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Performance of the Ti doped graphite RG-Ti-91 at the divertor of the Tokamak ASDEX Upgrade

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Abstract

During the 1994/1995 discharge period two graphite tiles at the outer and the inner lower divertor plates of the tokamak ASDEX-Upgrade have been replaced by tiles of RG-Ti-91 which is a graphite, doped with about 2 at% of Ti and subsequently treated at high temperatures and pressures to achieve a high thermal conductivity perpendicular to one direction. The RG-Ti-91 tiles have been installed with the directions of high thermal conductivity normal to the plasma exposed surface. The plates have been exposed to about 670 tokamak discharges each lasting about 2 to 3 s. The performance of the discharges has not been influenced by the presence of the RG-Ti-91 tiles, i.e., no additional impurities, such as Ti, have been observed in the plasma. The temperature increase of the RG-Ti-91 tiles during high power loads was about a factor 2 lower than the temperature increase of fine grain graphite plates. The surfaces of the tiles showed preferential erosion of the carbon, and TiC crystallites staying out on the surfaces. This is similar to the surface structure which develops at D-ion bombarded surfaces of this RG-Ti-91 material in the laboratory.

Keywords: ASDEX Upgrade; Poloidal divertor; Low Z wall material; Wall particle retention; Energy balance

1. Introduction

In most of today's fusion experiments good plasma performance is achieved when carbon is installed at the vessel wall areas facing the hot plasma [1-5]. However carbon has a relatively high erosion yield at hydrogen and oxygen bombardment, due to chemical sputtering [6-8]. Its use in fusion experiments was further found to result in a large hydrogen isotope inventory in the surfaces layers of the vessel walls. This is due to eroded and subsequently redeposited carbon being implanted with hydrogen atoms and ions from the plasma [9-11] which are permanently trapped at concentrations of about 30 at% [12]. Further the mostly used fine grain graphite has only a relatively low thermal conductivity of the order of 60 to 100 W/mK [14]. Therefore carbon-based materials with higher thermal conductivity, such as carbon fibre composite [13,14], is now mostly applied. Several of the disadvantages of fine grain carbon material can also be overcome by doping the carbon. Boron or silicon doping of carbon reduce chemical sputtering at higher energy ion bombardment [8], however the thermal conductivity is even lower than for fine grain graphite [14]. Graphite doped with about 2 at% of Ti and subsequently treated at high temperatures and pressures, such as RG-Ti-91, has a high thermal conductivity of the order of 600 W/mK at room temperature [14,15], a high thermal shock resistance [16], chemical sputtering is largely reduced [17] and permanent hydrogen trapping is low, at least at elevated temperatures [18]. Thus this material is expected to show good performance especially at highly loaded vessel wall areas, such as limiters and divertor plates. The first test of RG-Ti-91 material at a limiter in TEXTOR [19] was unfortunately only partly successful, due to residual impurities in the RG-Ti-91 material and the exposure to high power loads of about 30 MW/m^2 result-

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ing in surface temperatures of up to 2400°C. In this work we report about the test of clean RG-Ti-91 at the divertor in ASDEX-Upgrade.

2. Experiments

2.1. Installation in ASDEX Upgrade

Fig. 1 shows a view into the ASDEX-Upgrade vessel and the plates of the single null divertor at the bottom with the areas where the RG-Ti-91 tiles were mounted. Before the start of plasma discharges after each opening the inner vessel walls had been conditioned by boronization which was performed by a glow discharge in 10% B_2H_6 + 90% He. The RG-Ti-91 tiles have been in place during the discharge period from December 1994 until August 1995. They have been exposed to about 670 plasma discharges of which about 260 were Ohmic discharges (plasma current $I_p = 0.6$ to 1 MA, toroidal magnetic field $B_t = -2$ to -2.5 T, plasma density $\bar{n}_e \approx 3\text{–}8 \cdot 10^{19}\ m^{-3}$). The rest of the discharges (with $I_p = 0.8\text{–}1$ MA, $B_T = -2$ to -2.5 T, and plasma densities of $\bar{n}_e \approx 6\text{–}8 \cdot 10^{19}\ m^{-3}$, central electron- and ion-temperatures of the order of 1 keV) were mostly additionally heated by neutral beam injection (NBI).

