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Risks and benefits of Incoloy 908

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Abstract

The central solenoid and toroidal field coils of ITER are designed with cable-in-conduit Nb_3Sn superconducting conductors jacketed with Incoloy 908. This material, developed to limit the critical current degradation of the Nb_3Sn strands, shows excellent mechanical properties at 4 K, particularly under cycling. Nevertheless, it is a crack prone material when heat treated in the presence of oxygen, which requires careful control of the atmosphere during manufacture. A programme of extensive mechanical testing of samples and manufacture of a pancake with incoloy conductor jacket was carried out in Europe. The origin of cracks in the incoloy jacket after heat treatment was investigated.

Keywords: Incoloy 908; Nb_3Sn conductor jacket; Cracks

1. Introduction

The design of the central solenoid (CS) and toroidal field (TF) coils of the International Thermonuclear Experimental Reactor (ITER) [1] relies on the use of cable-in-conduit Nb_3Sn superconducting conductors. These conductors are made of a circular cable inserted in a jacket providing helium tightness, stiffness and strength for the conductor. A nickel base alloy, designated as Incoloy 908, was developed as a jacket material in order to limit the critical current degradation of the Nb_3Sn strands [2]. This material was selected for both the CS conductor (thick square shaped jacket) and for the TF conductor (thin circular shaped jacket). Parallel to the manufacturing of the toroidal field model coil (TFMC) [3], designed with a stainless steel jacketed conductor, a complementary development programme was started in Europe to use Incoloy 908 as a jacket material. This programme included mechanical characterisation of the material at low temperatures, manufacture of a pancake using a dummy incoloy jacketed conductor and manufacture and test of a Toroidal Field Full-Size Joint Sample (TF-FSJS).

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Table 1
Incoloy 908 chemical composition

Element	Fe	Ni	Cr	Nb	Ti	Al	N	Mn	C	Co
% weight	40.7	49	3.98	2.92	1.74	0.93	0.002	0.041	0.01	<0.1

2. Material design

Incoloy 908 is a γ' precipitation strengthened nickel base alloy (Table 1). The critical current of Nb_3Sn strands is well known to be strongly dependent on the axial strain applied to the strand [4]. This axial strain is substantially affected from the differential thermal contraction occurring between the jacket and the strand during cooling down from the heat treatment temperature to the cryogenic operational temperature. Whereas 316LN stainless steel thermal contraction from 923 K down to 4 K is in the order of 1.6%, that of Incoloy 908 is only 1.1%, a value closer to the 0.7% contraction of Nb_3Sn, which results in a lower residual strain at 4 K, corresponding to a higher critical current in the Nb_3Sn strands (Fig. 1) [5].

3. Mechanical testing

The characterisation programme of Incoloy 908 performed in Europe included tensile tests in order to determine elastic and tensile properties at room and low temperature, and fracture mechanical tests to determine fracture toughness and crack growth rate. The elastic properties are summarised in Table 2 and the tensile properties in Table 3. Fracture mechanical measurements were performed on samples which had undergone heat treatments representative of the coil manufacture (annealing at 980 °C, 1 h and reaction at 650 °C, 200 h at vacuum).

Fracture toughness measurements are shown in Table 4 and a comparison with 316LN steel is given for crack growth rate in Fig. 2. It can be observed that the crack growth rate of Incoloy samples is much lower than that of 316LN at relatively low variation of stress intensity range (~ 20 MPa $\sqrt{m}$), whereas the difference is smaller for higher variations (~ 40 MPa $\sqrt{m}$).

4. Incoloy pancake

The TFMC conductor was jacketed with a thin (1.6 mm thick) 316LN stainless steel jacket, whereas the reference design of the ITER TF coils was made with a thin (1 mm thick) incoloy jacket. To qualify Incoloy 908 for the manufacture of

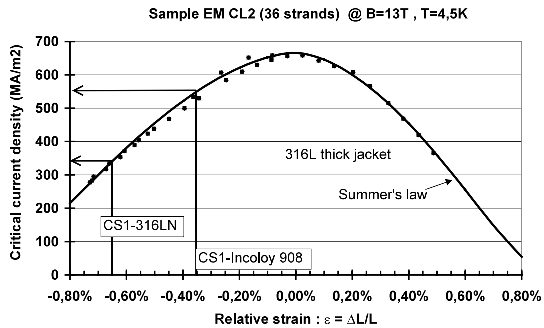

Fig. 1. Critical current of Nb_3Sn strands.

Table 2
Elastic properties of aged Incoloy 908

Temperature (K)	295	76	4
Young's modulus (GPa)	171	174	177

Table 3
Tensile properties of aged Incoloy 908

Temperature (K)	295	76	4
YS (MPa)	1110	1170	1216
UTS (MPa)	1302	1580	1694
Uniform elongation (%)	22	23	22
Reduction of area (%)	38	40	28

YS: Yield strength, UTS: Ultimate tensile strength.

