Research On New High-strength Structural Materials For Low-temperature Applications In The Next Generation Of Fusion Reactors

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ABSTRACT

- The CHSN01 (formerly N50H) austenitic stainless-steel conductor jacket developed for China's future fusion reactor exhibits excellent strength and toughness with a YS exceeding **1500 MPa at 4.2 K**, approximately 40% higher than that of the 316LN jacket used in ITER.
- This study systematically investigates the effects of **cold working (CW: 0%, 5%, 10%, 20%) and long-term cryogenic exposure** on its mechanical behavior and microstructure.
- The research identifies the optimal **CW deformation (5%)** for enhancing the CHSN01 jacket's comprehensive mechanical performance, indicating that prolonged exposure to the liquid He service environment **did not significantly affect** the mechanical properties of the CHSN01.

BACKGROUND

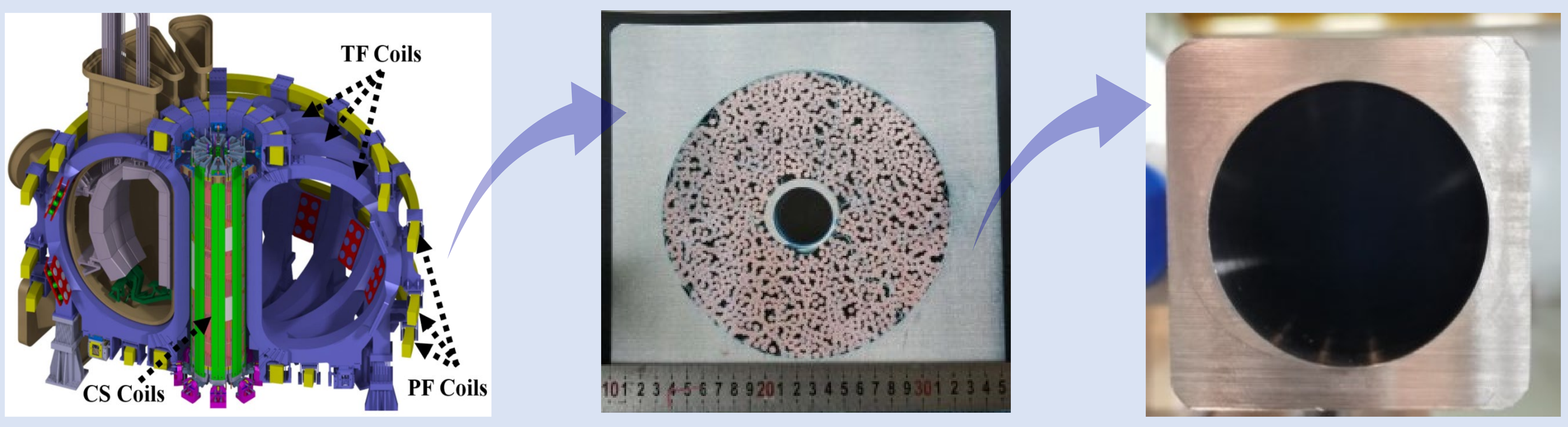

Fig. 1 The China Fusion Engineering Demo Reactor (CFEDR) and CICC structure

- As a strategic initiative, China is currently developing **the China Fusion Engineering Demo Reactor (CFEDR)**. The CFEDR central solenoid (CS) coil will keep using a **Cable-In-Conduit Conductors (CICC)** structure.
- According to the current design and operational conditions of CFEDR's CS magnets, future jacket materials must meet the following mechanical property requirements: **a yield strength (YS) exceeding 1500 MPa, ultimate tensile strength (UTS) exceeding 1800 MPa, elongation (EL) at break exceeding 25%, and a fracture toughness (K_{IC}) target value of at least 130 MPa·m$^{1/2}$ at 4.2 K.**

