FEM investigation and thermo-mechanic tests of the new solid tungsten divertor tile for ASDEX Upgrade

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HIGHLIGHTS

- New solid tungsten divertor for fusion experiment ASDEX Upgrade.
- Design validation in the high heat flux (HHF) test facility GLADIS (Garching Large Divertor Sample Test Facility).
- FEA simulation.

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ABSTRACT

A new solid tungsten divertor for the fusion experiment ASDEX Upgrade is under construction at present. A new divertor tile design has been developed to improve the thermal performance of the current divertor made of tungsten coated fine grain graphite. Compared to thin tungsten coatings, divertor tiles made of massive tungsten allow to extend the operational range and to study the plasma material interaction of tungsten in more detail. The improved design for the solid tungsten divertor was tested on different full scale prototypes with a hydrogen ion beam. The influence of a possible material degradation due to thermal cracking or recrystallization can be studied. Furthermore, intensive Finite Element Method (FEM) numerical analysis with the respective test parameters has been performed. The elastic–plastic calculation was applied to analyze thermal stress and the observed elastic and plastic deformation during the heat loading. Additionally, the knowledge gained by the tests and especially by the numerical analysis has been used to optimize the shape of the divertor tiles and the accompanying divertor support structure.

This paper discusses the main results of the high heat flux tests and their numerical simulations. In addition, results from some special structural mechanic analysis by means of FEM tools are presented. Finally, first results from the numerical lifecycle analysis of the current tungsten tiles will be reported.

1. Introduction

The plasma fusion experimental facility ASDEX (Axial Symmetric Divertor Experiment) Upgrade [1] is a mid-size tokamak experiment. Beginning with the experimental campaign in 2007, the plasma facing surface was stepwise transformed from a carbon to a tungsten first wall experiment. Details on tungsten first wall plasma interaction can be found in [2]. The first step in the transition from carbon to tungsten was realized by coating of fine grain graphite with tungsten physical vapour deposition (W-PVD) and with tungsten vacuum plasma spraying (W-VPS). In the second step, the thermal most stressed elements, the so-called divertor tiles, will be replaced by solid tungsten elements.

The first design of the solid tungsten divertor, called divertor III (Div-III) has been done based on the existing design and in particular on the existing divertor attachment system. ASDEX Upgrade is equipped with an adiabatically loaded divertor as a compromise between available heating power, plasma discharge length and heat removal capability of the divertor tiles. First tests with a tungsten-graphite sandwich target under plasma operation were successfully performed in the ASDEX Upgrade campaign 2011 [3]. Nevertheless the design validation in the high heat flux (HHF) test facility GLADIS (Garching Large Divertor Sample Test Facility) [4] has shown some shortcomings of such a design. Based on the first experiences and on extensive application of finite element analysis (FEA) the target and clamping design was improved to simplify the installation and to increase the thermal performance. This improved design for the solid tungsten divertor III was HHF tested with different full scale prototypes with main dimensions of 229 mm × 75 mm × 15 mm. Moreover, to simulate the thermal loading due to high power plasma operation in ASDEX Upgrade,

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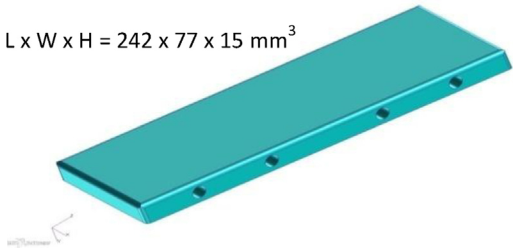

Fig. 1. Divertor III tile – first conceptual design.

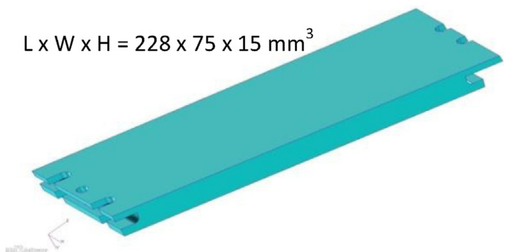

Fig. 2. Divertor III tile – final design.

