Fusion Engineering and Design 135 (2018) 65–73

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Numerical analysis of the manufacturing processes of a mock-up of the ITER NHF First Wall Panel

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ARTICLE INFO

Keywords:
Hiping
First Wall
ITER
Manufacturing
Thermo-Mechanics
Plasticity

ABSTRACT

The objective of ITER is to build a new Tokamak, with the goal of demonstrating the scientific and technical feasibility of fusion power. The First Wall Panels are the inner component of the reactor, built with different materials that must support high heat flux levels inside the vacuum vessel. The manufacturing processes of the First Wall are a complex procedure including bending, hipping and cutting procedures which, in general, lead to residual stresses and distortions of the fabricated component. In this work, the analysis of the thermo-mechanical response of a simplified prototype of the ITER NHF First Wall Panel is presented from the numerical point of view. The experimental procedure within each phase of the whole manufacturing process is described. Residual stresses and distortions have been measured and analyzed. The numerical simulation of the manufacturing process includes the description of the main hypothesis, the applied loads and the boundary conditions assumed at every stage of the process. Special attention is paid to the simulation of machining and cutting by means of an *ad-hoc* element deactivation strategy. The numerical results are compared with the experimental evidence to show the prediction capability and the limitations of the proposed numerical model.

1. Introduction

ITER is an international project involving many research centers, universities and industrial companies from different countries worldwide to develop a new and clean energy source.

The ITER reactor is based on the *Tokamak* concept of magnetic confinement in which the plasma is contained in a doughnut-shaped vacuum vessel (Fig. 1a). The fuel, a mixture of deuterium and tritium (two hydrogen isotopes) is heated to temperatures over 150 million °C forming the plasma. Strong magnetic fields are used to avoid the contact between the plasma and the vessel walls. The Blanket System of ITER is the inner component of the reactor directly exposed to the plasma. The main function of the Blanket System is to provide the main thermal and nuclear shielding to the vacuum vessel or any other reactor component [12]. Depending on their location, the First Wall (FW) panels will be able to sustain two different levels of heating loads referred to as the Normal Heat Flux (NHF – design load up to 1 MW/m^2) and the Enhanced Heat Flux (EHF – design load up to 4.7 MW/m^2).

In order to reduce the eddy currents induced by the electromagnetic loading during ITER operations, the final design of the First Wall panel is cut into a number of longitudinal *fingers* as shown in Fig. 1b. Each one of these fingers is cooled by pressurized water introduced into the cooling system at 70 °C and extracted at 110 °C, approximately.

The First Wall panel is fabricated according to the following manufacturing sequence:

- Drilling operations
- Bending operations
- Machining operations
- Assembly procedures
- Hot Isostatic Pressure (HIP) cycles
- Heat Treatment (HT) and gas quenching
- Cutting operations
- Final Machining operations

The Hot Isostatic Pressure (HIP) cycles are used to join the Copper Chromium Zirconium (CuCrZr) alloy to the Stainless steel (SS) structure and later to the Beryllium (Be) layer of the final arrangement [7,15,19]. These are the most critical phases of the manufacturing route because of their influence on the final distortion and residual stresses accumulated by the component. Several works have been carried out on this issue, specially about the influence over the CuCrZr properties [13,16,4].

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https://doi.org/10.1016/j.fusengdes.2018.07.012
Received 15 December 2017; Received in revised form 26 June 2018; Accepted 15 July 2018

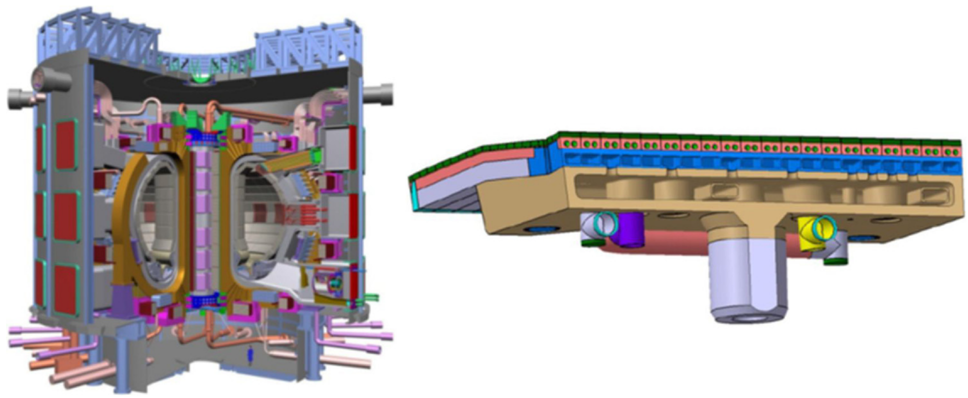

Fig. 1. a) Cross section of the ITER reactor b) Vertical cross section of the First Wall (F4E).

