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Damage and fatigue crack growth of Eurofer steel first wall mock-up under cyclic heat flux loads. Part 1: Electron beam irradiation tests

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HIGHLIGHTS

- Clear evidence of microscopic damage and crack formation at the notch root in the early stage of the fatigue loading (50–100 load cycles).
- Propagation of fatigue crack at the notch root in the course of subsequent cyclic heat-flux loading followed by saturation after roughly 600 load cycles.
- No sign of damage on the notch-free surface up to 800 load cycles.
- No obvious effect of the pulse time duration on the crack extension.
- Slight change in the grain microstructure due to the formation of sub-grain boundaries by plastic deformation.

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ABSTRACT

Recently, the idea of bare steel first wall (FW) is drawing attention, where the surface of the steel is to be directly exposed to high heat flux loads. Hence, the thermo-mechanical impacts on the bare steel FW will be different from those of the tungsten-coated one. There are several previous works on the thermal fatigue tests of bare steel FW made of austenitic steel with regard to the ITER application. In the case of reduced-activation steel Eurofer97, a candidate structural material for the DEMO FW, there is no report on high heat flux tests yet. The aim of the present study is to investigate the thermal fatigue behavior of the Eurofer-based bare steel FW under cyclic heat flux loads relevant to DEMO operation. To this end, we conducted a series of electron beam irradiation tests with heat flux load of 3.5 MW/m^2 on water-cooled mock-ups with an engraved thin notch on the surface. It was found that the notch root region exhibited a marked development of damage and fatigue cracks whereas the notch-free surface manifested no sign of crack formation up to 800 load cycles. Results of extensive microscopic investigation are reported.

1. Introduction

The first wall (FW) is an in-vessel component constituting the plasma-facing part of the shield blanket module in a fusion reactor [1]. The FW stands in direct contact with the edge plasma through a boundary layer and is to be subjected to a variety of plasma–wall interactions. Thus, the FW is supposed to withstand the intense flux of energetic particles (hydrogen isotopes and neutrons) and heat loads [2]. The reduced activation steel Eurofer97 is currently considered as the main structural material for the FW (inclusive of the heat sink) of the DEMO reactor [3]. Eurofer97 is a ferritic/martensitic 9Cr steel with W (1%), Mn (0.6%), V (0.2%) and Ta (0.1%) as major alloying elements [4].

According to the hitherto developed design concepts of DEMO, the surface of the FW shall be covered with a thin tungsten coating in order to reduce the surface erosion which causes plasma contamination [3]. It is noted that tungsten, as a high-Z metal, is known to exhibit an extremely low sputtering yield under hydrogen particle bombardment [5]. Thus, armoring the FW with tungsten coating has been the conventional approach.

Recently, the idea of bare steel FW is drawing attention motivating several research activities to study the physical feasibility in terms of sputtering and hydrogen retention behavior [6–8]. As the name suggests, the surface of the bare steel FW is not coated but remains bare being directly exposed to high heat flux loads as well as sputtering erosion. Hence, the surface of the bare steel FW will undergo a different damage process than the tungsten-coated case. In the present study, we focus on the thermo-mechanical impact of heat flux loads on the bare steel FW owing to direct exposure.

While the heat flux loads to be imposed on the FW of the DEMO reactor is not precisely defined yet, the ITER design delivers

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reference loading parameters that might be relevant to the DEMO FW as well. The ITER FW panels are designed to accommodate 1–2 MW/m^2 in the normal heat flux regime and 4.7 MW/m^2 in the enhanced heat flux regime including the plasma ramp-up phase [9]. According to the Power Plant Design Studies [3], the heat flux loads expected for the DEMO FW will not substantially differ from the ITER thermal loads.

In the case of pulsed plasma operation, the FW experiences a cyclic fluctuation of temperature and thermal stress. If the highest loaded surface region of the FW undergoes plastic yield and cyclic plastic straining, plastic fatigue (low cycle fatigue) or ratchetting will occur on the FW surface layer [10]. The accumulated plastic damage may cause crack initiation and growth leading to global failure. The fatigue-cracking becomes even more likely in the presence of a sharp notch. In the literature, there are a couple of previous reports on the thermal fatigue testing of bare steel FW components carried out by Merola et al. [11,12]. In their thermal fatigue test campaign, the FW mockup was made of austenitic 316L steel and water-cooled during cyclic infrared light heating (1 MW/m^2). This experiment showed a clear evidence of fatigue cracking in the surface layer of the 316L steel (including notch root). To the author's knowledge, there is no comparable report in the literature for the FW of Eurofer97 steel yet.

In this work (part I) we report the first results of cyclic high-heat-flux loading tests on a bare steel FW mock-up made of Eurofer97. The aim of this campaign is to investigate the thermal fatigue behavior of the Eurofer-based bare steel FW under a DEMO-relevant load condition with emphasis on the damage evolution.