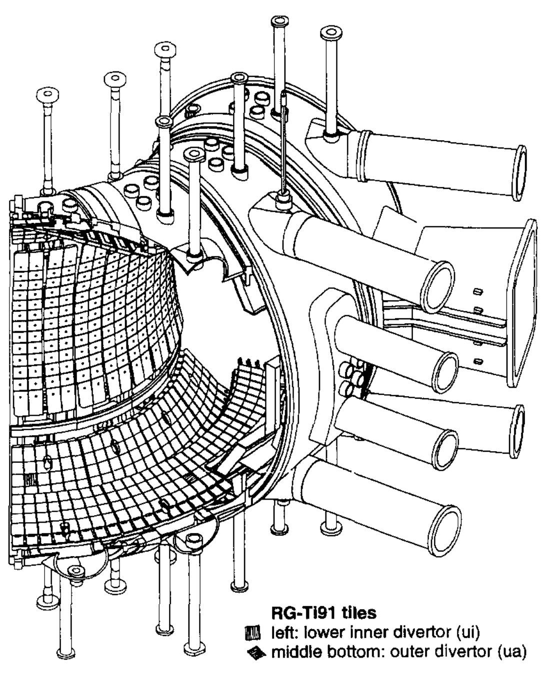

Fig. 1. View into the toroidal vessel of the divertor tokamak ASDEX-Upgrade. The poloidal positions of the RG-Ti-91 tiles are marked. They are installed in sectors 7 (inner divertor) and 16 (outer divertor), the figure shows one representative sector.

Approximately 150 discharges had a NBI heating power of about 7.5 to 10 MW for a duration of 1 to 3 s, resulting in a heat flux to the area of the divertor tiles where the separatrix intersects of up to 6 MW/m^2. On the average the divertor tiles were exposed to the plasma for about 3000 s. More than 80% of the discharges had a deuterium filling, however the plasma always contained a few % of hydrogen ions.

After opening of the ASDEX-Upgrade vessel in July 1995 the RG-Ti-91 tiles have been removed and the surface layers have been analyzed by scanning electron microscopy (SEM), secondary neutral mass spectroscopy (SNMS), X-ray diffraction, Rutherford backscattering spectrometry (RBS) and elastic recoil detection analysis (ERDA).

3. Results

3.1. Thermography

During the plasma discharges the surface temperatures of the tiles have been measured by thermography with an infrared (IR) camera and the results are compared with the surface temperatures measured at the fine grain graphite tiles close by at the same poloidal position. For discharge #6060, the results are shown in Fig. 2. The maximum heat flux to the inner divertor tile was about of 2 MW/m^2, while the RG-Ti-91 tile received a heat flux of about 3 MW/m^2. For this discharge the separatrix was very close to the very surface area on the RG-Ti-91 tile where the temperature was recorded. The measured temperature increase was moderate, and it was only about 1/2 of the temperature increase of the fine grain graphite (EK-98) tile

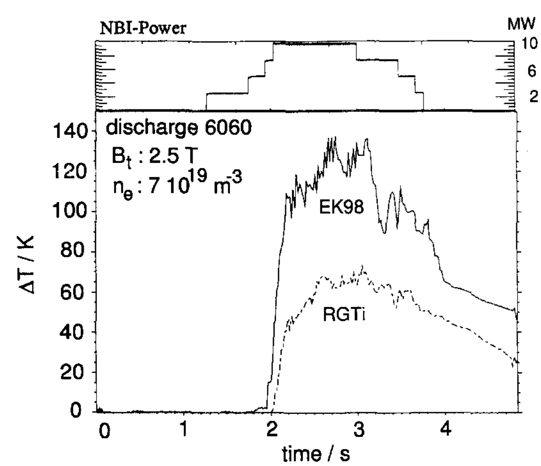

Fig. 2. Increase of the surface temperatures of the RG-Ti-91 tile and the fine grain graphite tile at the outer divertor during a power load of about 3 MW/m^2 as measured by thermography.

