Research on the Mechanical Properties of Jacket Used for Bi-2212 Cable-In-Conduit Conductor

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***Abstract*—The China fusion engineering test reactor is a new tokamak device. It is a commercial reactor, which demands a superconducting magnet with higher magnetic field. The maximum field of CS and TF will get around 15 T, which is much higher than that of present reactors. In order to meet the requirements, the new conductor with $Bi_2Sr_2CaCu_2O_x$ is considered as one potential material for the superconducting magnets. Because Bi2212 wire needs to endure special heat treatment with oxygen, the jacket material is one key issue. As one new material, Ni80Cr has an excellent performance, which cannot react with Bi-2212 wire. It could be one potential material as Bi-2212 cable-in-conduit conductor jacket. In order to understand the mechanical properties of Ni80Cr, the samples with different conditions were prepared, and tested at high, room, and low temperature (4.2 K). The results are analyzed in this paper.**

***Index Terms*—Cable-In-Coduit Condutor, Bi2212, Conductor jacket, Mechanical property.**

I. Introduction

CHINE FUSION Engineering Test Reactor (CFETR) is a new tokamak device in China, whose geometry and target parameters of plasma are given according to physics design [1], [2]. The magnet system is made of sixteen Toroidal Field coils (TF), a Central Solenoid (CS) and six Polodial Field coils (PF) [3]. The magnet is core of tokomak device, whose technology is a challenge, especially for CS and TF coils. The maximum field of CS and TF will be much higher than present devices, which could reach to 15 T. The new materials have been considered to apply for the next generation magnet system.

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The Bi-2212 material is one of the most attractive because of its high upper critical field ($H_{c2} > 100$T) which could be used in high background field environments [4], [5] among the high-temperature superconducting materials. Compared to Nb_3Sn, Bi2212 has a bigger temperature margin during operation under peak magnetic field in 12-15 T of the magnet system for fusion reactor. Bi2212 can be made into round-wire (RW), which makes its possibility to develop a Cable-In-Conduit Conductor (CICC), which is made of jacket and cable.

Unfortunately, the current carrying capability of Bi2212 is sensitive to strain, because it is brittle after reaction. The application fields are also limited by the low mechanical strength of Ag/Bi-2212 wire. The commercial PIT Ag/Bi-2212 wires are heat treated with melt processing in 1 bar O_2 in order to achieve high J_E. But the wire needs to be in direct contact with structural materials, and heat treated with a maximum temperature reaching 900 °C in O_2, which could be a significant challenge for structural materials. They need to maintain high strengths after the heat treatment with O_2 and then cooling down to cryogenic temperatures. Meanwhile, they should not make critical current density J_c of Bi-2212 wire degrade distinctly. In nature, these demands are similar to those required for Nb_3Sn CICC magnets manufactured with the wind-and-react method [6]. They actually demand that some new materials have to be developed and qualified for the application, because Ag/Bi-2212 wire was found to be quite reactive [7]–[9].

As CICCs, the jacket is one very important component [10], [11]. During high pressure heat treatment of Bi2212 CICC, O_2 needs to go through the inner of conductor in future [12]. Firstly, the jacket material can not react with Bi2212. Secondly, the jacket material could sustain high pressure (at least 50 atm) and high temperature (890 °C). Thirdly, the jacket should have high mechanical performance during operation at low temperature. For general CICCs, the material of jacket is mainly 316L or 316LN, e.g. ITER PF or TF. But they could reduce the critical current of Bi2212 wire during reaction from the present research. T. Shen made the research on four different materials, which are INCONEL 600, INCONEL X750, Fe-Cr-Al, and Ni80Cr [13]. The results show that Fe-Cr-Al and Ni80Cr have less impact on J_c reduction of Bi2212.

From the present results, Fe-Cr-Al and Ni80Cr are potential materials for development of Bi2212 CICC jacket. But Fe-Cr-Al is fragile after heat treatment with O_2. Ni80Cr is the preferred material for Bi2212 CICC jacket. For the CICC jacket, the mechanical properties are very important, which should be mainly considered.

TABLE I
CHEMICAL COMPOSITION OF NI80CR

Chemical composition	wt%
C	0.063
Si	0.160
Mn	0.300
P	0.003
S	0.001
Cr	20.35
Ni	80.05
Co	0.029
N	0.145
Ti	0.320
Cu	0.070
Fe	0.480
Al	0.090

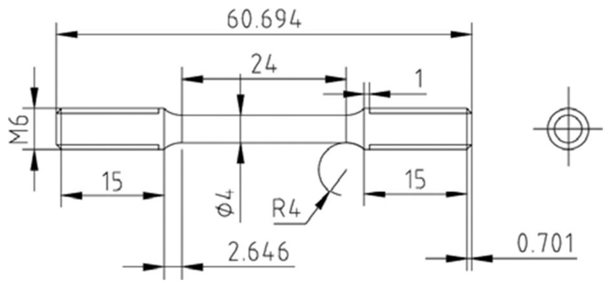

Fig. 1. Schematic of testing sample.

