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Generation and development of damage in double forged tungsten in different combined regimes of irradiation with extreme heat loads

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ABSTRACT

Armour materials in fusion devices, especially in the region of divertor, are exposed to a continuous heat and particle load. In addition, several off-normal events can reach the material during a work session. Calculations show that the effects of plasma and heat during such events can lead to cracking, erosion and detachment of the armour material. On the other hand, mutual and combined influences of different kinds of heat and particle loads can lead to the amplification of defects or *vice versa*, to the mitigation of damages.

Therefore, the purpose of the study is to investigate the plasma induced damages on samples of double forged tungsten, which is considered a potential candidate for armour material of future tokamak's divertor.

The combined effect of different kinds of plasma induced damages was investigated and analysed in this research. The study was conducted by irradiating the samples in various irradiation regimes twice, to observe the accumulation of the damages. Afterwards the analysis of micro-topography, scanning electron microscopy images and electrical conductivity measurements was used. Results indicate that double-forging improved the tungsten's durability to irradiation. Nevertheless, powerful pulses lead to significant damage of the sample, which will lead to further deterioration in the bulk. Although the average micro-roughness on the sample's surface does not change, the overall height/depth ratios can change.

1. Introduction

Long and thorough theoretical and experimental investigations have revealed that different powerful fusion devices with magnetic or inertial plasma confinement planned for the future have a serious problem in common: the damage of plasma facing components (PFCs) occurs due to steady state and transient thermal loads and interaction with plasma particles. There has been some progress in understanding the interactions between powerful plasma fluxes and materials' – in several cases, the calculated heat flux factors for off-normal events on ITER have been used for carrying out experiments on materials. The aforementioned predicted reference values for ITER are as follows: edge-localized modes (ELMs) – 2–6 kW $s^{1/2}/cm^2$; vertical displacement events (VDEs) – 60 kW $s^{1/2}/cm^2$; disruptions 10–20 kW $s^{1/2}/cm^2$ [1]; and up to 10–47 kW $s^{1/2}/cm^2$ for HiPER [2] and until 100 kW $s^{1/2}/cm^2$ for NIF [3]. JET and many different special plasma-material interaction facilities are using those values on plasma generators (such as Pilot-PSI, Magnum-PSI, QSPA Kh-50, PISCES-B, etc) [4–7], ion beam facilities (MARION and GLADIS) [8,9], electron beam facilities

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(JUDITH-2) [10] or pulsed lasers, to irradiate PFCs.

Although, there is still no device that can obtain exactly the same values of the parameters characterizing plasma-material interaction (e.g. power flux density, duration of interaction, energy of D/T/He plasma, etc) as have been predicted for ITER, DEMO or NIF, thorough research on such values of the parameters is needed. Research can be done by using different plasma facilities that are capable of generating high temperature plasma with the same heat flux factors.

The main factor of the plasma or heat flow is the so-called heat flux factor (or heat damage factor), defined as $F = q{\cdot}\tau^{1/2}$, where q is the power flux density of the plasma load (falling onto material) and τ is the duration of plasma/heat/particles flow. The heat flux factor is proportional to the temperature increase on the surface of material. This relation has been used as an indicator of thermal shock damage for graphite [11] and is widely used to characterize plasma heat loads on fusion-related materials [12–14]. By varying the influence time of heat flow and power flux densities during experiments on suitable devices it is possible to achieve such values of the heat flux factor that have been predicted for off-normal events on ITER or for other fusion devices.

One of the little investigated areas is related to the study of combined effects of different kinds of plasma and heat flows on the PFCs surfaces. This is investigated for example by using combined effects of H/He ion fluxes and electron beams on samples of pure tungsten (W) or specially processed double forged tungsten (DFW) [4,15–17]. Lately, the effects of different kinds of plasma flows on DFW have been investigated and studied in comparison with materials irradiated with only one kind of pulses [18].

Nevertheless, it would be beneficial to study how different kinds of plasma-material interaction events may interplay. Thus, in the current research tungsten samples are irradiated twice. At first, series *a*, the samples are irradiated with plasma-ions streams which have heat flux factors that are in concurrence with either the disruptions or VDEs on ITER. The specific heat flux factors depend on the facility and the specific used regimes. Those regimes are referred to as ”harsh” regimes because of their strong influence. The second, *b* series of irradiation are conducted with plasma-ion streams with heat flux values either similar to the occurrence of ELMs on ITER or below that i.e. with the ”mild” regime.