SPECIMEN PREPARATION AND TEST PROCEDURES

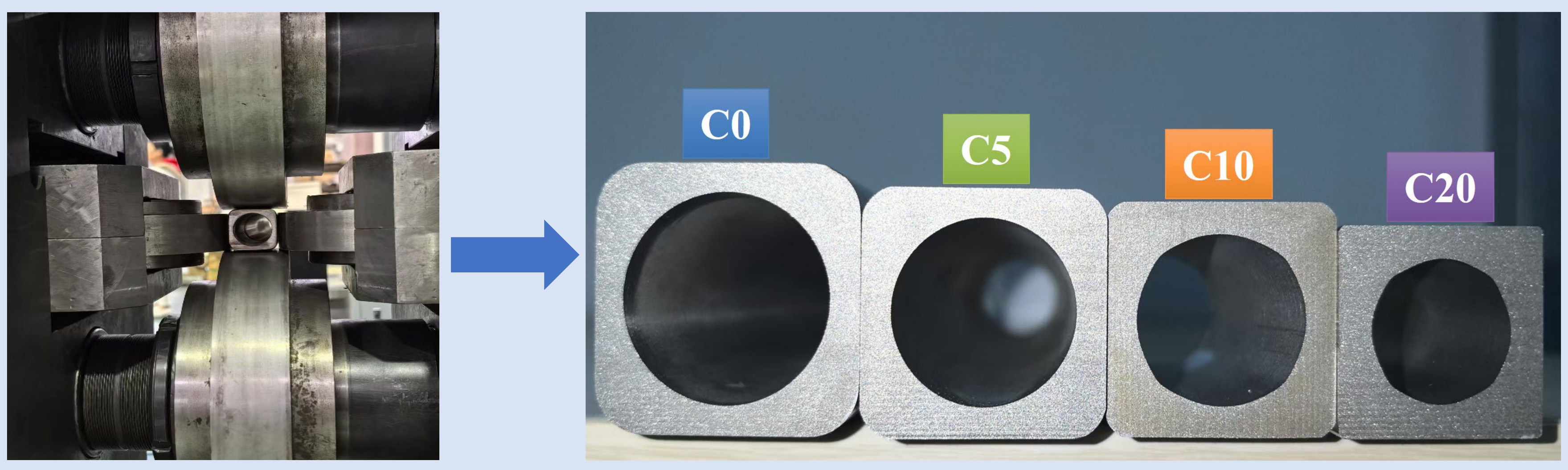

Fig. 2 The cold working (CW) process.

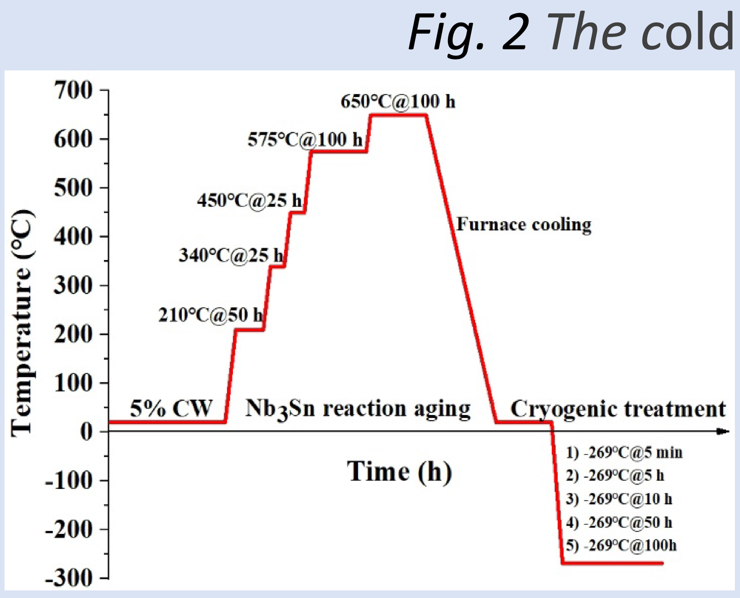

Fig. 3 The 5% CW, Nb_3Sn RA treatment and liquid He exposure durations.

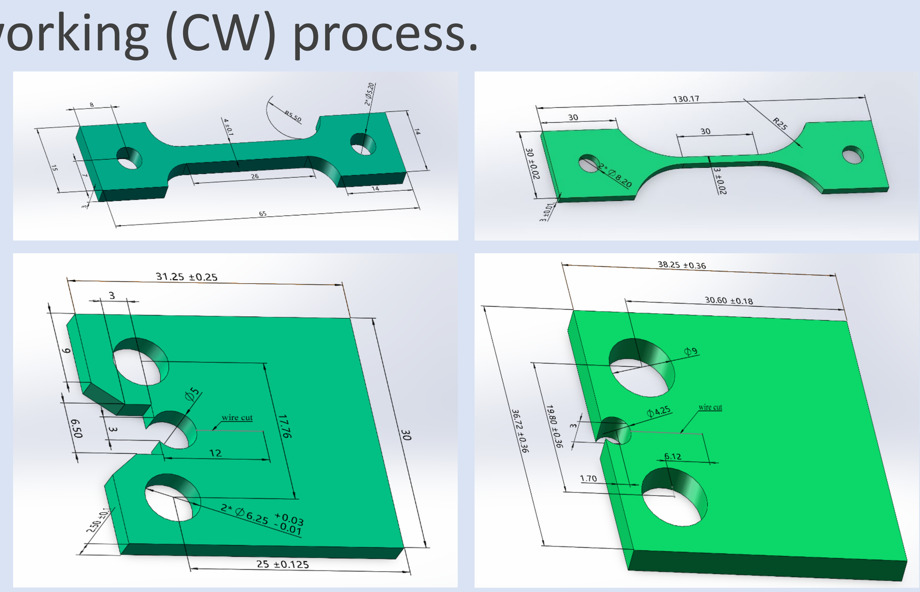

Fig. 4 Standard specimens.

