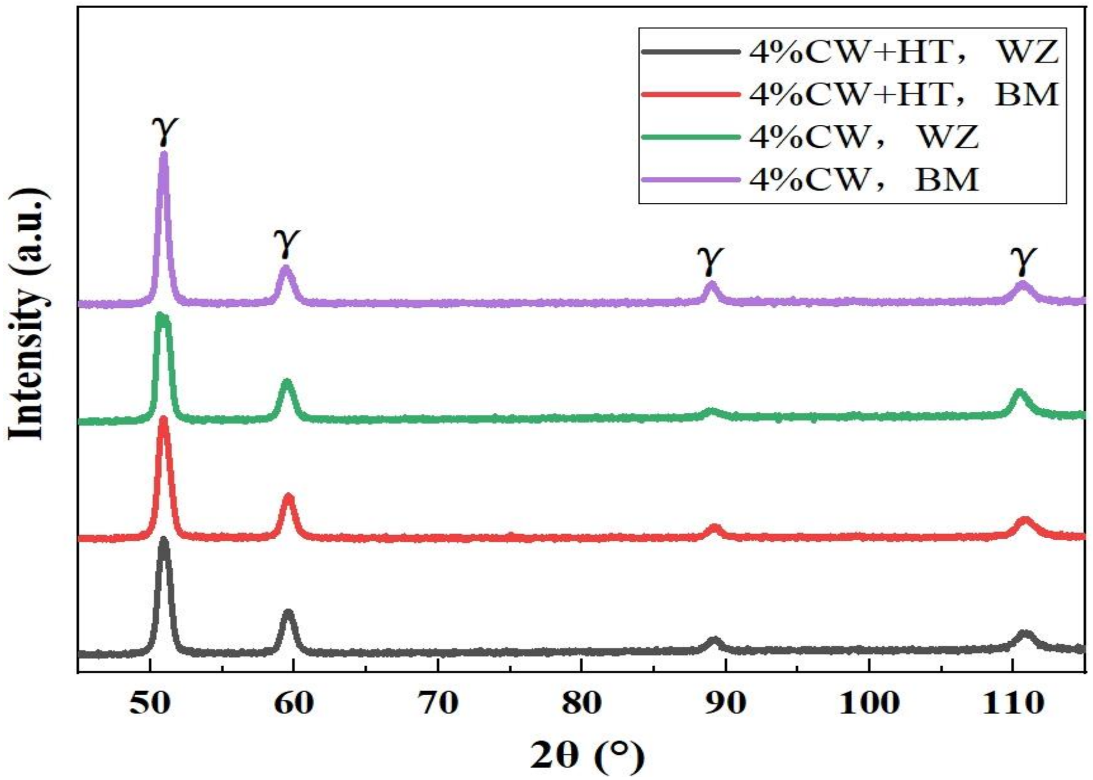
The YS of the welded joint can reach 95% of the target value.

HT leads to decrease in EL.

Both the CHN01 and welding joint (welding zone) exhibits fully austenitic structure and it is non-magnetic.

