EUROFUSION WPDIV-CP(16) 15315

Muyuan Li et al.

Design options to avoid deep cracking of tungsten armor at 20 MW/m2

Preprint of Paper to be submitted for publication in Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Design options to mitigate deep cracking of tungsten armor

Muyuan Li*, Jeong-Ha You*
Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany

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 field 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.

Keywords: tungsten armor, high heat flux loads, deep cracking, fracture mechanics, PFC design, finite element method

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, a 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, 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. Thus, 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/m².

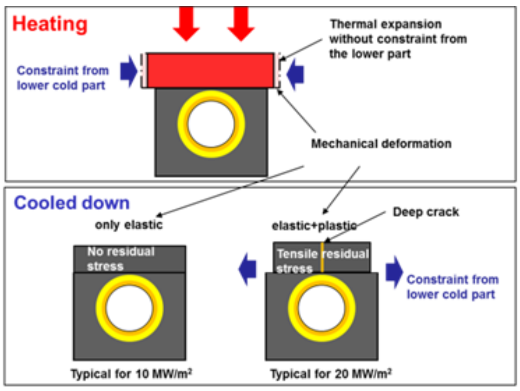

Fig. 1. Illustration of deep cracking mechanism in W armor under excessive heat flux loads.

Plastic deformation produced on the loading surface plays a key role. Upon HHF loading the surface region is stressed under compression by restrained thermal

*Corresponding authors.
Email addresses: muyuan.li@ipp.mpg.de (Muyuan Li), you@ipp.mpg.de (Jeong-Ha You)

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 the material reaches the state of elastic shakedown with no plastic dissipation already after a few initial load cycles. In an actual HHF loading case at 20 MW/m², 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 mm³ (width, height, thickness). Considering the cause of cracking as described above, three design variants were devised based on following rationales:

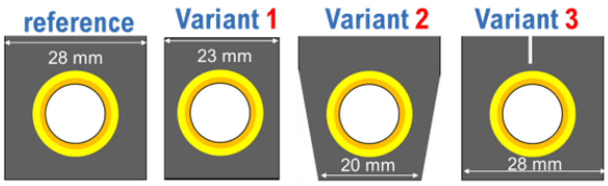

Fig. 2. Design variants to mitigate deep cracking.

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 enhanced by reducing the width so that the overall stress intensity and plastic strains are reduced even in the central region. Furthermore, a reduction of width leads to a lower maximum surface temperature. In this study, the width was reduced from 28 mm to 23 mm.

ii) Applying an inverse trapezoid shape

In this concept, the reduced volume and mass (thus reduced stiffness) in the lower part leads to reduced kinematic restraint on the thermal expansion of the surface layer resulting in reduced compressive thermal stress in the surface region. Plastic yield can be avoided. The trapezoid shaping is made below the sacrificial armor thickness. To ensure mechanical stability during fabrication, a minimum required lateral thickness should be reserved (e.g. 3 mm).

iii) Pre-castellation of the W armor

It is well known that adequate castellation can reduce thermal stress. This can easily be justified by a stress analysis. The in-plane stress component vanishes at the free flank as it is the normal component and does not reach the theoretical maximum value as the width is too small for the stress to fully build up. In this study, a castellation with 0.5 mm gap and 4 mm depth was applied. The gap width of 0.5 mm was chosen in such a way that it is large enough to avoid any contact between the notch flanks during heating. The depth of 4 mm would allow that the notch tip be positioned well away from the tensile stress zones during both heating and cooling phases [3]. Overheating at the leading edges may be an issue.

4. Finite element analysis model

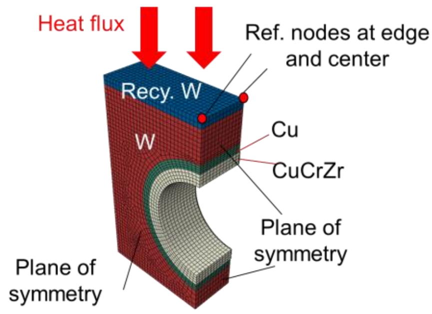

Fig. 3. Mesh of the FE model for the reference case.