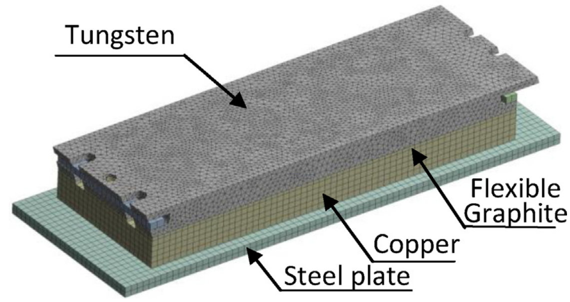

Fig. 3. FE model assembly of the final design.

cyclic loading tests have been performed as well. The applied loading profiles in GLADIS are Gaussian with a central heat flux of 10–30 MW/m^2 and an integrated absorbed power between 100 and 280 kW, simulating the expected highest averaged power and energy loads during the operation. These loadings result in maximum surface temperatures between 1500 °C and 3300 °C. All test procedures in the GLADIS facility have been simulated by FEA as well. These simulations are essential for a better understanding of the origin of phenomena observed during tests.

More details about the physics and functional principle of the new Div-III can be found in [5].

2. Experimental tests and modelling

Fig. 1 shows the first conceptual design of the tungsten divertor tile and Fig. 2 shows the final versatile optimized design. The characters L, W and H in both pictures denote the main dimensions of the tiles. Major investigations of the thermo-mechanical performance have been carried out on the tungsten tile with final design (Fig. 2) and will be the main subject of this paper.

The characteristic feature of the tungsten tile optimization was the way of its attachment to the supporting structure. The holes across the tile body needed for the fastening (Fig. 1) cause the overheating of the tile, because they are located in the region with highest thermal loading. The optimized fastening system has been shifted to the thermal less loaded regions on the top and bottom of the tile body. The fastening system is a clamping device with the claws at the both tile ends, which have a particular flexibility to compensate the thermal dilatation without increasing the stresses in the tile body additionally.

The tungsten tile with the final design was subjected to mainly three load case (LC) scenarios (Table 1), the design load (I), the overload (II) and the double overload (III).

Table 1
HHF – test scenarios with load cases.

Load case	Power at beam [MW/m^2]	Duration [s]	Energy on target [kJ]
I	10.5	3.5	367.5
II	23.5	1.5	303
III	30	2.5	700

To simulate the thermal loading due to high power plasma operation in ASDEX Upgrade, cyclic loading tests with up to 200 cycles have been performed. This corresponds to about 4 years of operation with about 50 high power discharges per year.

The GLADIS heat flux profile can be approximated by a two-dimensional Gaussian function $f(x,y)$ according to:

$$f(x,y) = A\exp\left(-\left(\frac{(x-x_0)^2}{2\sigma_x^2} + \frac{(y-y_0)^2}{2\sigma_y^2}\right)\right) \quad (1)$$

where A is the heat flux intensity in the beam centre, $\sigma_x = \sigma_y = 61.0$ mm is the variance, $x_0 = 80$ mm and $y_0 = 35$ mm are the coordinates of the beam centre at the target. The values in Table 1 are related to power of one pulse and they are constant over the pulse duration.

The assembly of the FE model according to the parts arrangement during the thermal test procedures is shown in Fig. 3.

The tungsten tile is attached to the water-cooled copper part by two screws at both ends. The flexible graphite layer in-between serves as compliant layer to improve the heat transfer.

The model is multiple nonlinear, both in geometrical and material property law definition. Between all single model parts the contact surfaces with the coefficient of friction (0.2) are defined. Main material parameters of tungsten used for simulations are presented in Table 2.

In addition, the elastic–plastic temperature dependent material constitutive law for tungsten (Fig. 4) was used.

