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Design options to mitigate deep cracking of tungsten armor

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HIGHLIGHTS

- 3 divertor target design options are proposed to mitigate armor cracking at 20 MW/m^2.
- The risk of crack initiation and propagation is evaluated.
- The prediction agrees with the previous HHF test results.
- All three variants are shown to mitigate deep cracking of tungsten armor.

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ABSTRACT

Recent high heat flux (HHF) tests showed that the tungsten monoblock armor often suffered from deep cracking, when the applied HHF load approached 20 MW/m^2. The deep cracks were initiated at the armor surface and grew toward the cooling tube. The deep cracking seemed not to affect the heat removal capability of tungsten divertor, as most of the cracks were perpendicular to the loading surface. However, the inherently unstable nature of brittle cracking may likely increase the risk of structural failure. In this work, three variants (reduction in width of armor, inverse trapezoid shape in the lower part and castellation) of full-W divertor armor design based on the ITER divertor design are proposed to mitigate deep cracking at 20 MW/m^2. The temperature, stress and strain fields are simulated with finite element method. The possibilities of crack initiation and propagation are evaluated by calculating the low cycle fatigue lifetime and J-integrals, respectively. All three variants can mitigate deep cracking of tungsten armor.

1. Introduction

In late 2013, the ITER Council endorsed the proposal to commence the plasma operation of ITER using the water-cooled full-tungsten (W) divertor target plate. The ITER-like full-W divertor target plate with monoblock design is also currently considered as one of the baseline design concepts for the European DEMO divertor target.

Divertor target plate is a plasma-facing component (PFC) and a high-heat-flux (HHF) component as well, since it shall be exposed to the highest heat flux loads by intense plasma particle flux and radiation on the surface and partially by nuclear heating in the materials. Pulsed operation produces cyclic variation of temperature and thermal stresses. The divertor target plate is supposed to withstand the thermal fatigue loads within the specified component lifetime. In terms of structural design, the structural reliability under HHF fatigue loads is one of the major engineering requirements.

In the last two decades, plenty of experimental HHF fatigue tests have been conducted for the qualification of the W monoblock target technology developed for ITER [1]. The design criteria against HHF fatigue specified for the ITER W monoblock target are: 5000 cycles at 10 MW/m^2 (normal fusion operation) and 300 cycles at 20 MW/m^2 (slow transients). The same criteria are assumed for the European DEMO divertor project [2].

The HHF fatigue tests conducted so far using small or medium scale mock-ups showed that the acceptance criteria specified for the ITER divertor target PFC were indeed a demanding requirement in the case of the slow transient thermal load (20 MW/m^2) whereas the normal load (10 MW/m^2) indicated no serious challenge in terms of fatigue resistance [1]. At 20 MW/m^2 deep cracking (so called self-castellation) occurred frequently in the W armors after a few tens or hundreds of loading cycles. Such deep cracks started at the armor surface and grew vertically often reaching the cooling tube. It seems that a deep crack would not necessarily affect the heat removal capability of a W monoblock PFC before it reaches

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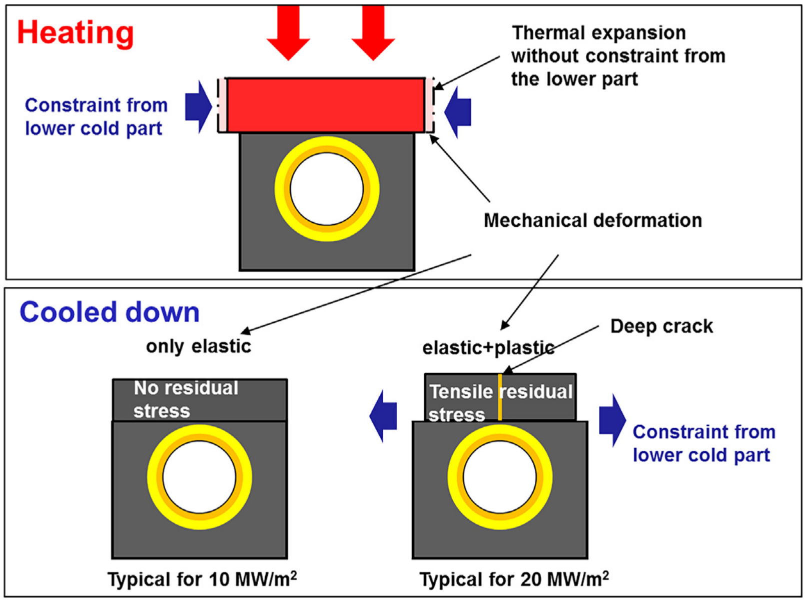