Fig. 3 shows the finite element analysis (FEA) model created for the reference design as an example. The material properties used in this work are found in [3]. The entire thermal history (fabrication, preheating to the stand-by stage and continual HHF loading cycles) was taken into account. A DEMO-relevant loading (20 MW/m²) and cooling conditions at strike point (150 °C, 16 m/s and 5 MPa) were applied. The armor thickness from the surface to the Cu interlayer was assumed to be 5 mm for all concepts. The impact of armor thickness can be found elsewhere [4]. It is noted that when the armor thickness (23 mm width) is less than 4 mm, no cyclic plastic yield takes place even at 20 MW/m^2.

5. Results and discussions

5.1. Thermal and stress analysis

Fig. 4 summarizes the FEA results of temperature (1st row), accumulated equivalent plastic strain after 5 load cycles (2nd row) and residual stress during cooling (3rd row) in the W armor. Results are compared between the reference model (1st column) and the three variants with reduced width (2nd), inverse trapezoid shape (3rd) and pre-castellation (4th), respectively.

The design with a reduced size shows a notable drop in maximum temperature at the surface edge by 220 °C compared to the other concepts, but at the mid position, the temperature difference is insignificant. The presence of castellation has no impact on heat conduction. The increase of maximum temperature in variant 2 might enlarge the leading edge impact.

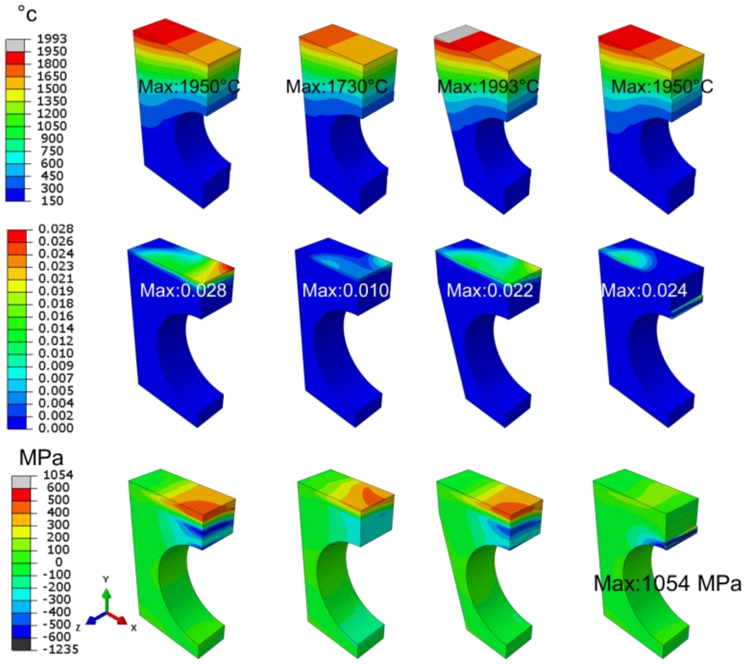

Fig. 4. Comparison of temperature during HHF loading (1st row), accumulated equivalent plastic strain after 5 HHF cycles and residual stress in x direction during cooling after 5 HHF load cycles between the reference design and the three variants. (From left to right: reference model, variant 1, variant 2 and variant 3. Only the W armor block is shown in rows 2 and 3. HHF load: 20 MW/m^2).

Regarding the accumulated plastic strain, the three variants exhibit considerable reduction of plastic strain, in particular, the variant 1 (with reduced width) remains mostly in elastic regime except some local areas of thin surface layer. In the variant 3, small scale plastic yield is found at the castellation notch tip, but the amount of plastic strain concentration is small (< 0.5 %). The effect of strain reduction is less prominent in the variant 2.