The boundary conditions for thermal analysis have been defined as follows: all free surfaces have a radiation to ambient with an emissivity of 0.2, the convection of 2000 W/m^{2}K is defined at the bottom surface of the steel plate to simulate the active cooling of the cooper, all contact surfaces have a conductance value of 2000 W/m^{2}K except the flexible graphite surfaces which have a value of 200 W/m^{2}K. These values have been taken firstly from literature [8] and additionally proven by experiment. The applied thermal load (LC I) in GLADIS facility at the tungsten surface of the final design is shown in Fig. 5.

Table 2
Tungsten – main material parameters [6,7].

Temp. [°C]	Young's Modulus [GPa]	Thermal Expansion [K^{-1}]	Thermal conductivity [W/mK]
200	396	4.5E^{-6}	155
400	393	4.5E^{-6}	140
600	387	4.6E^{-6}	128
800	379	4.8E^{-6}	118
1000	368	5.1E^{-6}	110
2000	285	5.6E^{-6}	99

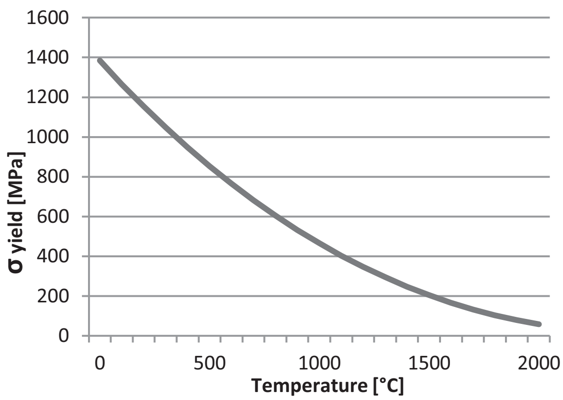

Fig. 4. Tungsten yield stress [6].

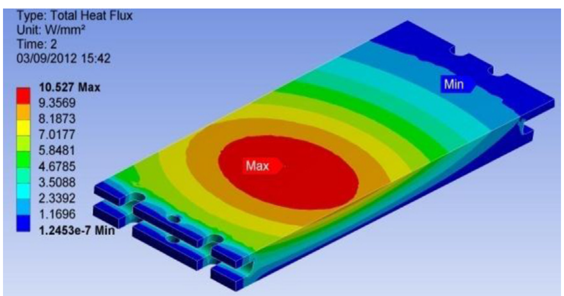

Fig. 5. Tile final design – thermal loading LC I.

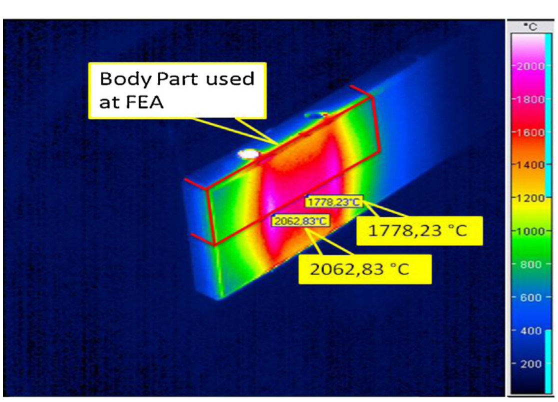

Fig. 6. Maximal temperature – of the conceptual design (Fig. 1) as measured during LC I.

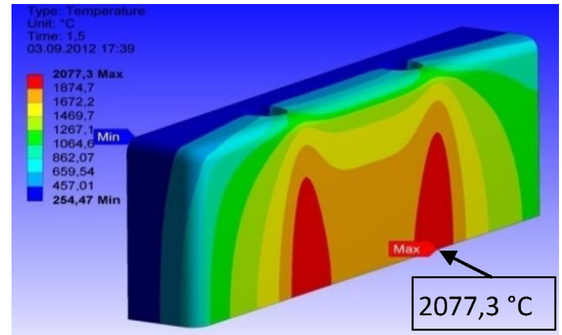

Fig. 7. Maximal temperature – FEA results.

