Measures to overcome deep cracks of tungsten tiles in the ASDEX Upgrade divertor

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A massive tungsten divertor, Div-III, was installed in ASDEX Upgrade (AUG) in 2014. Div-III is an adiabatically loaded component and consists of massive tungsten tiles clamped into their supporting structures. Before installing the new component, extensive studies, including Finite Element Modeling (FEM) and high heat flux tests in the test facility GLADIS, were carried out. After the first experimental campaigns the tile inspection reveals most of the tiles were cracked. The difference between the high heat flux tests and the AUG behavior was attributed to mechanical loads due to disruptions and/or the thermal load profile and history. The actions to understand the cracks comprise tests with the divertor manipulator, DIM-II, and FEM analysis of different target design options. DIM-II was used to test 'split' tiles, i.e. the deep crack is avoided by cutting a wide tile into two small tiles. FEM calculations were done to investigate the behavior of castellated targets with reduced tensile stress on top of the target and a clamping with a more elastic material, titanium instead of stainless steel. In addition more ductile tungsten heavy alloy was qualified for use in AUG. Based on this, a new set-up of tungsten tiles was installed in 2016 with different divertor configurations. After about 1000 plasma shots a thorough inspection of the tiles reveals that only 2 configuration out of 4 get rid of deep cracks in the tungsten tiles. Outcome of this inspection are here discussed and the final divertor setup is described.

Keywords: ASDEX Upgrade, tungsten divertor, tungsten heavy alloy, tungsten crack.

1. Introduction

ASDEX Upgrade (AUG) is a mid-size tokamak with the aim to study physics in preparation of ITER and DEMO. With this leitmotiv, over the years, many upgrades were conducted and several of them were carried out in the tokamak lower divertor [1]-[3].

AUG operates with plasma pulse length up to 10 s and with a dwell time of 20 minutes, during which the in-vessel components are passively cooled. For AUG maximum values for plasma heating and Psep/R are respectively 110 MJ and about 2.5 MW/m.

The main components of the outer divertor are illustrated in Fig. 1. Briefly, the AUG outer divertor consists of a water cooled stainless steel structure on which 8 tiles are fixed with stainless steel clamps.

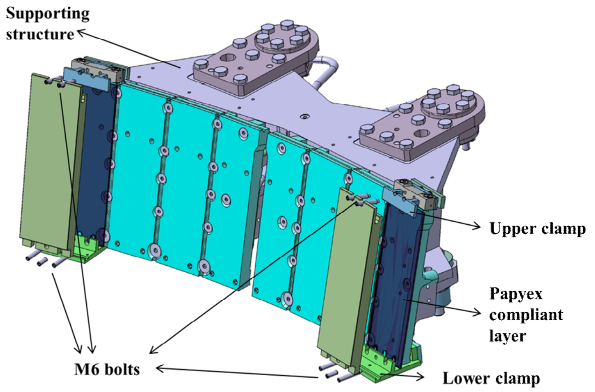

Fig. 1. Overview of one sector of the DIV-III: only the tiles in the outermost position are illustrated.

Papyex compliant layers are placed between tiles and steel structure to improve the thermal conductivity and to allow some geometrical adjustment between adjacent tiles.

Since 2007, all the plasma facing components made of graphite were coated with tungsten but erosion of the tungsten layer in the most loaded region of the lower divertor called upon the replacement of the tiles in that region. Based on this, in 2013 the lower outer divertor coated tiles were replaced by bulk tungsten tiles.

Preliminary experiments in the high heat flux test facility GLADIS [4] and studies based on FEM analyses did not prevent problems related to deep cracks in the bulk tungsten tiles [5][6]. In fact, after just one experimental campaign, almost all the tungsten tiles showed severe damage. A typical crack pattern is shown in Fig. 2. In this picture the two main categories of cracks are identified: 1) shallow cracks, localized in the most loaded region of the tile, clearly characterized by a dense ramification of few µm depth cracks 2) deep cracks, running in poloidal direction of the tungsten tiles and in most of the cases passing through the entire thickness of the tile.

The difference between the results of the tests and the tokamak environment was attributed to the superposition of disruption loads and thermal load. To tackle the problem different measures were adopted and they are described in section 2. The new divertor setup was equipped with a new set of tungsten tiles and tested for one entire experimental campaign in 2017: outcome of

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the tile inspection is outlined in section 3. Finally, in the last section discussion of the findings and conclusions are reported.

