Applied Surface Science 443 (2018) 311–320

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Full Length Article

Effects of fusion relevant transient energetic radiation, plasma and thermal load on PLANSEE double forged tungsten samples in a low-energy plasma focus device

S. Javadi [a], B. Ouyang [b], Z. Zhang [c], M. Ghoranneviss [a], A. Salar Elahi [a], R.S. Rawat [b],*

[a] Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] NSSE, National Institute of Education, Nanyang Technological University, 637616, Singapore
[c] Institute of Materials Research and Engineering, A*STAR (Agency for Science, Technology and Research), #08-03, Fusionopolis Way, Innovis 138634, Singapore

ARTICLE INFO

Article history:
Received 8 August 2017
Revised 26 January 2018
Accepted 5 March 2018
Available online 6 March 2018

Keywords:
Plasma facing component material
Tungsten
Fusion relevant transient load
Structural defects
And plasma focus device

ABSTRACT

Tungsten is the leading candidate for plasma facing component (PFC) material for thermonuclear fusion reactors and various efforts are ongoing to evaluate its performance or response to intense fusion relevant radiation, plasma and thermal loads. This paper investigates the effects of hot dense decaying pinch plasma, highly energetic deuterium ions and fusion neutrons generated in a low-energy (3.0 kJ) plasma focus device on the structure, morphology and hardness of the PLANSEE double forged tungsten (W) samples surfaces. The tungsten samples were provided by Forschungszentrum Juelich (FZJ), Germany via International Atomic Energy Agency, Vienna, Austria. Tungsten samples were irradiated using different number of plasma focus (PF) shots (1, 5 and 10) at a fixed axial distance of 5 cm from the anode top and also at various distances from the top of the anode (5, 7, 9 and 11 cm) using fixed number (5) of plasma focus shots. The virgin tungsten sample had bcc structure (α-W phase). After PF irradiation, the XRD analysis showed (i) the presence of low intensity new diffraction peak corresponding to β-W phase at (211) crystalline plane indicating the partial structural phase transition in some of the samples, (ii) partial amorphization, and (iii) vacancy defects formation and compressive stress in irradiated tungsten samples. Field emission scanning electron microscopy showed the distinctive changes to non-uniform surface with nanometer sized particles and particle agglomerates along with large surface cracks at higher number of irradiation shots. X-ray photoelectron spectroscopy analysis demonstrated the reduction in relative tungsten oxide content and the increase in metallic tungsten after irradiation. Hardness of irradiated samples initially increased for one shot exposure due to reduction in tungsten oxide phase, but then decreased with increasing number of shots due to increasing concentration of defects. It is demonstrated that the plasma focus device provides appropriate intense fusion relevant pulses for testing the structural, morphological and mechanical changes on irradiated tungsten samples.

1. Introduction

Materials that are considered to be candidates for plasma facing component (PFC) in fusion reactors have to withstand a multitudes of extreme loading conditions. Transient heat loads lead to the material degradation like thermal shock and thermal fatigue related cracks, recrystallization and melting. The collision of energetic fusion neutrons cause the material degradation affecting the lifetime of wall components. Energetic plasma species cause the chemical changes in materials as well as physical sputtering which causes the erosion and re-deposition processes of mixed layers. For high atomic number (Z) materials, such as tungsten W, the maximum acceptable impurity concentration in the plasma is very low as it would lead to very high bremsstrahlung radiation energy loss resulting in plasma cooling. There is a limited selection of the suitable PFC materials that can be used under extreme fusion environment such as the one expected in International Thermonuclear Experimental Reactor (ITER), the biggest Tokamak device currently in construction phase and expected to be operational in later half of next decade [1]. The candidate materials and their compounds for the deuterium/tritium operation phase of ITER device include beryllium, tungsten and carbon fiber composite. Tungsten is one of the most important material for first wall of fusion reactor [2–4] in the divertor and baffle regions. The divertor is the component in the Tokamak machines with most intense plasma

---

* Corresponding author.
E-mail address: rajdeep.rawat@nie.edu.sg (R.S. Rawat).

https://doi.org/10.1016/j.apsusc.2018.03.039

contact which covers the bottom part of the plasma-facing surface (expected to be 210 m^2 for ITER). The plasma-facing material of the divertor must be bonded to a high thermal conductivity heat sink material as they will be subjected to high heat flux plasma up to 20 MW/m^2. The excellent properties of tungsten which makes it to be a main candidate as PFC material, are its high melting point (3422 °C), high atomic number, high sputtering resistance to energetic particles, high thermal conductivity (173 $W\,m^{-1}\,K^{-1}$ at room temperature and 100 $W\,m^{-1}\,K^{-1}$ at 1527 °C), low tritium retention and better thermo mechanical properties. Since the PFC materials are prone to damage due to its direct contact with extreme radiation and intense continuous as well as transient heat load conditions, the researchers have concentrated their work on the evaluation of radiation induced damages on fusion reactor materials [5–10]. Results of tungsten material performance and brittle crack formation under transient heat loads and its dependence on base tungsten temperature and absorbed power density can be found in literature [11–14].