1. During the manufacture of CICC coils, the jacket is subjected to both **cold working (CW) and Nb_3Sn superconductor reaction-aging (RA) treatment.**
2. Following the CW and RA treatments, the jacket is immersed for **5 min, 5 h, 10 h, 50 h, and 100 h** at liquid He temperatures.
3. Various **mechanical property standard specimens**, including tensile, fracture toughness, fatigue strength, hardness, and FCGR, were extracted from the four jackets through precise wire-cutting methods.

RESULT

1. Cold Working Effects on Mechanical Properties of CHSN01 Jacket

- Mechanical properties exhibit the characteristic trend of **increasing strength but decreasing plasticity** as CW deformation increases.
- The 5% CW deformation specimen achieved an optimal **strength-ductility balance (YS ＞ 1500 MPa; EL ＞ 30%; K_{IC} ＞ 200 MPa·m$^{1/2}$).**
- The Fatigue strength of the CHSN01 jacket is superior to N50 and 316LN modified under identical conditions.

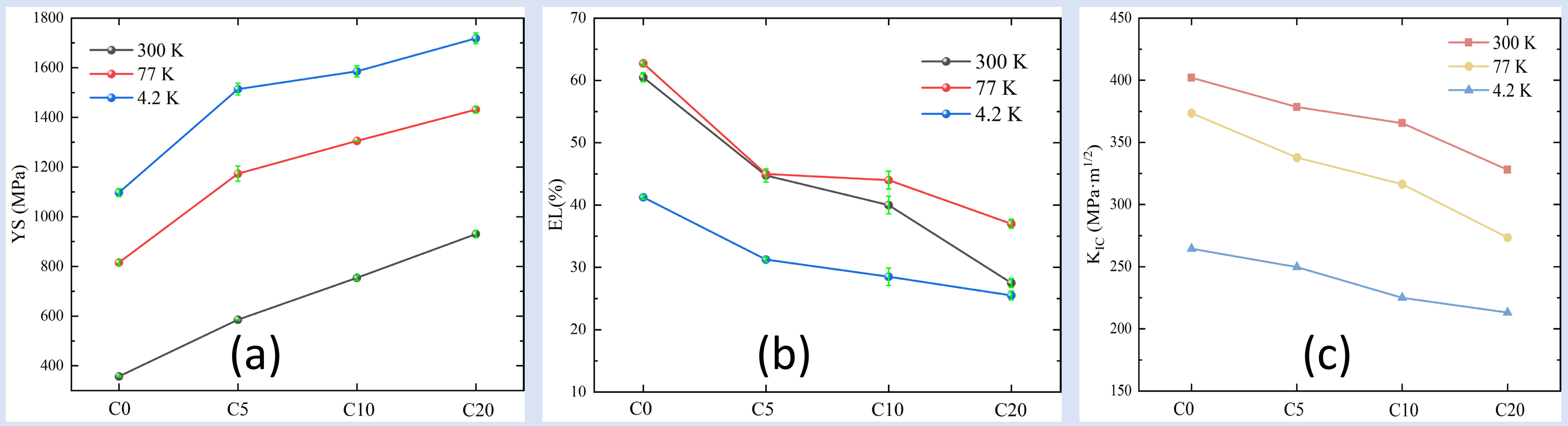

Fig. 5 (a) YS; (b) EL; (c) K_{IC}

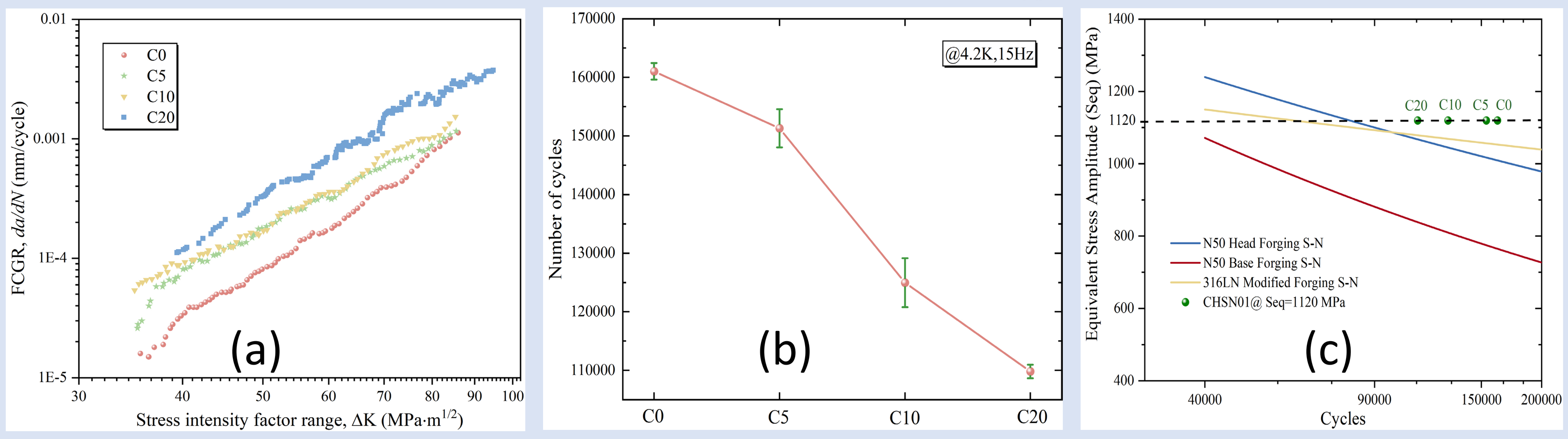

Fig. 6 (a) FCGR; (b) Fatigue strength; (c) S-N fatigue curves comparison for different materials at 4.2 K.

2. Mechanical Properties of CHSN01 jacket under long-term cryogenic service

