Fusion Engineering and Design 87 (2012) 1–6

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Assessment of thermo-mechanical behavior in CLAM steel first wall structures

Fubin Liu*, Man Yao

School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, Liaoning, China

ARTICLE INFO

Article history:
Received 15 November 2010
Received in revised form 6 August 2011
Accepted 8 August 2011
Available online 14 September 2011

Keywords:
Thermal stress analysis
First wall
ITER
Reduced activation ferritic martensitic

ABSTRACT

The temperature and strain distributions of the mockup with distinct structural material (SS316L or China Low Activation Martensitic steel (CLAM)) in two-dimensional model were calculated and analyzed, based on a high heat flux (HHF) test recently reported with heat flux of 3.2 MW/m^2. The calculated temperature and strain results in the first wall (FW), in which SS316L is as the structural material, showed good agreement with HHF test. By substituting CLAM steel for SS316L the contrast analysis indicates that the thermo-mechanical property for CLAM steel is better than that of SS316 at the same condition. Furthermore, the thermo-mechanical behavior of the FW was analyzed under the condition of normal ITER operation combined effect of plasma heat flux and neutron heating.

1. Introduction

China low activation martensitic steel (CLAM) is a candidate as structural material for plasma facing components, blanket and divertor of future reactors for its negligible irradiation induced swelling even at high doses and its relatively small thermal expansion in comparison to austenitic stainless steel [1,2]. In ITER, the first wall (FW) panels face the plasma directly and are exposed to high heat flux from plasma as well as intense irradiation from high-energy neutrons during the normal operation. Hence, durability of FW materials is one of the most critical issues in ITER.

In the current ITER design, FW material composes of the following three metals: beryllium (Be) armor used as a plasma facing material, Cu-alloy (CuCrZr) layer as a heat sink material, and 316L(N) austenitic stainless steel (SS316LN) as a structural material [3,4]. Investigation of the effects of plasma heating and neutron heating loads is essential for the performance of the FW panel in actual ITER operation conditions.

During the past decade, researchers performed a considerable amount of work on the experimental tests and finite element (FEM) simulations to examine the performances of FW under heat flux and neutron with SS316LN as a structural material [4–19]. Hatano et al. [3] examined the integrity of the HIP bonded interface, fatigue life time, and fracture behavior of the panel. In their test conditions, the average heat flux was 5.0–7.0 MW/m^2 and the duration time was 15 s by ABAQUS code. You and Bolt [4] calculated the temperature and stress distributions for plasma facing materials with heat load of 5.0 MW/m^2 and duration time of 10 s. Cardella et al. [5] calculated and analyzed the temperature and stress of FW under the average heat flux was 0.5 MW/m^2 and neutron load was 1.19 MW/m^3. Dell'Orco et al. [6] presented a thermal–mechanical calculation for FW mock-ups under a heat flux of 0.8 MW/m^2. Recently, Lee et al. [8,9] investigated HIP bonded Be/Cu/SS mock-ups for the FW under high heat flux conditions (1.5 and 2.0 MW/m^2); only surface heat flux load and water cooling were considered. Youchison et al. [18] performed stress analysis for FW by FEM codes. With EUROFER 97 as a structural material, Aktaa et al. [19,20] simulated the temperature distribution, equivalent strain and lifetime behavior.

So far, most previous studies focused on the effect of plasma heating and the heat flux values are usually higher than the ITER design with SS316LN as a structural material [3,4,8,9]. In the present paper, we focus on the thermo-mechanical behavior of CLAM steel as structural material in FW. Firstly, the temperature and strain distributions of the FW of SS316L as the structural material were obtained by the commercial software ANSYS code, in which only the surface heat flux was considered. Secondly, modeling and simulation of temperature and strain distributions of CLAM steel as the structural material have been carried out in order to compare with those of SS316L. Furthermore, the thermo-mechanical behaviors of CLAM steel or SS316L as structural material in FW were evaluated by considering the combined effects of plasma heating and neutron heating under actual ITER operation.

2. Simulation of surface heat flux test and analysis

Since a high heat flux (HHF) test is essential for investigating the thermo-mechanical performance of the FW, the Cu/SS FWQM mock-ups were first tested in the JAEA (Japan Atomic Energy

* Corresponding author. Tel.: +86 411 84707347.
E-mail addresses: liufubin_1216@126.com (L. Fubin), yaoman@dlut.edu.cn (Y. Man).

0920-3796/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.fusengdes.2011.08.004

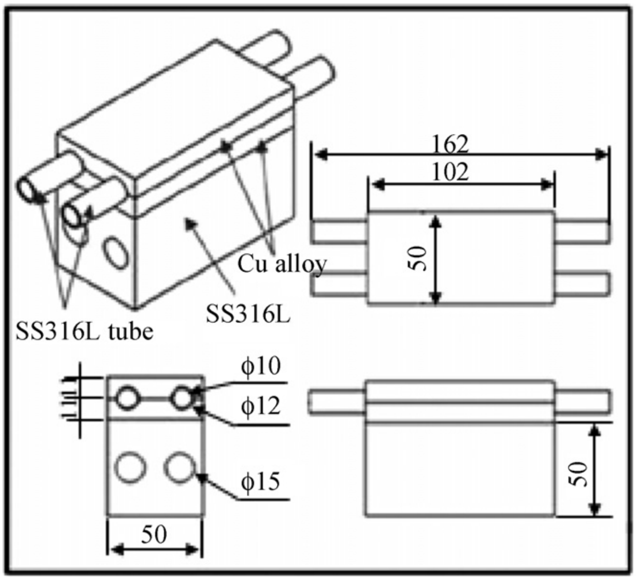

Fig. 1. Schematic of the Cu/SS mock-up.

