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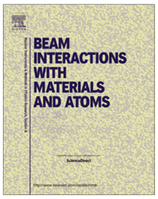

Impact of helium implantation and ion-induced damage on reflectivity of molybdenum mirrors

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ABSTRACT

Molybdenum mirrors were irradiated with Mo and He ions to simulate the effect of neutron irradiation on diagnostic first mirrors in next-generation fusion devices. Up to 30 dpa were produced under molybdenum irradiation leading to a slight decrease of reflectivity in the near infrared range. After 3×10^{17} cm^{-2} of helium irradiation, reflectivity decreased by up to 20%. Combined irradiation by helium and molybdenum led to similar effects on reflectivity as irradiation with helium alone. Ion beam analysis showed that only 7% of the implanted helium was retained in the first 40 nm layer of the mirror. The structure of the near-surface layer after irradiation was studied with scanning transmission electron microscopy and the extent and size distribution of helium bubbles was documented. The consequences of ion-induced damage on the performance of diagnostic components are discussed.

1. Introduction

Plasma diagnosis is essential to ensure effective operation of controlled thermonuclear fusion devices. Mirrors and windows are indispensable components of all optical diagnostic systems [1,2]. Processes of plasma-wall interactions (PWI) in tokamaks cause material erosion and migration [3–8] which may modify mirrors and windows. In a reactor-class machine, windows cannot be exposed directly to plasma as their transmissivity would be degraded under intense X-ray and gamma radiation. Mirrors facing plasma directly inside the confinement chamber are called "first mirrors". The transmission of all optical signals will rely on such mirrors while maintaining proper neutron shielding. This will be done by using metallic mirrors to guide plasma light through a labyrinthine path through the shielding block. In a reactor of high power and long duty cycle the impact of operation on first mirrors is expected to be much stronger than in current machines due to: (i) upscale in material erosion and migration from the first wall and – as a consequence – in the fluency of neutral particles escaping the plasma; (ii) neutron-induced effects such as damage and transmutation leading also to helium bubble formation; (iii) irradiation by helium from the deuterium–tritium fusion reaction: $D + T \rightarrow n + \alpha$.

Erosion by impinging particles will change roughness and chemical composition of material, while co-deposition of plasma impurities may lead to the formation of thick layers on the mirror's surface. In both cases the degradation of specular reflectivity will occur. Such phenomena arising from material migration will be decisive for diagnostics in the International Thermonuclear Experimental Reactor (ITER) [1,2]. For that reason, a comprehensive First Mirror Test (FMT) [9–14] for ITER has been carried out in the JET tokamak, which is the world's largest controlled fusion device. Dedicated experiments were performed also in other machines [15–21]. In a demonstration reactor of a fusion power plant (e.g. DEMO), in addition to material migration, there will be neutron-induced damage and implantation of helium from the D–T fusion reaction. The extent of these effects on the mirrors is still to be examined.

Earlier works in this field have shown a detrimental effect of helium irradiation on reflectivity of diagnostic mirrors [22]. However, nothing is known about the synergetic effects under neutron and helium fluxes. To our knowledge, there is also no information about the effect of particle-induced damage on mirror reflectivity. The aim of the study is to determine the impact of neutron damage (simulated by high-Z ion impact) and helium implantation on the

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reflectivity of molybdenum mirrors. The rationale for selecting molybdenum as a target material is presented in Section 3.1. The paper is organised in such a way that first an optically active layer in mirrors is defined. This is followed by the description of the irradiation conditions, material pre-characterisation and results on optical properties and near-surface composition.

It is perfectly well understood by the authors that the modification and damage generated in mirrors under ion irradiation is not equal to that caused by neutrons, but the test under fully realistic conditions will become possible only in a real working fusion reactor. Damage-related PWI phenomena, e.g. impact on fuel retention, are studied in materials irradiated by heavy ions [23–25].

2. Optically active layer

The function of a mirror is to reflect light specularly. Only the very top layer contributes to this task, whereas the rest of the mirror provides a structural base. The latter function is of extreme importance in the case of mirror blocks in a reactor, as they must have robust thermo-mechanical properties to prevent distortion or deformation. The following section explains how the thickness of the optically active layer is derived. This information will be used later to define the ion irradiation conditions in the experiment.