close by. For a pulse power heating of tiles with different thermal conductivities 'λ' but similar densities and specific heats, the ratio of the temperature increases should be inversely proportional to the ratio of the square roots of the thermal conductivities [20]:

$$\Delta T_{\text{RG-Ti-91}}/\Delta T_c = (\lambda_c/\lambda_{\text{RG-Ti-91}})^{1/2} \quad (1)$$

For the moderate temperature increases in this experiment the thermal conductivity's can be taken to be about constant. For the values of the thermal conductivity λ from reference [14] this gives about $(\lambda_c/\lambda_{\text{RG-Ti-91}})^{1/2} = 0.4$, which is in reasonable agreement with the value of about 0.5 measured at the divertor tiles. This result agrees with measurements at TEXTOR, where RG-Ti-91 was tested as limiter material [19].

3.2. Erosion and deposition

After removal from the ASDEX Upgrade torus, scanning electron microscopy (SEM) pictures have been taken

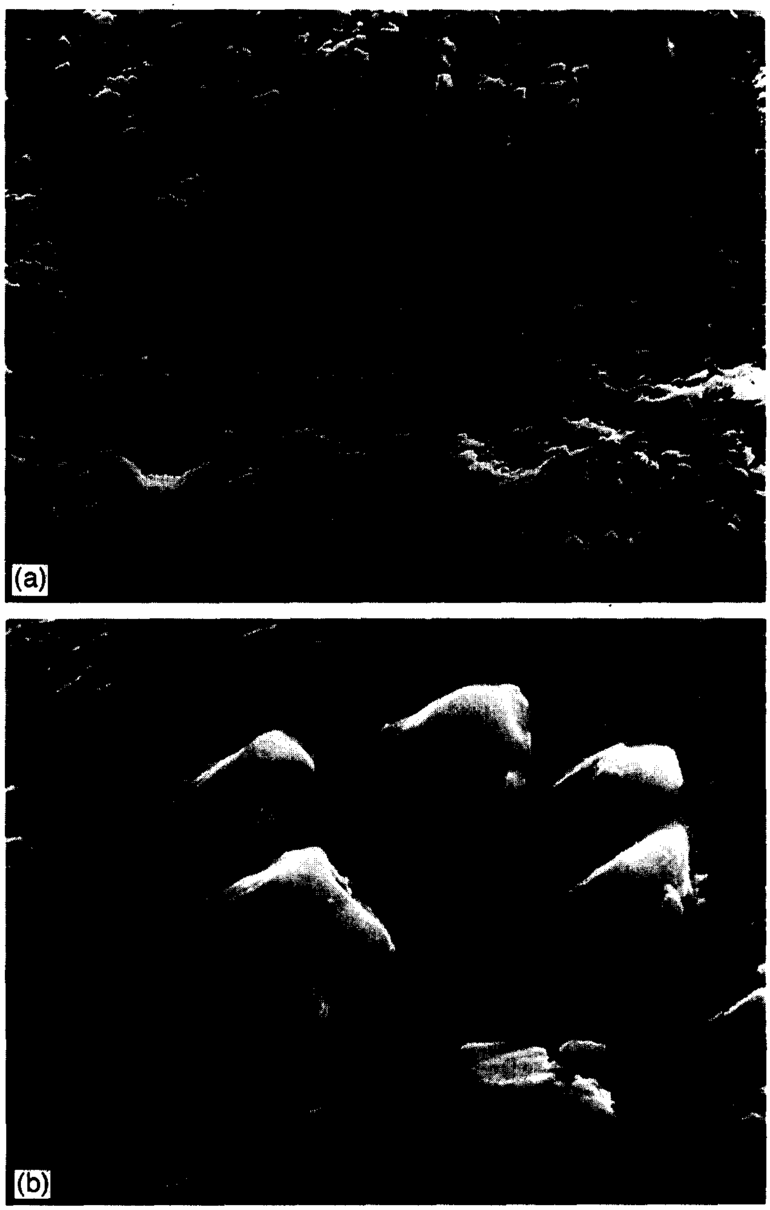

Fig. 3. (a, b) Scanning electron microscopy pictures of the RG-Ti-91 tile at the outer divertor from the area where the separatrix intersected (two different magnifications).

from the RG-Ti-91 tiles both at areas where the separatrix intersected the tiles and outside this area. For the tile at the outer divertor they are shown in Fig. 3a, b for the area where the separatrix intersected and in Fig. 4a, b outside the separatrix intersection. The initial flat surface shows erosion structures similar to the structures found on RG-Ti-91 after D-ion sputtering in the laboratory [17]. The erosion is directed along the incident magnetic field lines. Due to the erosion of TiC being lower than the erosion of carbon, predominantly in between the grains, TiC grains are left on the surface. From the dimensions of the grains a total erosion of the order of a few μm can be estimated at the areas where the separatrix intersected (Fig. 3b), while the erosion is much lower at the sides (Fig. 4b).