Table 4
Fracture toughness of Incoloy 908

Temperature (K)	295	4
K_{Ic} (MPa $\sqrt{m}$)	196	185–206

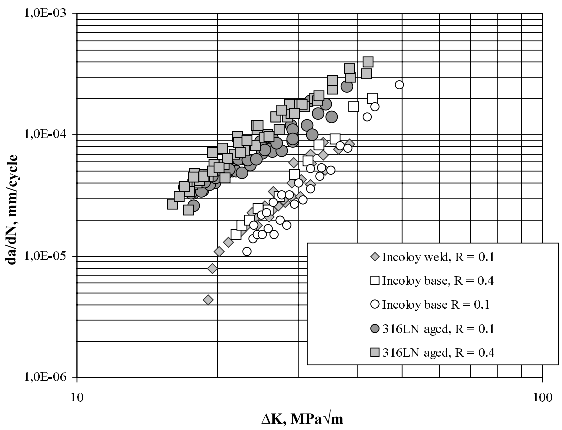

Fig. 2. Fatigue crack growth rate of aged Incoloy 908 and 316LN jacket materials at load ratios $R = 0.1$ and $R = 0.4$.

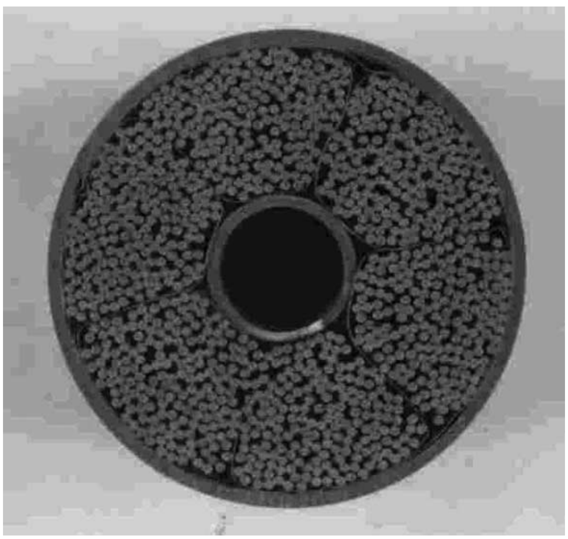

Fig. 3. Incoloy pancake conductor.

Table 5
Incoloy pancake conductor characteristics

Strand	Copper, 0.81 mm ∅
Cable	1080 strands, 37.4 mm ∅
Inner spiral	304 SS, 9.9 mm × 11.9 mm
Subcable wrapping	Inconel 600, 0.1 mm thick
Cable wrapping	304 SS, 0.025 mm thick
Jacket	Incoloy 908, 1 mm thick
Conductor	39.4 mm ∅

these coils, it was decided to build in Europe a pancake using an incoloy jacketed conductor. The aim of this manufacture was limited to the qualification of the wind-react-and-transfer process, which allowed the use of a dummy conductor since no testing of the conductor properties was planned. The conductor (Fig. 3) used a TF cable, manufactured in Japan by Showa with copper strands, and an Incoloy 908 jacket, made of tubes provided from United States by Inco Alloys and assembled by orbital welding in Russia.

The pulling through of the cable inside the jacket and the compaction was performed by VNIIKP [6]. The main characteristics of the conductor are summarised in Table 5.

The manufacture of the pancake was performed by AGAN/Ansaldo (Genoa, Italy), using the same tools as used for the manufacture of the TFMC pancakes. The main difficulty in this manufacture comes from the necessity to cope with the stress accelerated grain boundary oxidation (SAGBO) phenomenon [7]. Since the oven used for heat treatment was using argon at atmospheric pressure, shot peening was applied to the whole outer surface of the conductor jacket, and argon with very low oxygen content (< 0.1 ppm) was circulated inside the conductor. Nevertheless, despite these precautionary measures, after heat treatment cracks were discovered in the jacket (Fig. 4), and large propagation occurred during transfer (Fig. 5).

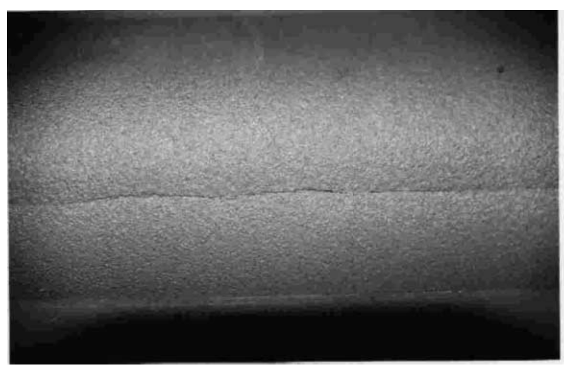

Fig. 4. Cracks in the incoloy pancake after heat treatment.