In recent decades, various methods such as inertial electrostatic confinement [15], new linear plasma device (MAGNUM-PSI) [16], divertor simulator [5], compact electron cyclotron resonance (ECR) device [17], magnetized plasma gun [18] and high average power laser [19] have been used to investigate the radiations and heat load effects on PFC materials. Plasma focus devices [9–10,20] have also been utilized as a tool to experimentally study the effects of radiations on different materials proposed for different parts of nuclear fusion devices. Plasma focus (PF) is a simple and cost effective pulsed plasma accelerator that makes use of the self-generated magnetic field to compress the plasma to a high temperature and high density for a short duration. The PF device during the implosion phase of the discharge and at the "current abruption" event generates powerful streams of plasma, relativistic electrons and fast ions, neutrons and hard x-rays resulting in intense transient heat loads on target surface placed down the anode stream. Gribkov [21] reported that the streams of high-temperature plasma ($\sim$1 keV) have a pulse duration $\tau \sim 100$ ns and power flux density on the target's surface $q \approx 10^{13}–10^{14}$ W/m^2. High-energy electron and ion beams ($E \sim 0.1\ldots1.0$ MeV) have a pulse duration in the range $\tau \sim 10–50$ ns, and their power flux density on an impediment plate may reach values up to $q \approx 10^{17}$ W/m^2 [21]. In current and future magnetic fusion reactors, operating on long current pulse duration such as ITER, the plasma facing material will still experience very high amounts of localized energy in a very short period of time due to transient events such as plasma disruption (PD), vertical displacement events (VDEs) and the edge-localized mode (ELM) [22]. The inner and outer plates of the divertor in ITER may experience loads of $\sim$7–40 MJ/m^2 and $\sim$4–25 MJ/m^2 due to plasma disruption. The energy deposition on the outer wall blanket modules during VDE may increase to $\sim$20–30 MJ/m^2 in $\sim$0.1–0.3 μs. The ELM, if it is controlled, may impose loads of 0.5 MJ/m^2 and 0.3 MJ/m^2 on the inner and outer plates, respectively, of the divertor, whereas the uncontrolled ELM can impart corresponding loads of 10 MJ/m^2 and 6 MJ/m^2 on the inner and outer plates of the divertor within $\sim$0.25 to 0.5 μs [23]. Moreover, in inertial fusion devices, such as National Ignition Facility, the thermal loads will occur only in transient form with transient power flux densities of about $10^{6\text{-}8}$ MW/m^2 with pulse duration of 0.1–10 μs [24]. Hence, the PF devices are highly suitable to emulate intense transient heat load conditions that are produced in both magnetic and inertial fusion devices. The significance of PF devices as a suitable laboratory tool for testing of candidate materials for fusion reactor is also evident by the participation of large number of PF device groups in IAEA organized dedicated Coordinated Research Programs (CRP). These CRP are: (i) F1.30.12 (2008–2011) on "Integrated approach to Dense Magnetized Plasma applications in nuclear fusion technology" [25], (ii) F1.30.13 (2011–2015) on "Investigations of Materials under High Repetition and Intense Fusion-relevant Pulses" [26], and (iii) recently started F1.30.16 (2016–2019) on "Pathways to Energy from Inertial Fusion: Materials beyond Ignition".

The PF device is a rich source of energetic ion beams [27,28], neutrons [29], X-rays [30] and relativistic electrons [31], and has been successfully used in various applications like a neutron source for pulsed activation analysis [32], a high flux X-ray source for microlithography [33], X-ray interstitial radio-surgery [34] and an electron source for microlithography [35]. Above mentioned applications of PF device, however, have been explored on limited scale with very limited isolated work. The major application of PF devices that has emerged very strongly in last two decade is its application for material synthesis and processing. More than 100 journal papers have been published in this field and this field is growing very fast due to several intrinsic key features of PF devices that are not available in other plasma devices used for material synthesis and processing. Excellent review of application of PF devices for materials science and technology is provided in few review papers published recently [36–38]. For example, the high energy ions produced in the PF devices have been used in applications like surface modification [39], thin film deposition [40–42], ion assisted coating and ion implantation [43] etc. The instability accelerated ions in PF devices have wide range of energies from tens of keV to few MeV [44,45]. Bostick et al. [46] studied the effect of deuterium ion irradiation on the plates of Al, Cu and Si using a PF device. They observed the formation of surface defects such as holes, pores and blisters on the plates. Bhuyan et al. [9] used a low energy PF device to investigate the proton induced damages on tungsten samples. They reported the development of compressive stress on tungsten surface and a reduction in hardness values of the treated sample. Pimenov et al. [47] used two different types plasma focus devices (PF-1000 (Mather type) and PF-60 (Filippov type)) to demonstrate phase-structural transitions, elemental composition changes and features of damage in austenitic and ferritic steels irradiated by pulsed ions and high temperature hydrogen and deuterium plasma, respectively. Dutta et al. [48] studied the irradiation effect of helium ions on tungsten sample using PF device to show the different types of crystalline defects, a shift of major peaks towards higher Bragg angles and a marginal reduction in the hardness value of the irradiated samples. Niranjan et al. [49] investigated the surface modification of different materials with fusion grade plasma by using an 11.5 kJ plasma focus device. They reported the formation of cracks, blisters, and craters after irradiations and the changes in the structural phase transformation in surface layers of the samples.

In the present paper, a low energy plasma focus device is used to study the effect of deuterium ions and neutrons irradiations on different physical properties of irradiated tungsten samples under various experimental conditions. The irradiated samples are characterized using X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM), X-ray photoelectron spectroscopy (XPS) and micro hardness tester. The key role of tungsten as a front runner choice for PFC material of next generation fusion reactor and the relevance of the plasma, radiation and heat loads generated in PF devices to tokamak and inertial fusion reactor, motivated us to use the PF device to study deuterium ions and neutrons irradiation effects on the structural, morphological, and mechanical properties of the tungsten samples.

2. Experimental set-up and methodology

The plasma focus device used in this investigation is a 3.0 kJ Mather type plasma focus device designated as United Nations University/ International Centre for Theoretical Physics Plasma