Concerning the plastically induced residual stress in the inter-pulse cooling stage, the pre-castellated armor exhibits nearly full relaxation of stress whereas highly localized strong tensile stress concentration (1050 MPa) occurs at the notch tip. The effect of this tensile stress intensity to trigger a cracking might be hampered by the proximate compressive stress field. The variant 2 (with reduced width) also exhibits significant stress reduction but the surface stress is not so much affected.

5.2. Plastic fatigue analysis: Crack initiation

In Table 1 are listed the calculated equivalent plastic strain range in % and low cycle fatigue (LCF) lifetime at 20 MW/m² estimated in the 5th HHF load cycle at the center and the edge positions, respectively, on the mid-line of the armor top surface (see Fig. 3). The LCF lifetime estimation was made in a conservative way that is, plastic deformation was assumed to be generated at room temperature and the fatigue life was evaluated using the LCF data of W measured at room temperature. This assumption leads to an underestimation of LCF life due to the brittleness at room temperature. However, the comparison of the results still holds qualitative validity, since the temperature values at the reference nodes are comparable between the design concepts.

The comparison of the assessed LCF life highlights the structure mechanical benefit of the variant 1 and 3 dramatically. In spite of the conservative assumption mentioned above, the LCF life of the variant 1 at 20 MW/m² is five times higher than the ITER specification (300 cycles). The risk of deep cracking for the variant 1 should be quite low since the driving force for fatigue crack extension is much lower than the reference model as will be discussed later. This prediction is in line with the previous HHF test results [5]. The strongest effect is found in the variant 3 where the LCF life at the notch tip should exceed 36,000 load cycles. Thus, at least in terms of LCF life, the variant 3 is proved to be most attractive. At the free surface edge, the effect looks less prominent due to the local stress and strain concentration.

Table 1. Calculated equivalent plastic strain range (%) and corresponding LCF life* at 20 MW/m² in the 5th load cycle estimated at the center and the edge positions on the mid-line of the armor top surface (see Fig. 3).

	Ref.	Var. 1	Var. 2	Var. 3
Edge	0.247 (1)	0.084 (37)	0.193 (2)	0.110+ (15)
Center	0.176 (3)	0.027 (1611)	0.105 (18)	0.0107++ (36293)

*The lifetime was assessed using the LCF data of tungsten at room temperature which yields conservative estimates.
+ Maximum value at the top surface for Var.3.
++ Maximum value at cast. tip for Var. 3.

5.3. Fracture mechanical analysis: Crack growth

Fig. 5 shows the evolution of J-integral (energy for crack tip extension) as a function of 5 different crack lengths at 20 MW/m^2. The crack was assumed to start at the center of the armor surface as most experimental observations showed. The plots show the evolution of the driving force for crack growth in the variant 1 and 2 and the reference model at two axial positions (left: symmetry plane edge, right: free surface edge). The comparison clearly demonstrates that the crack initiated in the variant 1 would readily lose the sufficient driving force once it has reached the depth of 1.5 mm and stop to further grow. On the contrary, the crack tip load in the variant 2 was not much reduced compared to the reference model.

Fig. 6 shows the evolution of J-integral at the notch root cracks in the castellated W armor at four distinct stages of thermal history (fabrication, preheating, HHF loading at 20 MW/m², cooling down). Plotted are the J-integral values of two types of notch root crack (C1: vertical, C2: horizontal) at two different axial positions (left: symmetry mid plane, right: free surface edge). It is found that the J-integral values are lower than the toughness of a rolled W material except the initial as-fabricated state. This means that the both types of notch root cracks would remain in a subcritical state even under the slow transient events once it has survived the fabrication process of the component. Therefore, the pre-castellation would not raise the risk of brittle cracking at the notch root.

