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Fracture mechanical analysis of tungsten armor failure of a water-cooled divertor target

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HIGHLIGHTS

- The FEM-based VCE method and XFEM were employed for computing K_I (or J-integral) and predicting progressive cracking, respectively.
- The most probable pattern of crack formation is radial cracking in the tungsten armor block.
- The most probable site of cracking is the upper interfacial region of the tungsten armor block adjacent to the top position of the copper interlayer.
- The initiation of a major crack becomes likely, only when the strength of tungsten armor block is significantly reduced from its original strength.

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ABSTRACT

The inherent brittleness of tungsten at low temperature and the embrittlement by neutron irradiation are its most critical weaknesses for fusion applications. In the current design of the ITER and DEMO divertor, the high heat flux loads during the operation impose a strong constraint on the structure–mechanical performance of the divertor. Thus, the combination of brittleness and the thermally induced stress fields due to the high heat flux loads raises a serious reliability issue in terms of the structural integrity of tungsten armor. In this study, quantitative estimates of the vulnerability of the tungsten monoblock armor cracking under stationary high heat flux loads are presented. A comparative fracture mechanical investigation has been carried out by means of two different types of computational approaches, namely, the extended finite element method (XFEM) and the finite element method (FEM)-based virtual crack tip extension (VCE) method. The fracture analysis indicates that the most probable pattern of crack formation is radial cracking in the tungsten armor starting from the interface to tube and the most probable site of cracking is the upper interfacial region of the tungsten armor adjacent to the top position of the copper interlayer. The strength threshold for crack initiation and the high heat flux load threshold for crack propagation are evaluated based on XFEM simulations and computations of stress intensity factors and J-integrals.

1. Introduction

The divertor is an important in-vessel plasma-facing component (PFC) of a fusion reactor. The essential function of the divertor is to exhaust the edge plasma in the scrape-off layer in order for helium ash and other impurities to be continuously removed from the burning plasma core. The plasma exhaust is achieved by intense particle bombardment onto the divertor target plate generating a high heat flux load into the target surface [1]. The maximum stationary heat flux load for the ITER divertor target reaches up to 10 MW/m^2, and slow thermal transient loads up to 20 MW/m^2 are expected [2]. In the case of the DEMO divertor, the range of possible heat flux load may be even larger. Under such high heat flux loads, the divertor target component (a bi-material joint structure) is subjected to high thermal stresses. Thus, the high heat flux loads impose a strong constraint on the structure–mechanical performance of the divertor.

In the current design concept for the DEMO as well as the ITER divertor, the material for the plasma-facing target armor is tungsten. This choice is owing to the advantageous properties of tungsten such as an extremely low sputtering yield, the highest melting point of metallic materials, an extremely low tritium solubility and a good thermal conductivity [3,4]. On the other hand, the inherent brittleness of tungsten at low temperature and the

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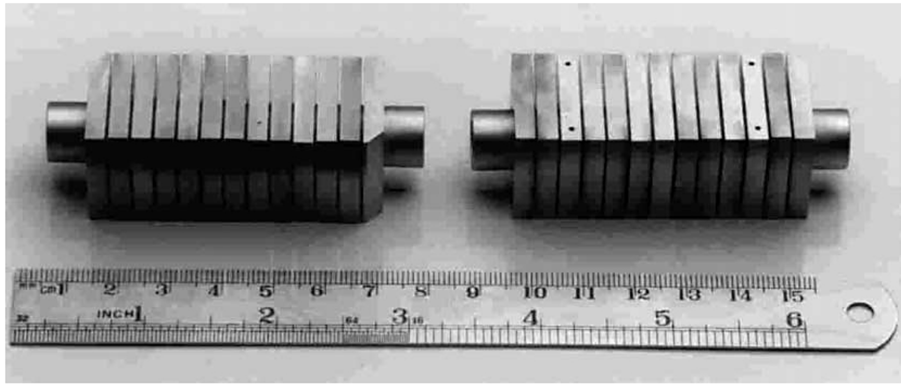

Fig. 1. Picture of representative mock-ups with 13 tungsten blocks [12].

embrittlement by neutron irradiation are the most critical weaknesses, in particular, when tungsten is considered as a structural material of a pressurized component [5]. The brittleness of tungsten should be a critical issue even for the functional application as an armor, if the operation temperature is below the ductile-to-brittle transition temperature (DBTT). This is the case in a water-cooled tungsten monoblock divertor. The DBTT of a commercial tungsten material ranges between 400 °C and 700 °C depending on the loading modes [6]. This means that most part of the tungsten armor in the water-cooled monoblock target will remain below the DBTT during typical high heat flux loadings. Furthermore, one has to consider the irradiation embrittlement effect in addition. Thus, the combination of brittleness and the thermally induced stress fields due to the high heat flux loads raises a serious reliability issue in terms of the structural integrity of tungsten armor.