The new set of tungsten tiles was delivered by two different producers: according the technical specification the tile consists of pure tungsten (99.97%) obtained by reducing, pressing, sintering, rolling, heat treatment and machining. Grain size 3 or finest and Vickers hardness ≥410 HV30 have been specified. Rolling direction has been specified along the poloidal direction of the tile and the tiles must be produced by a single tungsten batch, to guarantee a homogeneous behaviour of the material.

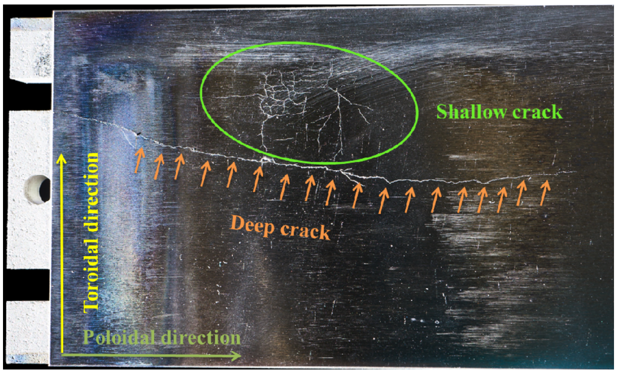

Fig. 2. Typical crack pattern in a tungsten tile: shallow cracks are identified by a dense superficial network, while the deep crack runs in poloidal direction from the lower part (left side) of the tile to the central one extending through the entire tile thickness.

2. Actions to reduce the occurrence of deep cracks

To overcome the crack issue a pragmatic approach was pursued, consisting in reducing the thermal and the mechanical stresses acting on the tungsten tiles.

2.1 Thermal stresses reduction

The tungsten tiles are exposed up to high heat flux of 10 MW/m^2 during the plasma discharge in AUG. During the 10 s pulse length a strong thermal gradient across the tiles thickness is responsible for a high compression stress and consequently plastic deformation on the surface of the tile. In the dwell phase, the deformed material is pulled back by the elastic recovery of the underneath cold tungsten tiles. After each high power discharge, plastic strain is accumulated, exposing the material to the fatigue failure.

A good practice to mitigate the accumulation of plastic strain due to thermal stresses is the reduction of the toroidal extension of the tungsten tiles: 2 possibilities were explored and a detail description of the FEM analyses is given here [7][8]:

- Splitting of a single wide tile, almost halving the stresses on top of the component;
- Two castellations with 10 mm depth for the wide divertor tile, reducing also in this case the stresses by a factor 2.

2.2 Clamping optimization

During the plasma operation in the event of plasma disruption, mechanical loads are superimposed to the thermal one: 1) local eddy current induced in the tiles causing poloidal moments 2) bypass current flowing through the tungsten tiles due to the lower electrical resistivity of tungsten in comparison to graphite. To reduce the by-pass current the steel clamps fixing the tungsten tiles were replaced with the titanium grade 5 which has a lower electrical conductivity. In addition, thanks to the elasticity of the titanium, a further stress reduction is expected. Since neutron flux is not an issue in AUG, no embrittlement of the titanium is expected.

3. Divertor setup and outcome of the inspection after one experimental campaign

The standard AUG outer divertor assembly is setup with standard stainless steel clamps fixing split tiles except for the outermost tiles positions. In fact, in those positions a heavy tungsten alloy (HPM1850) is preferred to the tungsten for its higher tensile strength and fracture toughness. The study of the heavy tungsten alloy in a tokamak environment is elsewhere extensively reported [9][10]. The standard solution is implemented in 13 out of 16 sectors.

Three special sectors are arranged:

- Sector 16: in all the divertor positions wide tungsten tiles with two deep castellations are installed. The fixing clamps are in stainless steel;
- Sector 15: in all the divertor positions split tiles are installed with the titanium clamps;
- Sector 7: wide tungsten tiles with titanium clamps are implemented.

In 2016 a new batch of tiles was manufactured by two different companies. In the acceptance phase, visual inspection revealed differences at surface level between tiles of the two companies. Nevertheless, testing at high heat flux test GLADIS did not show any difference between the manufacturers. The tiles were installed with a symmetrical distribution between the 2 suppliers, trying to follow possible differences between them: e.g. in sector 16, 4 tiles belong to one manufacturer and the other 4 tiles to the other.