The experimental work presented in this paper has been carried out by *Fundación LEADING INNOVA*. They provided the geometry of the mock-up, as well as the characterization of the manufacturing processes and the corresponding results to support this study.

The features of the ITER reactor and the First Wall, as well as the material properties employed to build the prototype have been provided by Fusion for Energy (F4E), the European agency for the procurement of the FW.

2. Description of the manufacturing process

Due to the geometrical complexity of the real components as well as the experimental and numerical strategy to study the manufacturing processes, the geometry of the First Wall Panel has been simplified [3].

At a first level of simplification, in the so called *semi-prototype,* the actual size has been reduced and many of the functional details have been neglected or simplified. Nevertheless, the main dimensions are kept unchanged as the length of the fingers and their section.

At a further level of simplification, the FW *simple mock-up* has more reduced dimensions, reduced model details and a lower number of manufacturing phases: the bending operation and the final HIP cycle used to add the Beryllium layer have not been considered.

Fig. 2 shows a view of the simple mock-up and the location of the different materials used. The initial configuration is a parallelepiped-like volume, 4344 mm wide and 718 mm long. The thickness varies between 61 mm and 77 mm. The diameter of the holes is 26 mm.

The manufacturing phases to fabricate the mock-up for the First wall panel are the following:

- Machining of individual pieces
- Assembling and sealing operations
- HIP cycle for SS/CuCrZr joining

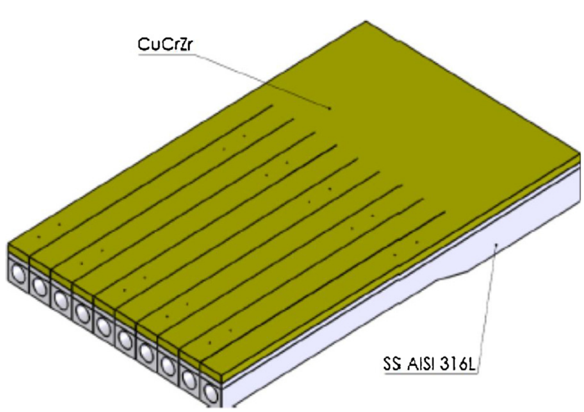

Fig. 2. Simple mock-up geometry and materials.

- Heat treatment (HT)
- Machining operation: top, lateral and back parts
- Fingers cutting: ten fingers 41 mm wide each.
- Final machining: front and back side

The objective of this paper is to study the influence of the different manufacturing stages required for the fabrication of the FW simple mock-up, and compare the numerical results obtained with the experimental evidence. To achieve such objective the component has been fabricated and both residual stresses and distortions have been measured at the end of the HIP and HT phases (once extracted from the HIP chamber) and after the machining/cutting operations at the end of the manufacturing process.

Some authors have presented a numerical approach to the HIP cycle [21,22] to support the experimental work. In this study, all the manufacturing phases have been simulated numerically by means of in-house Finite Element (FE) software adapted for this purpose. The hypothesis as well as the constitutive model adopted for the material characterization is presented in Section 4.3. Finally, Section 4.5 shows the comparison between the experimental evidence and the numerical predictions.

2.1. The HIP cycle

The objective of the HIP cycle is the joint between the stainless steel and CuCrZr alloy by diffusion bonding in the interphase of both materials. This is achieved by applying simultaneously the isotropic pressure and a high temperature field according to a prescribed loading function. In a first phase, both temperature and pressure are increased simultaneously until their maximum values are reached; these values are 1040 °C and 140 MPa for the temperature field and the isostatic pressure, respectively. The temperature and the pressure are kept constant during the second interval of 120 min.

Finally, the applied pressure and temperature decrease to reach the initial conditions. The total duration of the HIP cycle is about 320 min. At the end of the HIP cycle, the joining between the SS casing and the CuCrZr alloy by diffusion bonding is achieved.

2.2. The heat treatment process

After the HIP cycle, the mock-up goes through the Heat Treatment (HT) process. The objective of this treatment is to induce the solution annealing condition to improve both mechanical and thermal properties of the CuCrZr [5].

The HT process consists of a furnace chamber where the mock-up is placed. The temperature is increased to a peak of 1020 °C ± 10 °C and kept constant during 60 min ± 5 min. Finally, a rapid cooling phase is enforced by gas quenching using nitrogen at 10 bar. The peak temperature is slightly higher than 980 °C has been prescribed to improve