- The stress–strain curves for the different specimens are **remarkably consistent**, indicating that prolonged exposure did not significantly affect the mechanical properties of the CHSN01, **with a YS of ~1550 MPa, UTS of ~1835 MPa, and EL of ~29%.**
- The dimples present are predominantly equiaxed, indicating **ductile fracture**, and their uniform distributions across the fracture surfaces suggest that these specimens underwent **relatively homogeneous deformation** throughout the fracture process.

Table 1. Average mechanical test results obtained at 4.2 K

Soaking time	YS(MPa)	UTS(MPa)	EL(%)	K_{IC} (MPa·m$^{1/2}$)
5 min	1587	1833	32.5	190
5 h	1562	1831	34	212
10 h	1555	1832	35.8	188
50 h	1566	1835	30.1	199
100 h	1562	1846	34.6	185

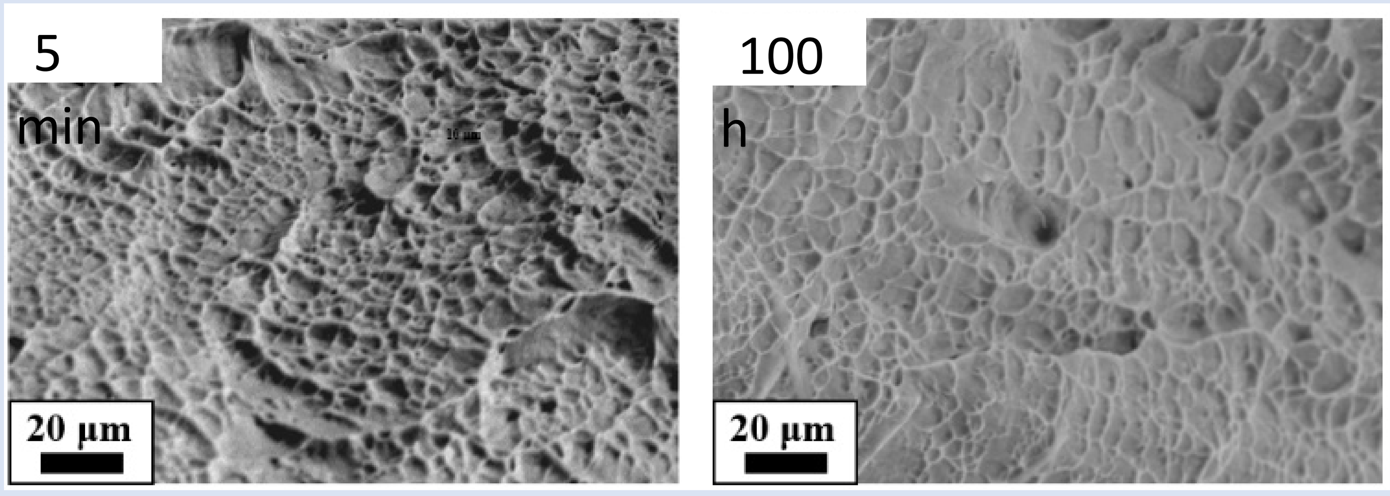

Fig. 7 Microstructures of the tensile fracture surfaces (5 min and 100 h).

CONCLUSION

- The 5% CW deformation specimen achieved an optimal strength-ductility balance at 4.2 K.
- The CHSN01 jacket exhibited excellent structural stability and cryogenic temperature resistance under any duration of immersion in liquid He.
- The batch preparation of CHSN01 CICC jackets that can accommodate 650 ℃ Nb_3Sn heat treatment without embrittlement has been successfully achieved in China.