Table 1
Simulation conditions of surface heat flux test.

Parameters	Value
Heat flux (MW/m^2)	3.2
Coolant velocity (m/s) 10-mm-ID channels/15-mm-ID channels	3.0/1.33
Heat transfer coefficient ($W/(m^2\,K)$)	14,887/6725
Duration heating (s)	30
Initial temperature cooling water (°C)	25

Agency) Electron Beam Irradiation Stand (JEBIS) without the Be layer [8]. The acceleration test was considered in this test by increasing the heat flux up to 3.2 MW/m^2. A higher heat flux shortens the test time, but should be avoided due to the evaporating temperature of the material.

The two-dimensional modeling was used, based on above HHF test. A uniform heat flux was applied on the Cu side, while the temperature and the pressure of the cooling water were 25 °C and 0.1 MPa for mock-up. Schematic of the Cu/SS mock-up for HHF test is shown in Fig. 1. The simulation conditions are summarized in Table 1. Values of most parameters and simulation conditions of model were cited in the literature [8]. The analysis of the 2D F-E model of surface heat flux test consists of 14,438 four-node elements.

The temperature dependence of the material physical properties of Cu-alloy and SS316L were taken from available experimental data, where the parameters are summarized in Tables A1 and A2, respectively. In our simulation, temperature varying values were used.

The calculated temperature and strain distributions of the mockup, at the heat flux loading 3.2 MW/m^2 with duration of 30 s are shown in Fig. 2. The maximum temperature at the front surfaces, at Cu/SS interface and at the inner surface of the SS cooling tubes are 441, 302, and 209 °C, respectively. In this case, the maximum deformation at the front surfaces is 0.236 mm and the maximum strain range at the inner surface of the SS cooling tubes is approx. 0.45%. The calculated temperature and strain results in the FW showed good agreement with the reported results of high heat flux test with Cu-alloy as the heat sink material and SS316L as the structural material [8] (Fig. 3).

Based on the above preliminary analyses, modeling and simulation of temperature and strain distributions of CLAM steel as the structural material have been carried out in order to compare with those of SS316L under the same condition (only the surface heat flux 3.2 MW/m^2). Chemical composition of China low activation martensitic steel (CLAM) and 316L steels are summarized in Tables 2 and 3, respectively. The temperature dependence of the material physical properties of CLAM is taken from available experimental data, where the parameters are summarized in Table A3.

The calculated temperature and strain distributions of the mockup, at the heat flux loading duration of 30 s and under a heat flux condition of 3.2 MW/m^2 are shown in Fig. 4. The maximum temperature of front surfaces, at Cu/CLAM steel interface and at the inner surface of the CLAM steel cooling tubes are 365, 251, and 176 °C, respectively. In this case, the maximum deformation at the front surfaces is 0.191 mm and the maximum strain range at the inner surface of the CLAM steel cooling tubes is approx. 0.38%. The values of both the temperature and strain for the mockup composed of CLAM steel and Cu-alloy are lower than those for the mockup composed of SS316L and Cu-alloy.

The large differences of calculated temperature and strain distributions in the FW have resulted from the differences of thermal conductivity, Poisson's ratio and Young's modulus between SS316L and CLAM steel. The calculated results also indicate that the

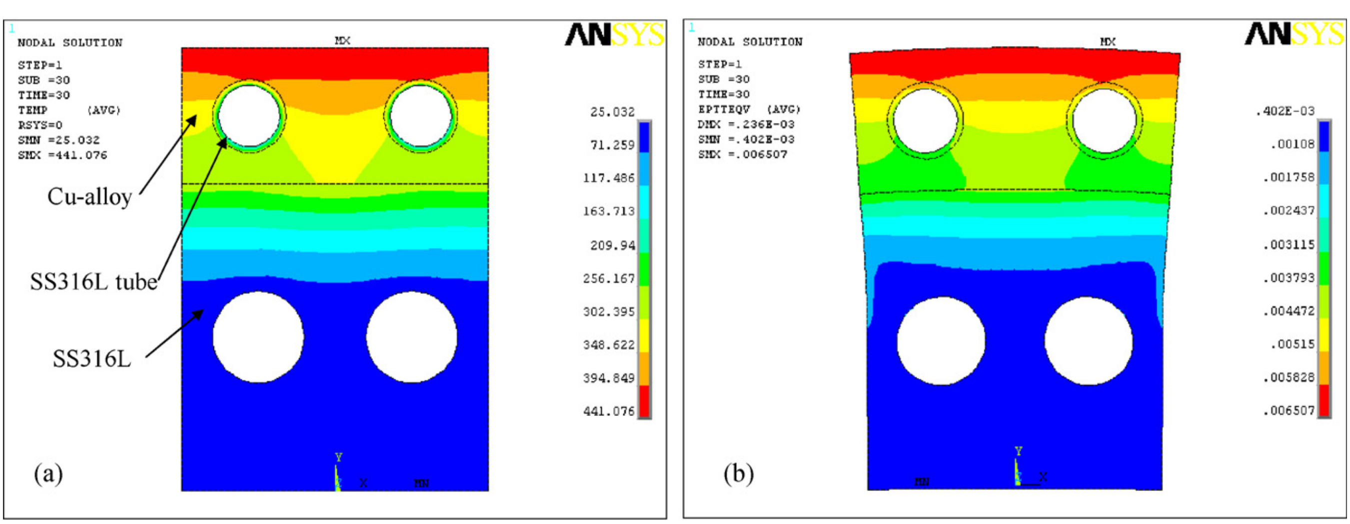

Fig. 2. Temperature (a) and strain (b) distributions for SS316L under heat flux of 3.2 MW/m^2.