The progress in the study of different tungsten grades and alloys must also be noted. Different researchers have studied different grades of pure tungsten (W) or tungsten doped with lanthanum-oxide, yttrium-oxide, titanium-carbide or tantalum [12,13,15–24]. In recent years research has also been conducted on tungsten grades in which the mechanical properties of tungsten have been improved by different methods. One of those grades is the aforementioned DFW, in which case the double forging has improved the samples' mechanical and thermal properties compared to the properties of the tungsten samples that have been forged only once. The DFW has been found to be one of the suitable candidates for divertor's plasma facing material.

In the present study, the changes of the surface structure and the properties in the bulk of the double forged tungsten are investigated after the samples have been irradiated twice with high temperature deuterium plasma with varying power fluxes. Six samples of DFW are irradiated with deuterium plasmas, which heat flux factors are related to off-normal events of ITER. To characterize the development of surface defects (mesh of cracks, blisters, droplets etc) scanning electron microscopy (SEM) is used. To find the bigger surface defects the irradiated samples are studied by 3D profilometry (3D micro-roughness). The effect of shock wave of fast ions and plasma in the bulk of samples is studied using measurements of electrical conductivity. The relations of damages and plasma pulses regimes (power flux density, heat flux factor, number of plasma pulses) is analysed.

2. Material and methods

As several previous studies have shown, the process of double forging has changed the properties of tungsten remarkably, often in a favourable way in context of using tungsten as a plasma facing material [25–28]. In several studies it has been found that due to double forging, DFW has lower anisotropy and greater hardness than single forged tungsten. The primary aim of double forging was the use the densification process to yield an isotropic material. Due to the manufacturing process of DFW, the disc-like shaped grains lay parallel to the surface. The elongated structure of tungsten grains is achieved due to the forging process. However, it was found that the double forging led to negligible porosity at the edges, and increasing amount of porosity (up to 1–2%) in the centre. The increasing porosity located within the grains and grain boundaries is connected to the recrystallization process as grain growth was prevented in the centre of tungsten disks. [28].

During current research, polished DFW with dimensions $12 \times 12 \times 5$ mm^3 was used as the material for samples. The material was prepared for experiments by PLANSEE and Forschungszentrum Juelich (Germany), and supplied by IAEA (International Atomic Energy Agency) for Round-Robin tests in different facilities.

The distribution of surface defects of the irradiated samples was analysed by scanning electron microscopy (SEM) using Zeiss EVO MA-15 with energy-dispersive X-ray spectrometry (EDS).

The 3D measurement of micro-roughness was carried out by Bruker 3D white light Optical Microscope Contour GT-K (vertical resolution < 0.01 nm, lateral resolution 0.38 μm, single image resolution 1280 × 960 pixels). This also allowed estimatingthe 2D micro-roughness parameters as average of five areas over the investigated surface. The results included in the current study are the arithmetic mean surface roughness (R_a) of height distribution and the total height of the roughness profile (R_t).

Instead of using the materials' cross-sectioning for estimating the damages in the bulk of the material non-destructive study method of electrical conductivity measurement was used. It is known, that electrical conductivity of solid material depends on concentration of point defects (vacancies, Frenkel pairs, impurities), dislocations, micro-cracks, and other occurring bulk defects. The measuring was carried out at Metrosert (Estonia), using the electrical conductivity etalons set NPL no 178 and the eddy current instrument Sigmatest 2.069, which enables to measure conductivity of non-ferromagnetic metals [29]. During the measurements the conductivity was measured from the centre of the damaged area of each of the samples. The frequencies that were used during the measurements were: 60 kHz, 120 kHz, 240 kHz, 480 kHz and 960 kHz. The results were adjusted to be in accordance with temperature of 20 C.

3. Experimental setup

The irradiation of each of the DFW samples was carried out in two separate series of experiments using plasma-ion pulses with different plasma and heat flow parameters. For that three different plasma-focus devices were used: PF-12 at Tallinn University (TU), PF-6 and PF-1000U at the Institute of Plasma Physics and Laser Microfusion, Warsaw (IPPLM), and also a quasi-steady plasma accelerator QSPA Kh-50 at Kharkov Institute of Plasma Physics (KIPP). In all of the PF-devices deuterium was used as working gas, in QSPA Kh-50 hydrogen plasma was used. In PF-devices slow plasma (E_i~0.1–1 keV) is generated (also see Fig. 1). When the plasma sheath is compressed to the pinch, also the fast ions (E_i~100 keV) and neutrons due to fusion processes (fast ions