According to the Beer–Lambert law, light intensity penetrating a metal falls exponentially with a decay constant known as absorption coefficient. The absorption coefficient depends on material and wavelength, as shown in Fig. 1(a) [26,27]. The depth distribution of reflected light is described as $R(x,\alpha) = 2\alpha e^{-2x\alpha}$, where x is the depth in a mirror and α is the absorption coefficient. This expression is derived by considering: (i) light intensity falls exponentially when entering and exiting the mirror, and (ii) the integral of $R(x,\alpha)$ over depth equals one. Fig. 1(b) shows the depth distribution of reflected light in a molybdenum mirror for the highest ($\alpha = 0.15$) and the lowest ($\alpha = 0.05$) absorption coefficients in the 300–2400 nm wavelength range. One perceives that most of the reflected light comes from the first 20 nm layer, which will be defined as the optically active layer.

3. Experimental

3.1. Material selection

The research has been carried out for mirrors made of polycrystalline molybdenum. The test, as mentioned in the introduction, was related to the simulation of neutron-induced effects that may degrade mirror performance in DEMO. Molybdenum has seven naturally occurring isotopes, three of which are measurably unstable with very long half-live times of more than 10^{14} years [28]. From an activation point of view, it is not the ideal material for in-vessel applications because of transmutation to long-lived radioactive isotopes of technetium, niobium, and molybdenum itself. Other major transmutation products include zirconium and helium, both originating mainly from (n,α) and $(n,n\alpha)$ reactions on the Mo isotopes.

However, all mirror-relevant materials will become partly transmuted and also activated under high neutron fluxes. Therefore, an argument for using a low-activation material as a substrate for highly reflective coating (e.g. vanadium with Rh film [29]) in a highly activated reactor environment would have to be carefully assessed from the practical point of view, i.e. verified with respect to necessary benefits: thermo-mechanical stability, optical and erosion/corrosion properties, etc. The rationale for choosing molybdenum for the test has been threefold: (i) Mo has been selected for mirrors in ITER [8]; (ii) there is a robust data base and experience with Mo mirrors which are used in JET in the Fist Mirror Test for ITER [9–14]; (iii) at present, there is no clear suggestion or indication regarding the mirror material for DEMO.

3.2. Irradiation conditions

The irradiation of molybdenum mirrors with $^{98}Mo^{+}$ and $^{4}He^{+}$ ions was performed at the Ion Technology Centre (ITC) of the Ångström Laboratory at the Uppsala University, Sweden. It was done using a 350 kV Danfysik 1090 implanter with a beam current up to 1 mA. Actual irradiations were preceded by SRIM [30] simulations of the damage and implantation depth-profiles. The reason for the simulations was to find the proper energy of the ion beam to target the optically active layer and to deposit ions within that surface layer. The damage and implantation profiles under helium and molybdenum bombardment are plotted in Fig. 2(a) and (b), respectively.

The irradiation of molybdenum mirrors was performed with a 30 keV $^{98}Mo^{+}$ beam at room temperature (RT) and at 573 K at three fluency levels: 1.5; 15 and 45×10^{14} cm^{-2}. Helium irradiation was performed only at room temperature with a 2 keV $^{4}He^{+}$ beam, and also at three fluency levels: 3, 6 and 9×10^{17} cm^{-2}. Helium irradiation was not performed at high temperature because the holder used for low-energy irradiations could not be externally heated.

The selection of ^{98}Mo as the irradiation ion is based on the fact that this isotope is the most common in Mo's naturally occurring composition (24 atomic %). Thus, recoils of this isotope would be the most frequent in an un-transmuted sample exposed to neutron irradiation. The actual neutron-induced process in a reactor would also produce recoils of other Mo isotopes, including those not present in the starting composition (such as ^{93}Mo and ^{99}Mo), as well as recoiling isotopes of other elements such as Nb and Tc [31].

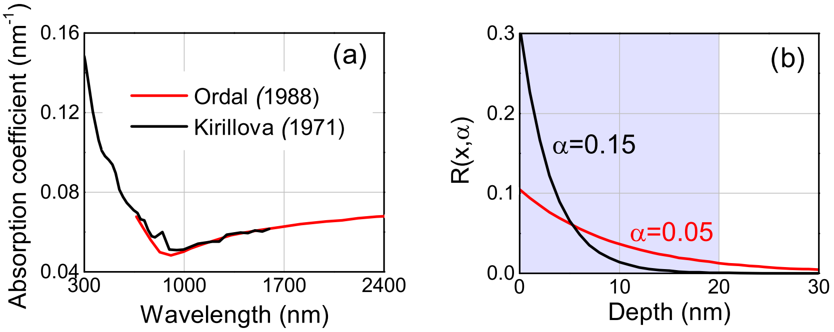

Fig. 1. (a) Molybdenum absorption coefficient as a function of wavelength [26,27], (b) depth distribution of reflected light in a molybdenum mirror at the highest and lowest absorption coefficient in the wavelength range from 300 to 2400 nm. The optically active layer is marked in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)