Fusion Engineering and Design 89 (2014) 294–301

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Damage and fatigue crack growth of Eurofer steel first wall mock-up under cyclic heat flux loads. Part 2: Finite element analysis of damage evolution

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HIGHLIGHTS

- The surface heat flux load of 3.5 MW/m^2 produced substantial stresses and inelastic strains in the heat-loaded surface region, especially at the notch root.
- The notch root exhibited a typical notch effect such as stress concentration and localized inelastic yield leading to a preferred damage development.
- The predicted damage evolution feature agrees well with the experimental observation.
- The smooth surface also experiences considerable stresses and inelastic strains. However, the stress intensity and the amount of inelastic deformation are not high enough to cause any serious damage.
- The level of maximum inelastic strain is higher at the notch root than at the smooth surface. On the other hand, the amplitude of inelastic strain variation is comparable at both positions.
- The amount of inelastic deformation is significantly affected by the length of pulse duration time indicating the important role of creep.

ARTICLE INFO

Article history:
Received 17 September 2013
Received in revised form 20 January 2014
Accepted 29 January 2014
Available online 12 March 2014

Keywords:
Eurofer97 steel
First wall
High-heat-flux loads
Thermal fatigue
Damage
Finite element analysis

ABSTRACT

In the preceding companion article (part 1), the experimental results of the high-heat-flux (3.5 MW/m^2) fatigue tests of a Eurofer bare steel first wall mock-up was presented. The aim was to investigate the damage evolution and crack initiation feature. The mock-up used there was a simplified model having only basic and generic structural feature of an actively cooled steel FW component for DEMO reactor. In that study, it was found that microscopic damage was formed at the notch root already in the early stage of the fatigue loading. On the contrary, the heat-loaded smooth surface exhibited no damage up to 800 load cycles. In this paper, the high-heat-flux fatigue behavior is investigated with a finite element analysis to provide a theoretical interpretation. The thermal fatigue test was simulated using the coupled damage-viscoplastic constitutive model developed by Aktaa. The stresses, inelastic deformation and damage evolution at the notch groove and at the smooth surface are compared. The different damage behaviors at the notch and the surface are explained in terms of hydrostatic stress and inelastic strain fields. The effect of heating pulse length on inelastic deformation is also addressed. It is demonstrated that the predicted damage evolution feature agrees well with the experimental observation qualitatively.

1. Introduction

The first wall (FW) is a plasma-facing component covering the shield blanket module in the vacuum vessel of a fusion reactor [1]. The FW is supposed to fulfill two-fold functions: on the one hand, it should protect the breeding blanket from the intense bombardment of energetic ions and neutrals. On the other hand, the FW should protect the core plasma as well from contamination (and thus radiation cooling) to be caused by the atomic sputtering of the wall surface [2]. The conventional design of the FW for the DEMO reactor is based on an actively cooled bi-material system consisting of a refractory armor (mostly coating) and steel heat sink substrate [3].

Reduced activation steel Eurofer97 is considered as the structural material for the FW as well as the breeding blanket of the DEMO reactor. Eurofer97 is a ferritic/martensitic (f/m) steel with alloying elements of 9% Cr, 1% W, 0.6% Mn, 0.2% V and 0.1% Ta [4]. Tungsten is currently the most preferred armor material owing to

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http://dx.doi.org/10.1016/j.fusengdes.2014.01.083
0920-3796/

many beneficial physical and thermal properties. However, tungsten is vulnerable to thermal shock loads such as ELM transients exhibiting severe damage and cracking on the armor surface, when exposed to the heat flux below the ductile-to-brittle transition temperature [5].

Recently, the idea of bare steel FW is drawing attention [6]. In this concept, the surface of the steel FW is not coated by protecting armor at all, but exposed directly to the boundary layer of edge plasma. Thus, the bare steel FW concept allows a simplified design and manufacturing. On the other hand, the reduction in the atomic mass of the surface material (from W to Fe) will surely enhance the sputtering erosion of the wall. But, this concern may be mitigated, as the selective sputtering of lighter atoms (e.g. Fe or Cr) will change the chemical composition in the near-surface layer causing enrichment of heavier W and thus decreasing the sputtering rate again.

From the structural design point of view, the bare steel FW concept raises another critical issue, namely, thermal fatigue. This issue is particularly relevant to DEMO, provided that the reactor has to be operated in pulsed modes. In this circumstance, the FW will be subjected to cyclic heat flux loads experiencing periodic variation of temperature, stresses and strains. The combination of temperature and stress fluctuations can initiate fatigue failure.

It is noted that the bare steel FW is as a whole a structural part subject to the structural design criteria of design codes. The thermal fatigue damage and cracking of wall surface are likely to affect the structural integrity of a FW segment leading to a premature failure. This situation would be less critical in the case of a tungsten-armored FW, since the tungsten armor is not classified as structural part not being bound to fulfill structural design criteria. Furthermore, tungsten armor is known to withstand heat flux loads up to 18–20 MW/m^2 without severe surface damage nor loss of structural integrity at least up to 1000 cycles [7].

