Fusion Engineering and Design 96–97 (2015) 388–391

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Mock-up qualification and prototype manufacture for ITER current leads

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HIGHLIGHTS

- Vacuum brazing and electron beam welding qualification.
- Machine and assembly strategy of fin type heat exchanger.
- Soldering and joint resistance test of superconducting joint.
- Pre-preg technology with vacuum bag on insulation.

ARTICLE INFO

Article history:
Received 17 September 2014
Received in revised form 15 March 2015
Accepted 23 April 2015
Available online 16 May 2015

Keywords:
Current lead
Heat exchanger
NbTi
Bi-2223
Prototype

ABSTRACT

Three types of high temperature superconducting current leads (HTSCL) are designed to carry 68 kA, 55 kA or 10 kA to the ITER magnets. Before the supply of the HTS current lead series, the design and manufacturing process is qualified through mock-ups and prototypes. Seven mock-ups, representing the critical technologies of the current leads, were built and tested successfully in the Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) in 2013. After the qualification some design features of the HTS leads were updated. This paper summarizes the qualification through mock-ups. In 2014 ASIPP started the manufacture of the prototypes. The preparation and manufacturing process are also described.

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) current leads connect the room temperature busbar and the 4.5 K busbar. 60 HTS current leads transfer 50 GJ of stored magnetic energy into and out of the magnet system. Three types of ITER current leads, Toroidal Field (TF) 68 kA, Poloidal Field (PF)/Central Solenoid (CS) 55 kA and Correction Coil (CC) 10 kA, were designed in 2011 [1]. ASIPP is responsible for all the technologies development and the timely supply of all the current leads. In 2012 ASIPP started the qualification of the technologies for the ITER HTSCL mock-ups and prototypes. In 2013, seven mock-ups (Fig. 1) representing the critical technologies were qualified: (1) TF HTSCL Electron Beam Welding (EBW) mock-up; (2) TF HTSCL Heat EXchanger (HEX) mock-up; (3) TF HTSCL Low Temperature Superconducting (LTS) mock-up; (4) CC HTSCL instrumentation mock-up; (5) CC HTSCL EBW mock-up; (6) CC HTSCL HEX mock-up; (7) CC HTSCL LTS mock-up. The insulation technologies are still in developing. So the qualification for two insulation mock-ups does not start.

Now in 2014 TF and CC prototypes are in manufacturing, except for the insulation. Before the mock-ups and prototypes qualification many documents, including the Manufacture and Inspection Plan (MIP), Manufacture Plan (MP), Quality Plan (QP), including detailed manufacturing procedures were prepared and approved to follow the ITER quality requirements [2]. In 2015, ASIPP plans to finish all the prototypes manufacture and test. After the prototype qualification the project will be pushed into stage III: HTSCL production.

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http://dx.doi.org/10.1016/j.fusengdes.2015.04.050

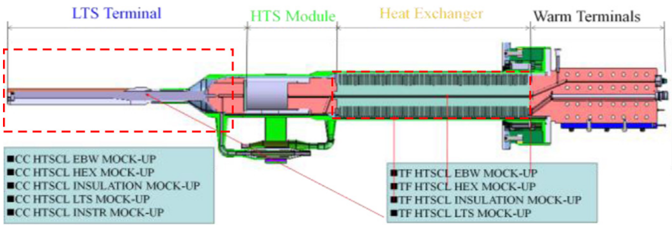

Fig. 1. HTSCL and mock-ups.

2. Welding and brazing qualification

The TIG welding was qualified according to the ISO 15617 standard. The vacuum brazing, for which there is no completely defined standard to support the qualification work, the acceptance criteria were discussed and finally approved by IO.

There were two major brazed subassemblies, room temperature (RT) terminal and HTS shunt, to be qualified before the prototype manufacture. Because the brazing quality relates to the mass of the component, the real size terminal and shunt were designed for the qualification. Because different mass of the components resulted in the different temperature increasing rates in furnace the thermocouples were mounted on the components to detect the temperature (Fig. 2). When the temperature difference was more than 5 °C the heating would be paused. Without heating the temperature would be converged after some minutes.

All the brazed joints were vacuum or pressure leak tested under real operation pressure conditions. The right photos in Fig. 2 are the cross sections of the brazed joint. No voids was found under 50 times magnifier. The tensile stress tests were performed on the shunt because the gravity will give rise to a bending moment here on the operation when the current lead is horizontally placed. The rupture stress was more than 190 MPa on copper section. This shows that the brazing joint has enough strength.