During the 2017 experimental campaign the outer divertor did not suffer of problem related to the above mentioned tiles. Nevertheless in summer 2017 the machine was opened to replace 2 special tungsten tiles with embedded Langmuir probes for which the solutions were not appropriate. The replacement of the broken tiles gave the opportunity to rapidly inspect the tungsten tiles [11].

Unfortunately, the 2017 AUG campaign ended one month earlier than scheduled, due to a severe water leakage during the baking phase. In conclusion, in the whole 2017 campaign the divertor was exposed to about 1000 shots, with an operation range similar to the previous campaigns.

A detailed inspection of the AUG divertor reveals the following:

- Standard sectors: no deep cracks in the tungsten tiles are occurred. Noteworthy is the HPM1850 integrity that was placed in the most loaded positions of the outer divertor (see Fig. 3).
- Sector 16: visually the castellated tiles appeared safe and sound as can be seen in Fig. 4. Nevertheless, after a thorough examination, the tiles reveal deep cracks in all of them. In particular, one is completely separated by a deep crack running along the groove of the castellation, as reported in Fig. 5.
- Sector 15: no cracks were found.
- Sector 7: 5 tiles out of 8 had deep cracks with their standard appearance.

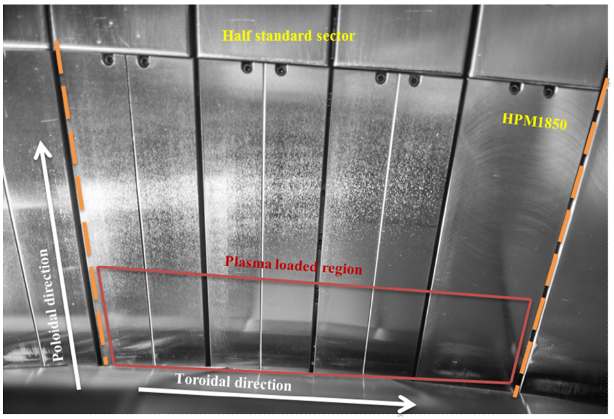

Fig. 3 Picture of half standard outer divertor: no cracks are visible on the split tiles; also the HPM1850 integrity is noteworthy. None roughening of the tiles is observed, but the gray spots on the picture are given by some reflection effect.

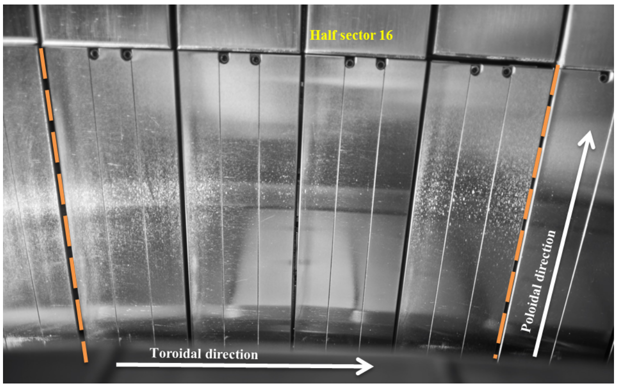

Fig. 4. Picture castellated tiles of half outer divertor: apparently no cracks are visible on the tungsten tiles. None roughening of the tiles is observed, but the gray spots on the picture are given by some reflection effect.

3.1 Analysis of the crack plane for the broken tiles

The rupture surface of the castellated tiles was investigated macroscopically and microscopically by Scanning Electron Microscopy (SEM). A naked eye inspection reveals a fracture surface with a pronounced slant appearance and with strong change in roughness due to cracks propagation. Two main regions are distinguished: the left part of the tile shown in Fig. 5, where many crack lines are visible; while on the right part of the tile in the same picture, the surface showed a shiny highly reflecting texture, without marks.

It appears that cracks started on the left part of the tiles, where the striking line of the plasma actually is. The cracks grow progressively for thermal fatigue, till the reduction of the cross section makes the tile incapable to withstand the disruption load, causing a sudden tile failure. Cracks seem to be originated in different positons: 1) as underlined by the prominent change of the crack plane identified in position A of Fig. 5; 2) as suggested by the marks close to the castellation tip.