In addition, the trace of an electrical arc can be seen also on the RG-Ti-91 tile on the area of separatrix intersection (Fig. 3a). Traces of electrical arcs with dimensions about 20 to 40 μm wide and 0.5 to 2 mm long have been frequently found (about 2 to 10 traces per mm^2) on fine grain carbon tiles at the area of separatrix intersection. The

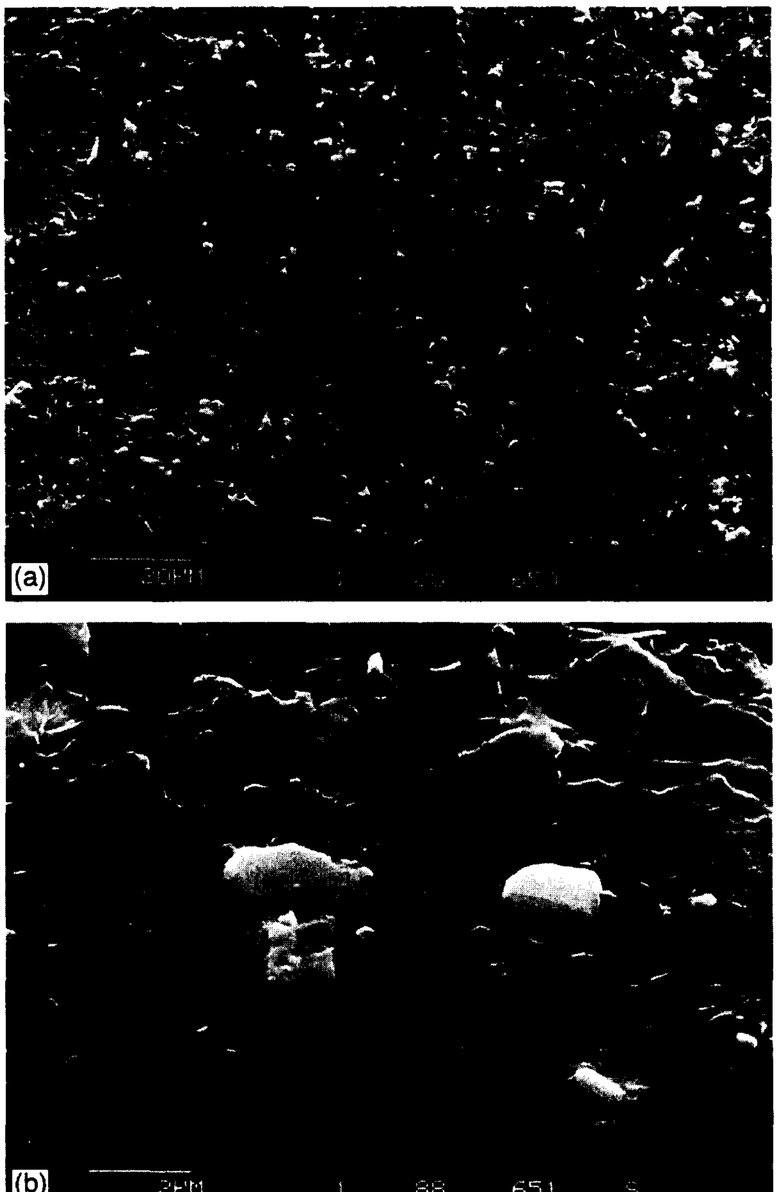

Fig. 4. (a, b) Scanning electron microscopy pictures of the RG-Ti-91 tile at the outer divertor from the area outside the separatrix intersection (two different magnifications).

ignition and burn of such arcs may be correlated to the presence of the boronized layer and the arcs seem to be very effective in removing this layer [21].