3. Mock-up qualification

3.1. HEX mock-ups

A fin type HEX is designed for the ITER current leads following the positive experiences from CERN [3]. The coolant will flow in zig-zag manner. The assembly tolerance H7/g6 between the HEX and the tube is very critical for the current lead performance. To ease the assembly of the close-fitting tube and heat exchanger, the tube was honed to a high precision finish surface. To avoid sticking during assembly the tube was heated to about 180 °C before the assembly. The diameters were increased by 0.25 mm for CC tube, and 0.43 mm for TF tube, which should allow smooth assembly. Given enough gap after the heating the assembly was finished in 10 s.

Because of the softness of the copper and the slim core design after machining, the straightness of the CC HEX core could exceed

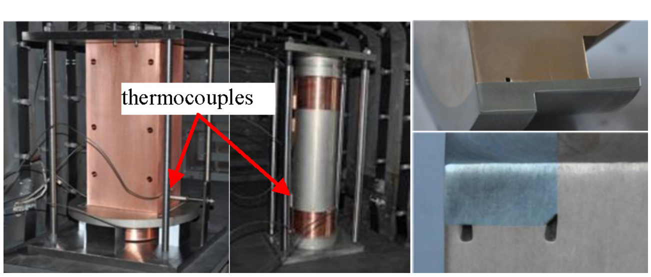

Fig. 2. Brazing qualification; left: RT terminal, middle: shunt, right: results of destructive examination.

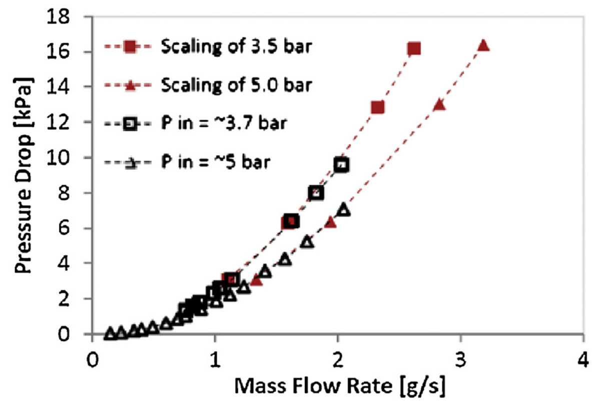

Fig. 3. Nitrogen pressure drop in the 10 kA mock up.

0.12 mm, mainly due to the deformation under the weight. Since this deformation is hardly avoidable, the fin machining is a challenge requiring special tooling. The lower straightness of the HEX core was also a major reason for the choosing of the tube heated method for assembly.

Both TF and CC HEX mock-ups were tested in ASIPP after the successful assembly. The mock-up model was calculated by CERN. In Fig. 3 the black points are the calculation results with finite element method. The red points are the test results. A very good agreement was found between the model and the test results (Fig. 3). It proves that the design and manufacture meets the operation requirements.

3.2. EBW mock-ups

The EB welding joints of the HEX to the RT terminal and shunt mainly convey the current. EB welding was chosen because of its: (1) larger welding depth to decrease the current density; (2) narrow heat-affected zone to give least deviation on the copper residual resistance ratio (RRR) value and keep the HTS stacks at a safe temperature during welding.

Two short size copper parts with the features of the real HEX were welded to the EBW mock-up (Fig. 4). Thermaxes were affixed to the right position of the mock-up to monitor the temperature on the HTS stacks. The recorded maximum temperature 171 °C was less than the melting point 183 °C of 63Sn–Pb solder for the stacks soldered to the shunt. The tensile strength of the four samples ranged from 194 to 205 MPa. The metallographical analysis, left photo in Fig. 4, proved that the welding depth 36 mm is larger than the defined value 30 mm, and no void was found in the joint.

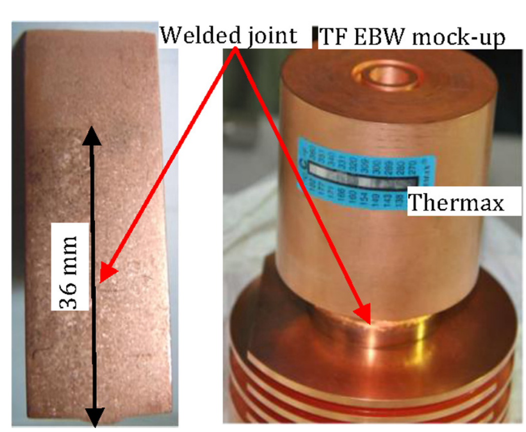

Fig. 4. Tensile and metallography test of EBW joint.