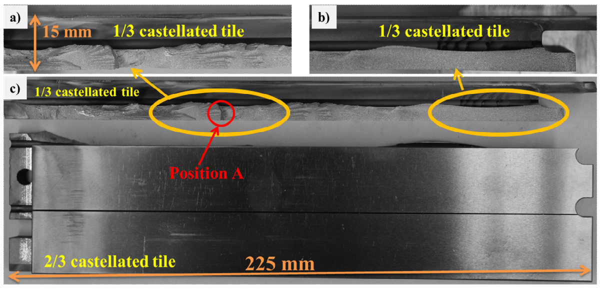

Fig. 5. Dismounted castellated tile belonging to sector 16: the deep crack has completely split up the tile in 2 parts: in figure c) to the left is the thermally loaded region, the right side is almost thermally unloaded.

Fig. 6 (a) illustrates the microstructure of the fracture surface in the heat loaded region: the zoom-in emphasizes the presence of: 1) intergranular fracture (fracture along the grain boundaries), to note the several flat separated grains; 2) transgranular fracture visible by cleavage facets. The microscopic view of the thermally unloaded part is given in Fig. 6 (b): in this case it seems that the tungsten section fails mainly for transgranular cleavage. Similar fracture behaviour is observed in the thermally loaded region for the castellated tile produced by the other manufacturing company.

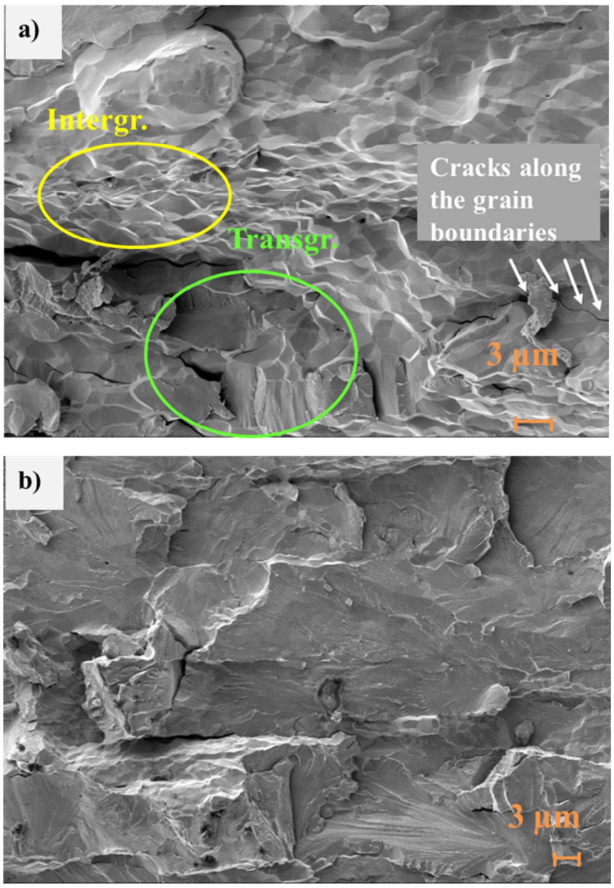

Fig. 6. Fractograph of the broken castellated tile: a) related to the thermally loaded region where intergranular and transgranular ruptures are identified; b) refer to the thermally unloaded part of the tile where mainly cleavage failures are visible.

4. Discussion and conclusions

In 2014 AUG came in operation with a re-designed outer divertor with massive tungsten tiles at the lower outer divertor. After two experimental campaigns, deep cracks were identified and to overcome them different actions were undertaken.

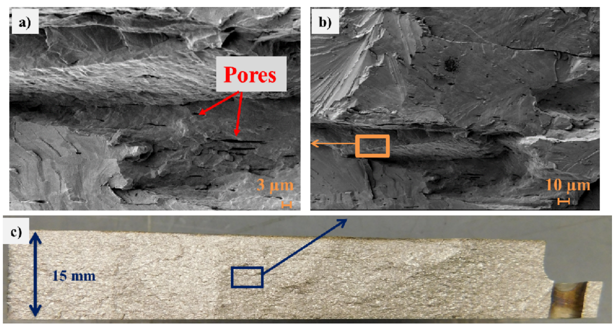

Fig. 7. Fractograph of a wide tile installed in the AUG outer divertor till the 2016 campaign: cleavage and intergranular rupture can be seen together with many elongated pores.

The AUG divertor was arranged in a sector-wise fashion combining different mitigation actions in order to get information of the origin of the deep cracks. A new batch of tiles was installed and this time, the material rolling direction was specified as the long side of the tile. After one campaign only the tiles in special sectors were again deeply cracked. Namely, sector 16 arranged with castellated tiles, full thermally optimized, and sector 7 equipped with tungsten tiles fixed with the optimized clamps.