On the contrary, the surface damage and cracking of bare steel FW due to direct exposure to heat flux loads may provoke serious reliability concern. The impact of direct exposure to high heat flux loads on the thermal fatigue behavior of bare steel FW was extensively investigated for austenitic steels (e.g. SS316L) [8,9], but there is no corresponding report for f/m steels like Eurofer97. Since f/m steels are less ductile than austenitic steels, it is expected that a bare f/m steel FW would undergo a different fatigue damage evolution than the austenitic ones.

In the preceding companion article (part 1) the experimental results of high-heat-flux fatigue tests conducted on a Eurofer97 bare steel FW mock-up was presented. The mock-up used there was a simplified model having only basic and generic structural feature of an actively cooled FW component. In that study, cyclic electron beam irradiation tests were carried out on the water-cooled mock-ups under the heat load of 3.5 MW/m^2.

In order to accelerate fatigue damage, the surface of the mock-ups was machined with a thin notch groove. Fig. 1 shows the photograph of the mock-up together with the cross sectional view and the heat-loaded area. The notch groove was machined using wire erosion method paying special attention to avoiding any damage at the tip. As shown in the SEM (scanning electron microscope) micrograph of the notch groove in Fig. 2, no crack was present in the initial state before the high-heat-flux fatigue test. After the cyclic thermal loading, however, a number of microscopic fine cracks were formed at the notch root already in the early stage of the fatigue loading between 50 and 100 load cycles (see Figs. 3 and 4). Subsequently, a primary crack grew stably further as the number of load cycles increased. In this circumstance, the failure behavior entered into the fracture mechanics regime. On the contrary, the notch-free smooth surface exhibited no evidence of overall damage or cracking up to 800 load cycles [10].

The aim of this paper (part 2) is to provide a theoretical interpretation for understanding the damage features observed in the preceding experiment. To this end, the high-heat-flux test of the companion paper is simulated by means of finite element analysis (FEA) using a rigorous constitutive model. For modeling the damage and the crack nucleation observed in the tests, one needs to incorporate continuum damage mechanics into a cyclic-viscoplastic constitutive model. Recently, Aktaa extended the conventional Chaboche-type constitutive equations by combining a damage evolution law formulated by him [11–13]. This model was proved to be

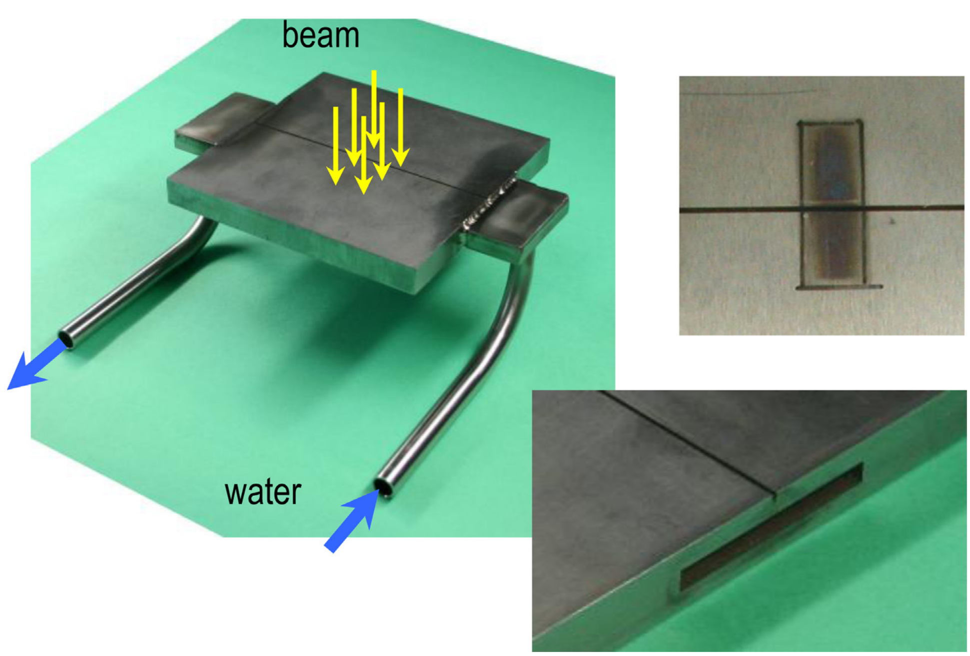

Fig. 1. Water-cooled Eurofer steel first wall mock-up used for the thermal fatigue tests in the companion paper, part 1 (width: 140 mm, height: 15 mm). The cross sectional view and the heat-loaded area are also shown.