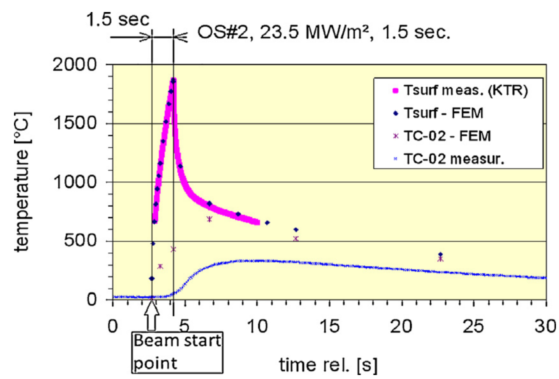

Fig. 8. Temperature profile – test and FEA results.

3. Results and discussion

All tiles have been examined after loading in GLADIS as follows: first a visual check of the tile surface for macroscopic changes, in particular the cracks, was done. Depending on the results, the measurement of the body shape and metallographic examination has been performed.

Due to the fact that stress–strain measurements during the tests were not intended and the values of displacements are very small and therefore difficult to measure, the most suitable value for comparison of the test and FEA results was the temperature field. Figs. 6 and 7 show the maximal measured and FEA investigated temperature for the complex geometry of the first conceptual design.

The comparison of both pictures shows very good agreement, both in the temperature field pattern and the values: 2063.0 °C measured and 2077.3 °C calculated by FEA. Note that the FE model (Fig. 7) contains 1/4 of the specimen body only.

Fig. 8 shows the temporal temperature profile at two points, for both measured and FEA calculated results, for LC II. The point, marked as "Tsurf" at the graph, is located at the beam centre. The measurement has been performed by infrared camera (IRC). These results are in a very good agreement as well.

The second point, marked as "TC-02" at the graph, is located at the tile bottom side and lying on the beam centre line. The temperature measurement has been performed by a thermocouple. The agreement of the results is not as good as in case of IRC due to the thermal contact resistance of the clamped thermocouple. Main results of the thermo-mechanical analysis are presented in Table 3. The values in the table are taken from the most thermal stressed region. These results were evaluated after single loading, the cyclic loading analysis was not performed in this case.

Typical temperature profiles at the central hot-spot area for the tiles are shown in Fig. 9. Fig. 10 shows the maximal total displacements at the end of the thermal heating (1.5 s) for the LC II.

The test under LC III, with the double overloading, was performed to find out the thermo-mechanical material limits. This case shows a modification of the surface due to recrystallization and grain growth with high plastic distortions of the shape.

Table 3
FEA – main results.

	Load cases		
	I	II	III
Max temperature [°C]	1315	1819	2988
Max. mises stress [MPa]	290	732	834
Residual plastic stress [MPa]	235	787	750
Max. deflection in *Z*-axis [mm]	0.89	1.61	2.568
Equivalent plastic strain	0.001035	0.00437	0.00479

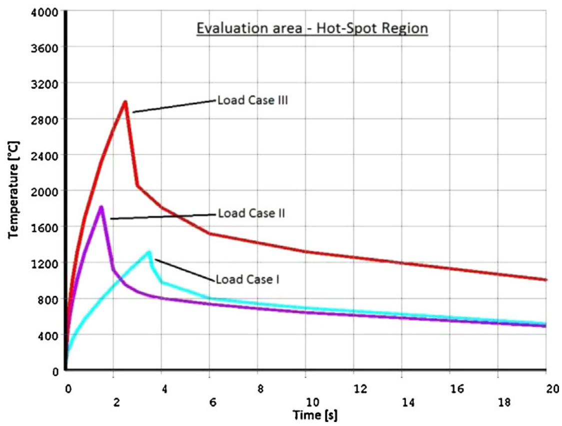

Fig. 9. Calculated temperature profiles – for LCs I, II and III.