The SNMS and RBS analysis showed further on the tile from the outer and from the inner divertor an overall surface contamination (in at%) of about:

inner divertor:	19% B
	0.6% Ti
	14–15% O (500 Å)
	≤ 0.15% Fe, Ni, Cr
outer divertor:	3% B
	2% Ti
	12% O (3000 Å)
	≈ 0.15% Fe, Ni, Cr.

The rest being C. The RBS analysis showed further a small amount of W of less than about 0.001 at%. The B originated from the boronization, the oxygen from the residual gas (H_2O). The Fe, Ni and Cr are partly due to erosion at the vessel walls partly and redeposited during plasma discharges but they are also bulk impurities in the RG-Ti-91 graphite. The W was transported from the few other divertor tiles which had W surfaces.

3.3. Hydrogen and deuterium trapping

For determining the hydrogen isotopes collected in the RG-Ti-91 tiles the surface layers had further been analyzed by elastic recoil detection analysis (ERDA) using 1.5 MeV ^{4}He ions.

The result for D is shown in Fig. 5. D is found up to depth of more than 400 nm at concentrations of $2 \cdot 10^{21}$ to $2 \cdot 10^{22}$ cm^3. This gives area concentrations of 2.3 to $4.4 \cdot 10^{17}$ D/cm^2. Hydrogen is found to be trapped at similar depth with even higher concentrations of $4 \cdot 10^{17}$ to 10^{18} H/cm^2. These concentrations, which built up partly in the deposited layers, are smaller but of the same order of magnitude as the D and H measured in the surface layers of the fine grain graphite tiles from the same discharge period. At the temperatures reached by the RG-Ti-91 tiles about the same D concentrations had also been found to be permanently trapped in RG-Ti-91 and graphite after D ion implantation in the laboratory [17]. However, H, D trapping in material with the composition of the deposited layers has not yet been investigated.

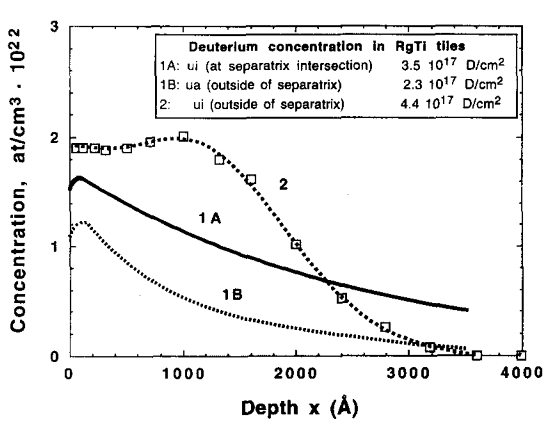

Fig. 5. Depth profile of D in the RG-Ti-91 from the outer and inner divertor tiles as measured with elastic recoil detection analysis (ERDA).

4. Summary

Tiles of the Ti doped graphite RG-Ti-91 have been installed at the divertor of the tokamak ASDEX-Upgrade and subjected to about 670 plasma discharges, mostly with a deuterium filling, including about 150 discharges with additional heating by neutral beam injection at powers of 7 to 10 MW. This resulted in a maximum heat flux up to 6 MW/m^2 on the divertor plates and a maximum surface temperature increase of up to 700 K. The surface temperature increase of the RG-Ti-91 tiles was about a factor of 2 smaller than for fine grain graphite tiles, in agreement with theoretical expectations and observations at the TEXTOR limiter. The surfaces showed an erosion structure similar to the erosion structure observed at D-ion bombardment. No major destruction was found. The deposited C layers found on the surface contain B from the boronization and of Fe, Ni, Cr, partly deposited during plasma discharges, but these are also bulk impurities in the material, and W originating from erosion at the few divertor tiles covered with W. These surface layers are saturated with hydrogen and deuterium at concentrations of about $4 \cdot 10^{17}$ to 10^{18} H/cm^2 and 2.3 to $4.4 \cdot 10^{17}$ D/cm^2. These concentrations are similar to those found in laboratory experiments at hydrogen implantation with keV energies in the surface layers of carbon or RG-Ti-91 at the low temperatures.

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