As a new material, Ni80Cr has an excellent performance without reacting with Bi-2212 superconducting wire. In this paper, the mechanical properties of Ni80Cr were made research because of its potentiality as Bi-2212 CICC conductor jacket material. In order to understand the mechanical properties of Ni80Cr clearly, we measured the Ni80Cr samples in low, room and high temperature, which were treated with normal solid solution treatment and similar procedure with heat treatment to Bi2212 wire.

The testing was performed in Technical Institute of Physics and Chemistry of Chinese Academy of Sciences (TIPC) and Jiuli Company. The mechanical properties of Ni80Cr were also compared to 316LN materials used for ITER TF conductor.

II. Sample Preparation and Experimental Procedure

A. Chemical Composition

The raw material is from Jiuli company. The chemical composition in weight is shown in Table I, which is provided by the material supplier. The samples were treated with solid solution treatment at 990 °C with different time. One is 20 min, and the other is 30 min.

B. Experimental Procedure

The tensile testing samples were prepared for high, room, and low temperature. The samples were machined and consistent with ASTM E8M, as shown in Fig. 1.

Fig. 2. The testing sample for high temperature.

The testing with high temperature was performed at Jiuli Company. The special equipment was used to keep 950 °C until sample was fractured, as shown in Fig. 2.

The tensile testing setup at room or low temperature is consists of a tensile testing machine, extensometer and cryogenic system. The tensile testing machine is Z100TEW which has 1100 Nominal temperature and 100 kN load at a maximum. The machine was applied to metal tensile test under room and high temperature. The initial strain rate is 2.5×10^{-4} /s according to ASTM E1450. The extensometer was assembled on the gauge length of the tensile samples to record the strain during testing. The yield strength of Ni80Cr is determined by the 0.2% offset method form the recorded stress-strain curve. Additionally, the low temperature tests are performed in a Dewar. During tensile testing at 4.2 K, the specimen and fixtures were immersed in liquid helium.

Normally, the Bi2212 conductor needs heat treatment at 950 °C under oxygen environment, and operates at low temperature. So, one tensile sample was heat treated as the same as one of Bi2212 conductor. It was heat treated at $T_{\max} = 890\,^{\circ}\mathrm{C}$ for 30 minutes. The temperature was reduced to 830 °C with the speed of 5 °C/h, and then heat treated at $T_{\max} = 830\,^{\circ}\mathrm{C}$ for 48 hours in a standard oxygen environment.

III. Testing Results and Discussions

Two samples at high temperature, two samples at 300 K, and three samples at low temperature were made tensile test. The sample informations are listed in Table II.

The fractured samples are shown in Fig. 3. The tested results are shown Table III.

From Table III, it can be seen that the Ni80Cr samples have similar properties at the same temperature for different states. At low temperature, the elongations at failure of these three samples are very close. Different solution annealing has no influence on

TABLE II
SAMPLE INFORMATION

Sample ID	Solution annealing (990 °C)	Heat treatment again	Testing condition
S1	20 min	No	1163 K, 300 K, 4.2 K
S2	30 min	No	1163 K, 300 K, 4.2 K
S3	20 min	Yes	4.2 K

Fig. 3. Fracture tensile test sample for different temperatures.

TABLE III
TENSILE RESULTS OF NI80CR

Temperature	Sample	Treatment time (Min)	Elongation at failure (%)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
4.2 K	S1-1	20	50	485	1050
	S2-1	30	49	490	1050
	S3-1	20	51	510	1077
300 K	S1-2	20	62	310	585
	S2-2	30	65	305	573
1163 K	S1-3	20	72	93	161
	S2-3	30	67	65	143

the property. Most important, the heat treatment similar to that of Bi2212 has less influence on tensile properties, which is similar to 316LN material used for ITER TF [14].

The elongation at failure decreases by the reduced temperature. The value at low temperature is about 20% lower than one at room temperature and about 28% lower than one at high temperature. As expected, the yield strength and ultimate tensile strength increased strongly by the reduced temperature. The values at low temperature are about two times higher than those at room temperature. The yield and ultimate tensile strength of samples decreased sharply at high temperature.

In order to investigate the failure mechanism, the fracture surfaces morphology of the specimens after the tensile test at 4.2 K and 300 K were investigated by means of scanning electron microscopy analysis. The Scanning Electron Microscope (SEM) analysis at 300 K indicates that the fracture mechanism is a ductile fracture, as shown in Figs. 4 and 6.

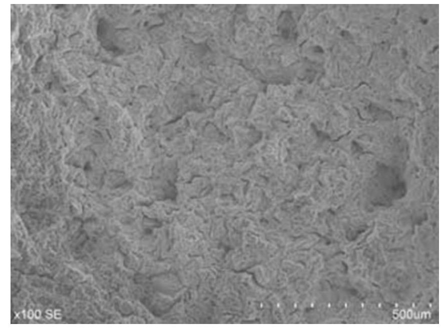

Fig. 4. SEM image of sample tested at 300 K with 20 min solution treatment.