To this end, we conducted a series of electron beam irradiation tests on two water-cooled mock-ups and examined the microscopic damage features. In the following companion article (part II), the results of computational analysis will be presented in terms of the damage mechanics behavior of the FW mock-up addressed in part I.

2. Design and fabrication of FW mock-ups

For this study, we fabricated two pieces of dedicated actively cooled bare steel FW mock-up using Eurofer97. Photographs of the test mock-up are presented in Fig. 1 (a: whole body with cooling tube attachments, b: cross section showing the cooling channel and a notch groove). The dimension of the geometry is illustrated in Fig. 2 (a: whole cross section, b: notch). The mock-up was designed with a wide rectangular cooling channel to produce temperature fields as uniform as possible. A line of thin notch was grooved on the surface to investigate notch effects in addition to the loading on the flat surface. The notch had a depth of 2 mm and width of 1 mm (radius of filet: 0.5 mm).

3. Thermal fatigue tests

The high-heat-flux thermal fatigue tests were conducted using the electron beam irradiation facility JUDITH 1 at Forschungszentrum Jülich GmbH. The technical data of the facility are found in [13]. The geometry and the array of the loading zones on the surface are illustrated schematically in Fig. 3. Each loading zone was defined as a rectangular area with a size of 30 mm × 10 mm and placed along the notch groove with a distance of 20 mm. This loading scheme was an outcome of the practical compromise between the economy and the accuracy of the electron irradiation tests. Since the electron beam scans the loading area with a very high frequency of 100 kHz, the heat flux loads can be regarded as uniform. The water coolant had ambient temperature and was circulated with a flow speed of 4 m/s and pressure of 3 MPa.

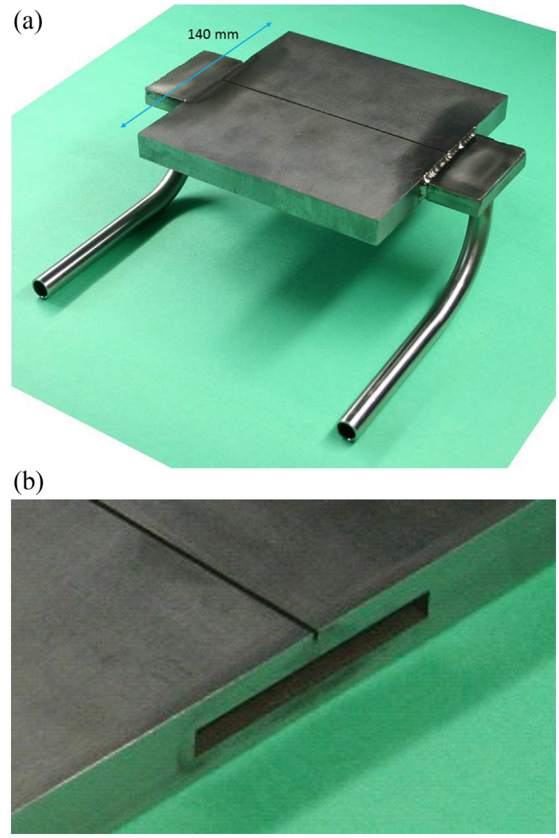

Fig. 1. Water-cooled bare steel test mock-up made of Eurofer97 steel. (a) Whole body with cooling tube attachments and (b) cross section showing the cooling channel and a notch groove.

The applied heat flux load was 3.5 MW/m^2. The value of this heat flux was derived from a finite element analysis and determined in such a way that the maximum surface temperature approaches the upper temperature limit allowed for Eurofer97 steel. This limit temperature is approximately 550 °C [4].

It should be noted that the applied heat flux load (3.5 MW/m^2) is by factor 3 higher than the surface heat load of the DEMO first wall under stationary condition (0.6–1 MW/m^2). Neutron wall loading is also foreseen which would cause additional thermal load to the first wall (2.5 MW/m^2) [3]. Thus, the presently assumed heat flux load may be considered as a potential upper bound heat load for the DEMO first wall. The upper limit surface heat flux load also needs

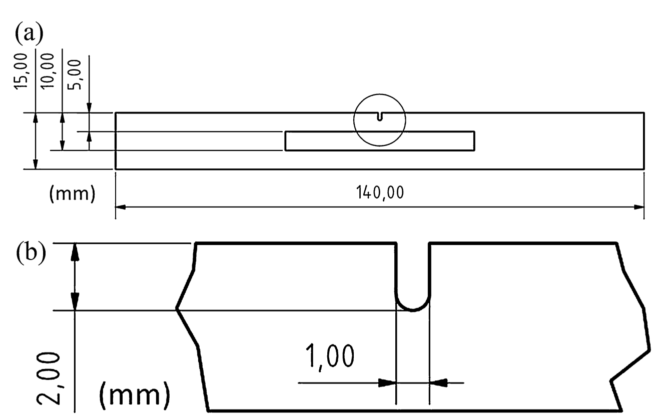

Fig. 2. Dimension of the test mock-up geometry. (a) Whole cross section and (b) notch.