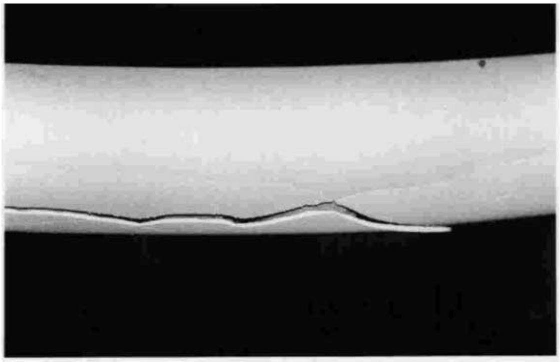

Fig. 5. Cracks in the incoloy pancake after transfer.

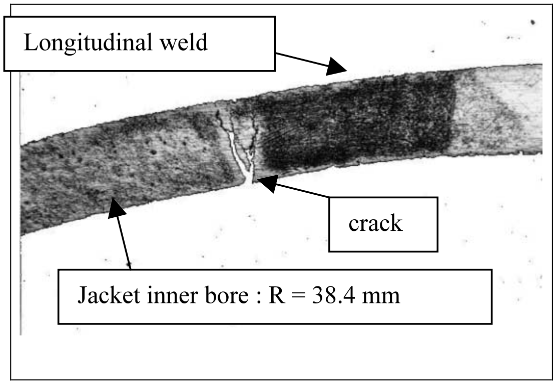

Fig. 6. Crack propagation in incoloy jacket.

5. TF-FSJS

Parallel to the manufacture of the incoloy pancake, the TF-FSJS was manufactured by Ansaldo and tested at CRPP (Villigen, Switzerland). This sample used a superconducting conductor, built with the same cable as that used in the TFMC and jacketed by Europa Metalli (Fornaci di Barga, Italy) with an Incoloy 908 jacket, made with tubes provided by Inco Alloys and assembled by orbital welding by Europa Metalli. Tubes used for both the incoloy pancake and the TF-FSJS had the same geometry and came from the same manufacturing process. The joint of the TF-FSJS was made according to the twin-box concept, with incoloy/copper termination boxes [8]. After heat treatment of the legs of the sample, a longitudinal kink very similar to that found on the incoloy pancake, was discovered, and later on, leaks occurred during testing leading to premature end of the tests.

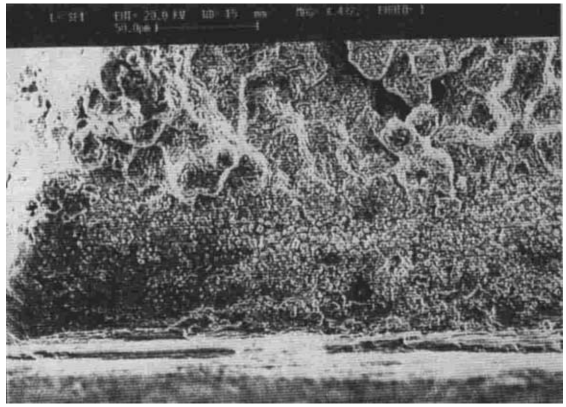

Fig. 7. Transgranular cracking morphology.

6. Investigation of crack origin

6.1. Crack initiation and propagation

To understand the origin of the cracks which occurred in both the incoloy pancake and the TF-FSJS, a complementary programme of investigations was set up by the European Home Team (EUHT). Micrographic examinations of the incoloy cracked part identified a crack propagation from the inner bore of the jacket, in the heat affected zone of the longitudinal weld of the jacket (Fig. 6). The origin of the crack could be clearly identified as an initial defect in the longitudinal weld of the jacket showing transgranular morphology (Fig. 7). On the contrary, intergranular morphology indicates that the crack propagation was due to oxidation combined with tensile stresses arising on jacket inner bore during heat treatment (SAGBO) (Fig. 8).

6.2. Origin of oxidation

After the results of the metallographic examination had shown that crack propagation was due to oxidation, some further investigations were performed to try to understand the possible origin of this oxidation. As the argon flowing through the conductor during heat treatment had a very low oxygen content (< 0.1 ppm), according to the experience in United States and Japan, no SAGBO phenomenon should have occurred. An unexpected outgassing of oxygen or water coming from the conductor itself was then considered.