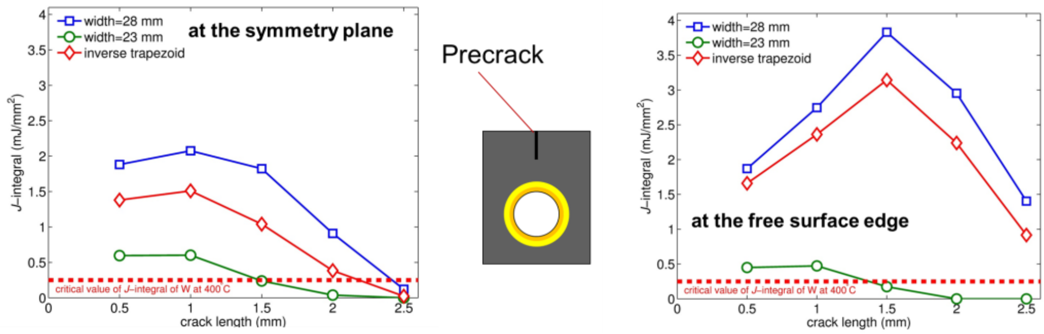

Fig. 5. J-integral values at the tip of an armor surface crack for four different crack lengths. Compared is the reference model with the variants 1 and 2. The J-integral was calculated for the cool-down stage after HHF loading at 20 MW/m^2.

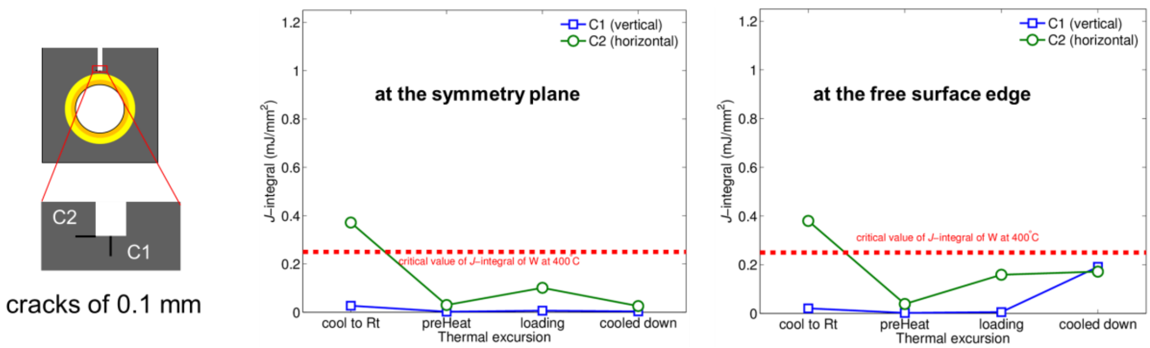

Fig. 6. J-integral values at the tip of notch root cracks (vertical and horizontal, 0.1 mm) at four distinct stages of thermal history (fabrication, preheating, HHF loading at 20 MW/m², cooling down). (left: symmetry plane, right: free surface)

6. Conclusions

In this study, three geometrical variants of the ITER-like W monoblock type divertor PFC were evaluated in terms of thermal and structural performances under the maximum required heat flux load (20 MW/m²) focusing on the plastic fatigue life of the armor and the driving force of armor cracking. Key findings are as follows:

1. Both the design variants with a reduced block width and a pre-castellation led to significant improvement with regard to plastic fatigue life and cracking risk. The benefit of the inverse trapezoid shape was marginal.

2. In the case of reduced block size or pre-castellation, the predicted fatigue life is far more than the specified requirement. The cracking risk was only subcritical.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] T. Hirai, Nucl. Mater. Ener., 10.1016/j.nme.2016.07.003
[2] J.H. You et al., Fus. Eng. Des. 109-101(2016) 1598-1603
[3] M. Li, J.H. You, Fus. Eng. Des. 101 (2015) 1-8.
[4] M. Li, J.H. You, Structural impact of armor monoblock dimensions on the failure behavior of ITER-type divertor target components. Submitted to Fus. Eng. Des.
[5] M. Roedig et al., J. Nucl. Mater. 329-33 (2004) 766-770.