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Experimental and computational study of damage behavior of tungsten under high energy electron beam irradiation

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ABSTRACT

In this work, damage behavior of tungsten under high heat flux loads was investigated both numerically and experimentally assuming a single heat pulse with duration of 0.5 s. Finite element simulations revealed that the thermal steady state was reached within several milliseconds after the onset of a heat flux pulse and tensile residual stress was produced during cooling providing the driving force for crack growth. The crack initiation and growth simulations and *J*-integral calculation at crack tips delivered consistent results on cracking mechanism. Electron beam irradiation tests on tungsten samples were performed, which confirmed the predicted damage behavior.

1. Introduction

Owing to unique combination of outstanding physical properties, tungsten has been preferably deployed for various applications in cutting edge technology sectors. Tungsten possesses the highest melting point (3422 °C), high thermal conductivity (173 W/mK at room temperature), modest thermal expansion (4.5 μm/mK), high elastic modulus (410 GPa), extremely low sputtering rate and negligible hydrogen solubility [1]. Prominent application examples include, for instance, the armor of plasma-facing components in thermonuclear reactors [2], anode of X-ray tubes [3] and nozzle of rocket propulsion engines [4], among others. A common operational characteristic of these applications is that tungsten is exposed to extreme loading conditions, in particular, severe thermal shock loads. The tungsten materials of the three aforementioned components are repeatedly subjected to transient high heat flux loads within a short pulse duration time during normal or off-normal operation scenarios. Non-uniform fluctuation of temperature is likely to produce high thermal stress that may possibly lead to structural or functional failure of the components [5].

Tungsten behaves in a brittle manner below its ductile-to-brittle transition temperature (DBTT). Thus, tungsten can be vulnerable to brittle cracking, when it is cooled to low temperatures after the thermal shocks. This means that the base temperature of a tungsten component has a direct impact on the fracture behavior of tungsten under thermal shock, which is confirmed by the thermal shock tests [6–9]. DBTT of tungsten ranges between 400 °C and 700 °C, e.g. depending on loading rate [10]. Fracture toughness, which is a measure of resistance to fracture, is found to be smaller at lower temperatures in the

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Nomenclature

d	length of the precrack
J_c	critical value of J-integral
P	power density of the electron beam
P_{avg}	average power density in the loaded area
r	distance from the center of the loaded area
R	radius of the loaded area
σ_{rr}, σ_{zz} and $\sigma_{\varphi\varphi}$	stresses in radial, axial and hoop directions
ε_{rr}, ε_{zz} and $\varepsilon_{\varphi\varphi}$	plastic strains in radial, axial and hoop directions
z	depth

fracture mechanical tests of tungsten [10,11]. The question raises as how to predict cracking patterns as we observe in the thermal shock tests using the data obtained in the fracture mechanical tests.

The failure process in a tungsten component under a single thermal shock load is controlled by the stress development. In the case of extreme high heat flux loads, the situation becomes more complicated due to thermal excursion in the surface layer followed by plastic flow of the softened material in this layer. During heating stage compressive thermal stress is produced in the surface layer, as thermal expansion is constrained by the colder part. On the other hand, cracking can occur only in a tensile stress state. Therefore, the experimentally observed surface cracking patterns indicate the presence of strong tensile stress developing during cooling stage. This circumstance can come about only through inelastic effects, which poses the second important question as to how plastic yield is related to evolution of tensile residual stress that provides driving force for cracking.

In this paper, these two questions are treated on the basis of computational and experimental simulation of high heat flux thermal shock loading on tungsten. The aim of the present study is twofold: 1. to clarify the underlying mechanism of tungsten cracking under thermal shock, and 2. to elucidate the cracking patterns of tungsten observed in extreme high heat flux operations. To this end, finite element analysis was carried out for assessment of crack tip load and for prediction of crack initiation and growth. Extended finite element method (XFEM) and virtual crack tip extension (VCE) method were employed as major tools. For experimental comparison, electron beam irradiation tests were conducted and the surface damage was characterized. To the author's knowledge, there is no previous fracture mechanics study on this topic. Related studies are found in literature which investigated stationary heat flux loading cases [12,13].

In this work, we considered such thermal loading conditions that are common to both off-normal plasma operation scenarios in a thermonuclear reactor (e.g. vertical displacement events) and electron beam loading conditions in an X-ray tube.

2. Experimental

2.1. Experimental settings

Plasma facing components in future fusion devices will be subjected to intense thermal loads. To investigate these thermal loads experimentally, electron beam facilities (e.g. JUDITH, Jülich, Germany) are used frequently [8]. In X-ray tubes, the tungsten anode is subjected to similar thermal loadings, since X-rays are generated by accelerating high energy electrons onto the anode material. The experimental facility involved in this work (as shown in Fig. 1) is set up at Siemens Healthcare and is used to study the failure of tungsten anodes in X-ray tubes. Tungsten samples used in our experiments were made of rolled tungsten delivered by PLANSEE AG, Austria and its purity is larger than 99.9 wt%. The sample size was 27.5 mm × 27.5 mm × 3 mm. The surface of the samples was polished before the electron beam exposure, and the final polishing was carried out using alkaline colloidal silica suspension (Logitech SF1 Polishing Fluid). The power density distribution of the electron beam at the surface of the samples was measured with an X-ray camera. The power density showed a Gaussian distribution in an oval focal spot, which has diameters of 1223 μm and 271 μm when the power density that less than 10% of the maximum value is neglected. For simplicity, a rectangle of 1223 μm × 271 μm is assumed to be the loaded area. The test positions lie on a circle with a radius of 11.5 mm, and the angle between two neighboring test positions is 17°, see Fig. 1. Numerical simulations have shown that, for an individual test position, the impact resulting from the electron beam exposure of the neighboring test position is negligible. The samples were loaded with single thermal loads of average power densities between 0.374 GW/m^2 and 0.624 GW/m^2. The average power densities were calculated by dividing the total input power rate by the loaded area and multiplying with an absorption coefficient of 0.48. This absorption coefficient is chosen by taking account of the values (0.46 and 0.55) found in literatures [8,14] and the correlation of numerically predicted and measured temperatures in the thermal shock experiments at Siemens Healthcare. The acceleration voltage was 65 kV and the tests were performed at room temperature. After the electron beam loading of 0.5 s, the sample was cooled to room temperature.