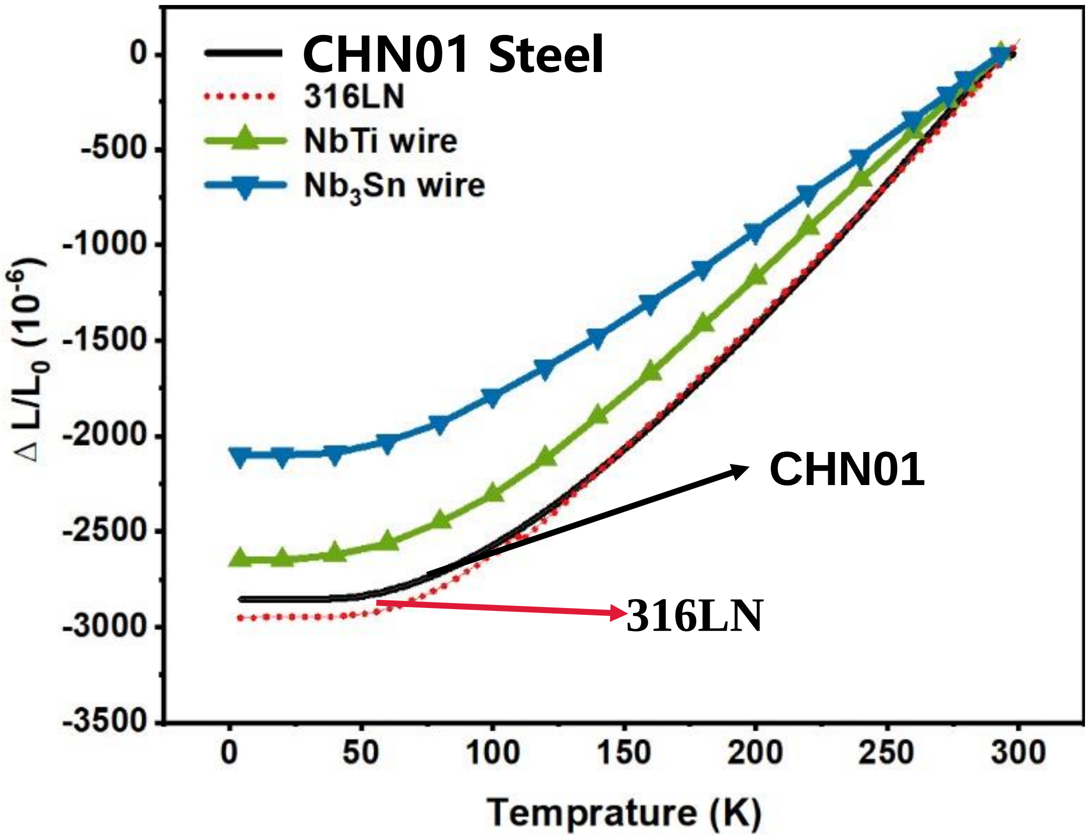


CHN01, RT and LT

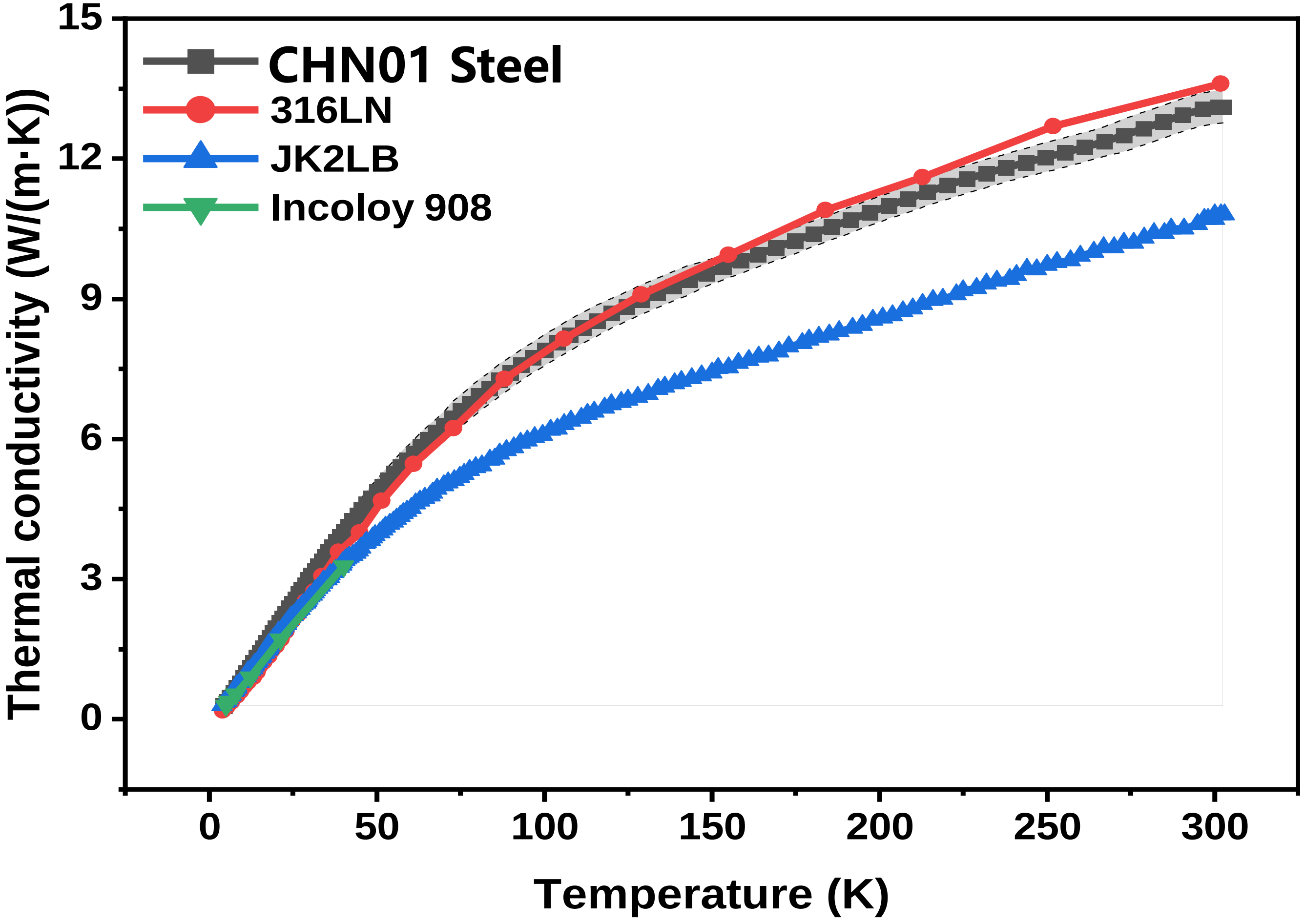


CHN01 and WZ with and w/o HT, RT

Thermal contraction of the CHN01 between 300 K and 4 K is about 0.285%.
It's the same as ITER 316LN (~0.294%).



Thermal conductivity between 300 K and 4 K



Manufacture of BEST CS and TF CICC jacket

BEST CS ReBCO CICC （CHN01）

BEST TF CHN01 dummy conductor

BEST TF CHN01 dummy coil

Part 3

Summary

A N-strengthened SS "CHN01" has been developed in China;

The CHN01 CICC jacket exhibits high strength, toughness and fatigue resistance, which meets the requirements of next-generation MCF (CFETR);

The developed welding materials and welding technology meet the requirements of jacket welding;

China has the mass production capacity of the CHN01 CICC jacket, and it has been used in manufacture of the BEST device.

Thanks your attention!