Fractographic studies of the castellated tiles showed thermal fatigue behaviour in the plasma loaded region. This is the first time that thermal fatigue marks are clearly exhibited in the AUG tungsten tiles. It's very likely that micro-cracks (few tens of µm) were introduced on the tip of the castellation during the manufacturing process [12]. During the operation superficial cracks were progressively growing under plasma load, till the tile suddenly fractures due to a disruption load. Fractographic studies [13][14] have investigated the failure mode of polycrystalline tungsten for specimens extracted along the rolling direction. It was shown that longitudinal specimens with crack in perpendicular direction are associated with transgranular cleavage at room temperature and intergranular failure at elevated temperatures. This would be consistent with the observation on the castellated tile if it were not the fact that the groove would act as a crack along the rolling direction. Most probably the difference is given by the production of the ground material: the tungsten tiles were produced by a rolled tungsten plate while the specimens tested in the paper were produced by a rolled tungsten rod.

The fracture surface of a wide tile, installed in the AUG outer divertor till 2016 campaign, appears homogeneous, shiny and reflecting, with just few imperceptible marks as reported in Fig. 7. Microscopic analyses of the fractured surface reveal intergranular and transgranular fractures together with elongated pores. Macroscopically and microscopically, the wide tiles with titanium clamps in sector 7 have shown the typical crack path observed in the previous batch of tiles. On the positive side, the tiles in this sector lasted longer without cracks than tungsten tiles with stainless steel clamps. From past experience, it is known that some tile got broken after 200 shots. Positive performances are recorded by the heavy tungsten alloy. After examination of these findings, just small changes were setup for the 2018 AUG campaign; the sectors with damaged tiles were replaced by the standard divertor setup and all the stainless steel clamps were replaced with the titanium grade 5, combining the positive effects of both proposals. It is worth mentioning that, for this first year of experiment no differences are recorded between the two tiles suppliers.

References

[1] A. Herrmann et al., Solid tungsten Divertor-III for ASDEX Upgrade and contributions to ITER, Nuclear Fusion, 55(6) (2015) 063015.

[2] A. Herrmann et al., Design and concept validation of the new solid tungsten divertor for ASDEX Upgrade, Fusion Engineering and Design, 88(6-8) (2013) 577-580.

[3] A. Herrmann et al., Experiences with a solid tungsten divertor in ASDEX Upgrade, Nuclear Materials and Energy, Nuclear Material and Energy, (2017) 205-209.

[4] H. Greuner et al., High heat flux facility GLADIS: operational characteristics and results of the W7-X pre-series target tests, Journal of Nuclear Materials, (2007) 367-370.

[5] N. Jaksic et al., FEM investigation and thermo-mechanic tests of the new solid tungsten divertor tile for ASDEX Upgrade, Fusion Engineering and Design, 88(6-8) (2013) 1789-1792.

[6] N. Jaksic et al., Results of high heat flux tests and structural analysis of the new solid tungsten divertor tile for ASDEX Upgrade, Fusion Engineering and Design, 98–99 (2015) 1333-1336.

[7] M. Li et al., Structural impact of armor monoblock dimensions on the failure behavior of ITER-type divertor target components: Size matter, Fusion Engineering and Design, (2016) 162-170.

[8] M. Li et al., Numerical design for avoiding deep cracks in the solid tungsten divertor target in ASDEX Upgrade, (submitted to Fusion Engineering and Design).

[9] R. Neu et al., Investigations on tungsten heavy alloys for use as plasma facing material, Fusion Engineering and Design, Fusion Engineering and Design 124, (2017) 450-454.

[10] R. Neu et al., Results on the use of tungsten heavy alloys in the divertor of ASDEX Upgrade, Journal of nuclear Material, (2018)

[11] I. Zammuto et al., Cracks avoidance with a modified solid tungsten divertor for ASDEX Upgrade, Fusion Engineering and Design, (2018).

[12] G. Holzner, cracks induced in tungsten By Electric Discharge Machining, (2015) Master Thesis.

[13] D. Rupp, Experimental investigation of the fracture toughness of polycrystalline tungsten in the brittle and semi-brittle regime, Journal of Nuclear Material, (2009), 591-593.

[14] D. Rupp, Anisotropic fracture behaviour and brittle-to-ductile transition of polycrystalline tungsten, Philosophical Magazine, 90 (2010), 4055-4069.