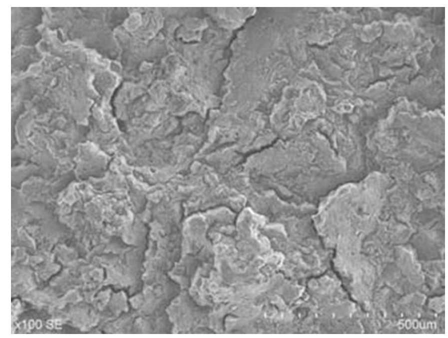

Fig. 5. SEM image of sample tested at 4.2 K with 20 min solution treatment.

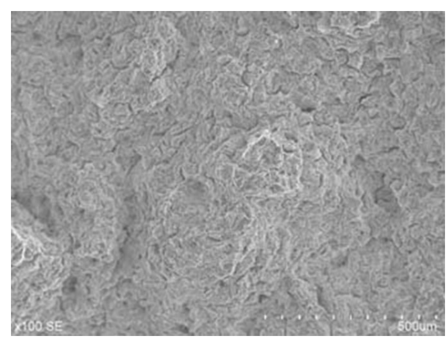

Fig. 6. SEM image of sample tested at 300 K with 30 min solution treatment.

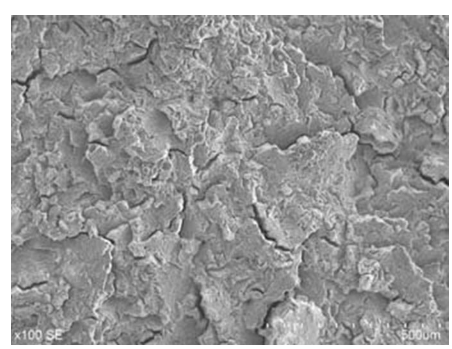

Fig. 7. SEM image of sample tested at 4.2 K with 30 min solution treatment.

The SEM images of fracture surfaces of samples tested at 4.2 K are shown in Figs. 5 and 7, which also display the ductile fracture.

From the fracture surfaces, Ni80Cr and 316LN have similar behaviors [14]. The mechanical property of Ni80Cr was com-

TABLE IV
COMPARISON OF MECHANICAL PROPERTIES

Temperature	Material	Elongation at failure (%)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	State
4.2 K	316LN	33	1080	1550	Solution annealing
	Ni80Cr	50	485	1050	
300 K	316LN	40	450	780	
	Ni80Cr	62	310	585	

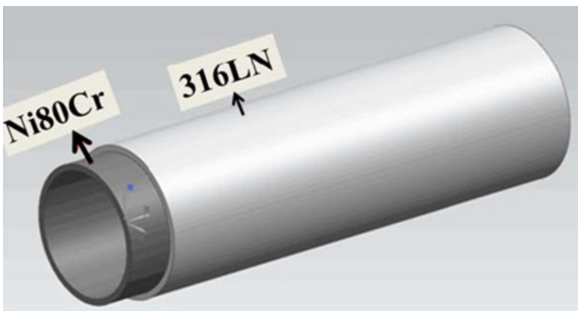

Fig. 8. Composited tube made of Ni80Cr and 316LN.

pared to 316LN material used for ITER TF conductor [14]. The compared results are shown in Table IV.

From Table IV, it's easily to be found that the strength of Ni80Cr is much lower than one of 316LN. But the elongation at failure of Ni80Cr is about 50% higher than that of 316LN. For the decreased elongation at failure from 300 K to 4.2 K, it is 17.5% and 19.3% for 316LN and Ni80Cr, respectively. The two materials have similar changed mechanical properties caused by temperature.

For future application on Bi2212 CICC, Ni80Cr is very risky as jacket because of large Lorentz force during conductor operation. But Ni80Cr has high elongation at failure and less influence on Bi2212 properties. So the composited tube could be considered for application on Bi2212 CICC, as shown in Fig. 8.

But, the different materials have different coefficient of thermal expansion, which could cause different contraction during cooling down from high temperature to low temperature. This problem could limit the use of Ni80Cr. In future, we will perform the research on it and find solutions.

IV. CONCLUSION

The mechanical properties of Ni80Cr were tested at 4.2 K, 300 K and high temperature. The results show that the elongations at failure are very close for different samples tested at same temperature. The heat treatment similar to that of Bi2212 has no visible influence on mechanical properties of Ni80Cr. From comparison between Ni80Cr and 316LN, the strength of Ni80Cr is much lower than that of 316LN. There is much risk for the Ni80Cr application on Bi2212 CICC. Because of good elongation at failure and less impact on Bi2212 properties, composited tube made of Ni80Cr and 316LN could be considered for future application on jacket of Bi2212 CICC.

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