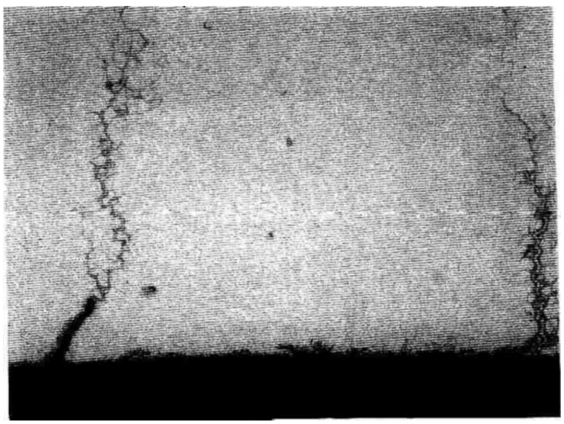

Fig. 8. Intergranular oxidation cracking from jacket inner bore.

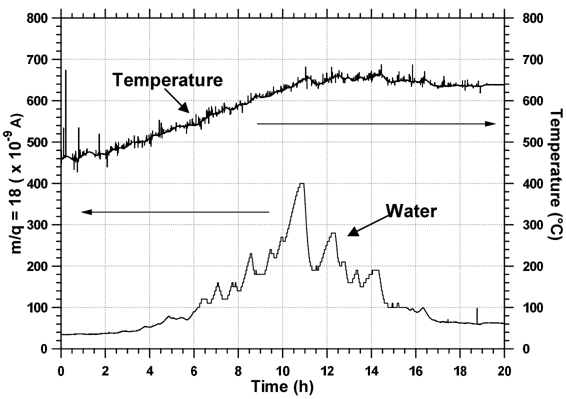

Fig. 9. Production of water during heating-up.

Table 6
Estimation of the gas composition of the outlet argon flow at room temperature

Ar	CO+N_2	H_2	H_2O	O_2	CO_2
93%	5%	0.6%	0.3%	0.6%	0.2%

6.3. Investigation of water outgassing

The records of water content during heat treatment indicated a peak of water during ramping up to 650 °C, so a set of water outgassing tests was performed at CEA/Cadarache: a thermodesorption experiment, under vacuum, of a sample of TF conductor (65 mm long) and the measurement of the water content of the argon flow circulating inside a piece of TF conductor during a heat treatment. The tests were carried out in a high vacuum vessel (background pressure $\sim 10^{-5}$ Pa, oxygen content $\sim$ 10%) inserted in an oven. The partial pressures of the desorbing species were recorded using a quadrupole mass spectrometer. For the second experiment, a piece of conductor (250 mm long) was equipped with stainless steel end caps and pipes and connected to an argon N60 (< 0.1 ppm O_2) circulation loop. A SHAW H_2O analyser and a second quadrupole mass spectrometer (using a differential pumping) both connected to the argon loop measured the water content of the argon flow.

6.4. Desorption of conductor sample

The desorption spectrum of water from the incoloy jacketed conductor (Fig. 9) exhibits one large peak in the 450–650 °C temperature range. The peak temperature corresponds to the end of the temperature ramp-up. The desorption of water at such a high temperature is odd. Since experiments carried out without samples showed that the water production from the stainless steel vessel alone is negligibly small compared with that recorded during the conductor sample test in the same temperature range, we can exclude the hypothesis of a temperature activated diffusion of water from the vessel wall (or an artefact due to the desorption of water from a colder part of the vessel). Nevertheless, this does not allow us to determine the exact origin of the water production: cable or incoloy jacket itself.

6.5. Argon circulation test

The gas composition in the argon loop, checked before the beginning of the heating (Table 6), shows an unexpectedly relatively high level of impurities. During the ramping from 450 up to 650 °C, the water partial pressure was found to be roughly equal to the one recorded at room temperature and showed a perfect correlation with that of argon, indicating that the water partial pressure only depends on the argon flux in the loop and could correspond to the background water level of the argon piping, not baked up before the experiment. No specific contribution from the conductor could be detected in the sensitivity range of the mass spectrometer, due to the high residual impurity content. On the other hand, the water analyser indicated a slight increase of the water content at the beginning of the ramping up, but this could hardly be considered as significant.

7. Conclusions

Incoloy 908 used for the Nb_3Sn conductor jacket provides reduced critical current degradation of strands and exhibits better resistance to crack growth propagation at 4 K than stainless steel. Its sensitivity to cracking at high temperature puts stringent requirements on the Nb_3Sn reaction heat treatment. The origin of cracks observed in the incoloy pancake and TF-FSJS is a combination of an initial welding defect and oxidation during heat treatment. Desorption of a conductor sample indicated water coming from the conductor but this was not confirmed when circulating argon inside it. If a thin incoloy jacket is to be used, then this phenomenon will require better understanding and the establishment of conservative avoidance measures.

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