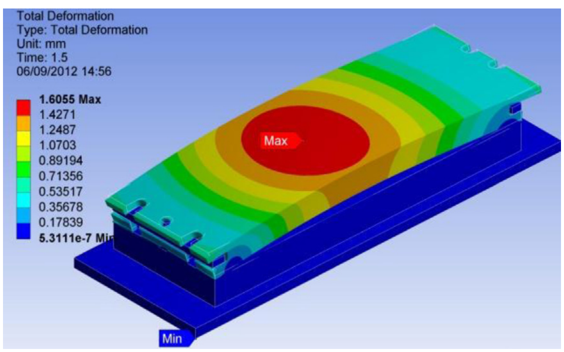

Fig. 10. Maximum total displacements of the final design tile – LC II.

The fatigue analysis has been performed on the results taken from the prior cycle load analysis for GLADIS load scenario II. The cycle load analysis provides important information about the fatigue of a single material with regard to advancing plastic deformation, also known as ratcheting.

The first two load cycles of the LC II were analyzed only, because of the very large scope of the analysis. This analysis shows a very low ratcheting, the maximal plastic strain was increased from 0.00437 to 0.0044 only, and hardly increasing of the region concerned.

According to the theoretical recommendations [8,9] for the thermal stressed structural elements, it is suitable to perform a fatigue assessment based on strain-life equations (2) also known as Manson–Coffin method:

$$\frac{\Delta\in}{2} = \frac{\sigma_f}{E}(2N_f)^b + \varepsilon_f(2N_f)^c \quad (2)$$

Or in the simplified form (3) known as "universal slops" equation:

$$\Delta\in = 3.5\frac{\sigma_f}{E}(N_f)^{-0.12} + \varepsilon_f 0.6(N_f)^{-0.6} \quad (3)$$

where $\Delta\in$ is the total strain amplitude, E is the modulus of elasticity, N_f is the number of cycles to failure and $2N_f$ is the number of reversals to failure.

The parameters required for a strain-life analysis are: $\sigma_f = 200$ MPa is the fatigue strength failure, $\varepsilon_f = 0.5$ is the fatigue ductility coefficient, $b = -0.12$ is the fatigue strength exponent (Basquin's exponent), $c = -0.6$ is the fatigue ductility exponent, $K = 250$ MPa is the cyclic strength coefficient and $n = 0.2$ is the cyclic strain hardening exponent. Note that the above listed values are taken from literature [6,10] or evaluated according to [11], on the basis of static test values. The influence of the operational temperature level on material properties has been taken into account as well. Fig. 11 shows a contour plot of fatigue life over the tungsten tile structural part.

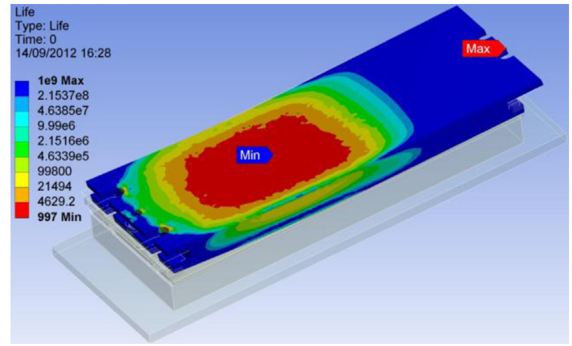

Fig. 11. Fatigue life for tungsten tile.

Under the assumptions made by load conditions II and fatigue material properties, in a first approach it can be said: the tungsten tile for the new divertor III will not fail before 997 load cycles at least.

4. Conclusions

A comprehensive investigation of the massive tungsten tile for the new divertor III of the plasma fusion experiment ASDEX Upgrade has been performed. After the tile shape optimization with the aim to improve the thermal performance, an intensive investigation of the optimized shape was carried out. First, the tiles have been tested in the high heat flux test facility GLADIS under three different load scenarios between 10 and 30 MW/m^2 heat load. After the successful tests, an intensive tile investigation by applying FEA has been performed. In consideration of both, the tests and the FEA investigation, it can be concluded: the tungsten tiles are designed with a reasonable safety margin for a permanent operation in ASDEX Upgrade with up to 200 load cycles with the load scenario I, including a short overloading according to the scenario II with up to 20 cycles.

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