In the literature one finds few previous works dealing with this issue. One relevant paper is the finite element method (FEM)-based probabilistic failure risk analysis of the tungsten armor in a water-cooled divertor target published by You and Komarova [7]. They used the weakest-link failure theory expressed by the Weibull statistics and calculated the impact of embrittlement on the failure risk probability of tungsten armor considering four different cracking criteria based on linear elastic fracture mechanics. Another related work [8] is the crack loading analysis of the bond interface between a tungsten flat tile and a copper heat sink in a water-cooled target model. Blanchard and Martin studied the fracture and creep behavior of an all-tungsten divertor for ARIES [9]. However, there is no previous report to be found in the literature dedicated to a rigorous fracture analysis of tungsten armor apart from these.

The aim of this study is to deliver quantitative estimates of the vulnerability of a tungsten monoblock armor to cracking under stationary high heat flux loads. To this end, a comparative fracture mechanical investigation has been carried out by means of two different types of computational approaches, namely, the extended finite element method (XFEM) and the FEM-based virtual crack tip extension (VCE) method. In the VCE method, the crack tip loading is described in terms of the stress intensity factor (SIF) or the J-integral. The results of a comprehensive parametric study obtained from both simulation methods are presented. In total, nine different load cases are considered as a combination of three different heat flux loads and three different coolant temperatures. The impact of the temperature level and the temperature gradient resulting from the different loading cases on crack initiation is discussed.

It is noted that the present study is not necessarily limited to specific target geometry (say, the ITER divertor), but rather devoted to investigation of generic failure features of water-cooled tungsten monoblock target under DEMO-relevant operation conditions. The geometry and dimension of the present monoblock model was taken from the optimized divertor target design of the ITER-like target concept obtained in a previous EFDA power plant Design Assessment Studies carried out in 2013 [10]. As we have no specified boundary conditions (e.g. constraint) yet for DEMO divertor, we assumed rather generic boundary conditions. The thermal loading conditions and thermohydraulic cooling conditions considered here are our best estimates for DEMO divertor operation conditions at the current stage.

2. FE model

2.1. Geometry, FE mesh and materials

The monoblock type divertor target model has already been applied to the water-cooled divertor target of ITER. Furthermore, it was also considered for the water-cooled divertor target of a fusion power plant in the framework of the Power Plant Conceptual Study (model A: WCLL) [11]. The monoblock target consists of a number of small rectangular tungsten blocks which are connected by a long cooling tube of high conductivity metal (e.g. copper alloy) running through the central region of each block, see Fig. 1. Two neighboring blocks are separated by a thin gap (~0.3 mm). The deposited heat is transported from the surface to the cooling

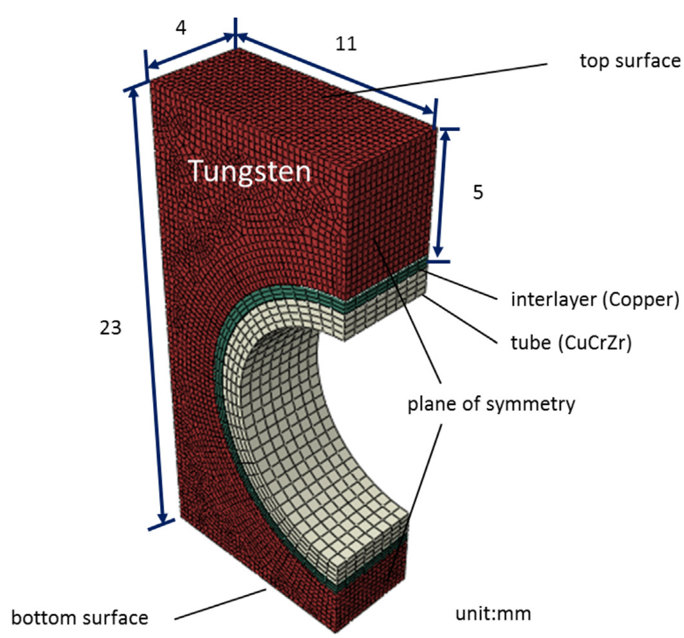

Fig. 2. The FE mesh of the monoblock divertor model. Due to symmetry only one half of the structure was considered.