Fig. 1. Illustration of deep cracking mechanism in W armor under excessive heat flux loads.

the interlayer, as the cracking path coincides with the heat conduction path. However, the uncontrolled cracking of a brittle armor may lead to a structural failure of a whole PFC. The most probable scenario of structural failure is that a major crack propagating through the tungsten armor from the surface toward the cooling tube begins to deviate from the original path along the bond interface upon reaching the interlayer. The cracks now bypassing the tube along the interface may possibly cause extensive interfacial debonding leading to excessive overheating by blocking of heat conduction and thus permanent failure or loss of the armor block. Therefore, to reduce or to eliminate the risk of deep cracking is of primary interest for the reliable structural performance of a target plate PFC. There have been intensive efforts to solve this issue mainly by means of metallurgical improvement of W quality.

In this work, a design-based approach is proposed. An extensive comparative design study is presented where three variants of monoblock geometry are evaluated and compared with the ITER baseline model as reference. Focus is placed on the plastic fatigue and fracture.

2. Mechanism of deep cracking in a W armor

For deriving rational design logic to suppress armor cracking, it is necessary to understand the mechanism of the deep cracking. Fig. 1 illustrates the mechanism of deep cracking in a W armor monoblock under the peak heat flux of 20 MW/m^2.

Plastic deformation produced on the loading surface plays a key role. Upon HHF loading the surface region is stressed under compression by restrained thermal expansion due to an extreme temperature gradient. The thermally softened surface layer readily undergoes plastic yield due to compressive stress. Upon shut-off of the heat flux pulse the plastically strained surface layer is pulled back by the elastic recovery of the underlying bulk being cooled while the surface layer begins to be subjected to tensile stresses. This plastically induced tensile residual stress is the origin of driving force to initiate a fatigue crack under repeated plastic straining. If the W armor would possess sufficiently high yield strength, a fatigue crack can hardly form since no plastic deformation takes place already after a few initial load cycles. This is owing to the phenomenon of so called elastic shakedown where an elasto-plastic structural body enters into the linear-elastic regime after having

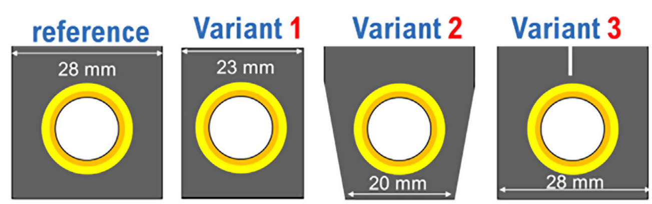

Fig. 2. Design variants to mitigate deep cracking.

undergone plastic deformation under variable loads due to the presence of plastically induced residual stress fields upon which the applied stress fields are superposed. Once the structural body exists in an elastic shakedown state, it does not experience plastic yield anymore under the given applied loads at which initially plastic yield took place in the body. In an actual HHF loading case at 20 MW/m^2, however, the W armor is normally recrystallized from the surface to a several mm depth where the yield stress is strongly reduced by softening due to the recrystallization. In this situation, plastic flow is facilitated leading to larger plastic strain amplitude under the repeated heat flux pulses, thus fostering plastic fatigue crack initiation. Once a macro-crack has been initiated, it can grow further in a brittle manner under the action of the tensile residual stress. The plastically induced tensile residual stress is the major driver of crack initiation as well as growth [3]. This explains also why no surface crack is found under the heat flux load of 10 MW/m^2. Thus, our design logic is based on this finding.

3. PFC design variants

Fig. 2 illustrates the schematic cross sectional view of the three variants of the monoblock type PFC design together with the reference design adopted from the ITER divertor design. The reference design has a block dimension of 28 × 28 × 12 mm^3 (width, height, thickness). Considering the cause of cracking as described above, three design variants were devised based on following rationales:

i) Reducing the width of the armor block

Plastic yield does not appear near the upper corners of the block because the in-plane thermal stress is low and the constraint by the colder mass is weak there. This effect can be