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Impact of low energy helium irradiation on plasma facing metals

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Abstract

Effects of helium ion irradiation for tungsten and other metals have been studied extensively as functions of ion energy, temperature and fluence, for a wide range of burning plasma conditions, using not only ion accelerators, but also large-sized plasma confinement devices such as TRIAM-1M and LHD. In this paper, recent results on blistering, erosion and many other irradiation effects such as internal damage evolution, change of mechanical properties and heat load resistance, and synergetic effects with neutron irradiation, are comprehensively reviewed for better understanding of the performance of tungsten under helium plasma bombardment. It is emphasised that helium irradiation is a serious issue for tungsten as a plasma facing material under burning plasma condition.

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Keywords: Tungsten; Helium; Bubbles; Plasma facing materials; Radiation effects

1. Introduction

Under burning plasma conditions, plasma-facing materials (PFM) suffer irradiation of helium in addition to that of hydrogen isotopes. Sputtering and blistering by helium ions with energy above a few keV were studied extensively many years ago [1]. More recently, the effects of helium ion irradiation on tungsten and other metals have been studied for reactor relevant plasma conditions as functions of ion energy (eVs to keVs), temperature (300–3000 K) and fluence (1×10^{19}–1×10^{27} He^+/m^2), using both accelerators and large-sized plasma confinement devices such as TRIAM-1M and LHD. In these studies, not only blistering and erosion, but also many other irradiation effects were examined such as internal damage evolution, change of mechanical properties and heat load resistance, retention and desorption of gas, etc. In this paper we review recent results to gain a better understanding of the performance of metallic PFMs under helium plasma bombardment relevant to burning plasma conditions. The main focus will be on tungsten.

2. Radiation effects by low energy helium ions

2.1. Distinctive features of helium irradiation effects

The behaviour of helium in metals is characterized by its fast thermal migration through the lattice and very strong attractive interaction with defects such as

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vacancies, vacancy clusters, impurity atoms and even themselves. In the case of irradiation by helium with keV range energy, the number of helium atoms implanted into the material is comparable to the number of radiation induced point defects (vacancies and interstitials). Moreover, the helium implantation and the resultant displacement damage are localized in the subsurface region of about some 10 nm or less. The radiation induced defects and helium atoms are accumulated there by cluster formation.

2.2. Fundamental defect possesses under helium ion irradiation

If the energy of the incident helium is higher than the threshold value for the displacement damage (0.5 keV for tungsten), interstitials and vacancies with the same number are formed in the narrow projected range beneath the surface. Due to the very low migration energy (0.08 eV for tungsten) the interstitials migrate thermally even at room temperature and form interstitial type dislocation loops at the start of the irradiation. Continuing the irradiation, the loops grow further and the less mobile vacancies are highly accumulated in the narrow damaged area. The majority of vacancies trap helium atoms. The behaviour of the vacancies and the vacancy-helium complexes depends on the specimen temperature, i.e., at low temperatures where thermal migration of the vacancies and the vacancy-helium complexes are scarcely expected, very dense fine helium bubbles (about 1 nm in diameter) are formed by absorbing more and more helium. On the other hand, large helium bubbles are formed at high temperatures where vacancies and helium bubbles can migrate thermally [2].

Radiation damage also occurs for irradiation with very low energy helium (less than about 0.5 keV for tungsten), where displacement damage is not expected to occur due to the absence of the required knock-on energy. Helium atoms, once injected into the material, aggregate by themselves and grow as bubbles by pushing out the host atoms from their lattice sites (formation of interstitials) and/or interstitial loops. We note that preexisting vacancies are not necessary for the formation of the helium bubbles. Of course, a supply of vacancies (radiation induced vacancies and thermal vacancies) is very helpful for bubble formation. Details of defect formation processes under helium ion irradiation are discussed in [2]. Such type of damage accumulation for the sub-threshold energy condition has not been observed in electron beam irradiations and hydrogen ion irradiations at relatively low fluxes [3].

2.3. Temperature dependence of internal damage

Formation of helium bubbles in tungsten at elevated temperatures was examined for impact energies of 0.25 keV and 8 keV, corresponding to cases with and without displacement damage, respectively [2]. Fig. 1 shows TEM micrographs of damage accumulation at different temperatures for 0.25 keV He^+ (flux: 10^{18} He^+/m^2 s; fluence: $\sim10^{21}$ He^+/m^2). Though the efficiency of damage accumulation is lower for 0.25 keV due the absence of vacancies supply, the fundamental damage processes are similar. Fine bubbles of about a few nanometer in diameter are formed densely at room temperature. The phenomenon does not change much up to 873 K, where thermal migration of vacancies is still inactive. The temperature range below 873 K is noted here as ‘low temperature regime’.

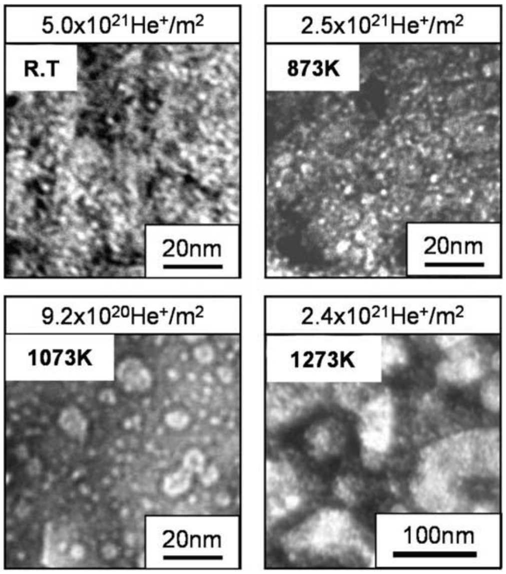

Fig. 1. Temperature dependence of bubble formation in tungsten due to 0.25 keV He^+ irradiation.

In contrast, the number of bubbles decreases but the individual bubbles grow larger at temperatures where sufficient thermal migration of vacancies is expected (1073 K and 1273 K). This temperature range is noted here as ‘high temperature regime’. It was found by Nishijima et al. [4] that large bubbles of ~2 μm in diameter were formed at 2600 K by a very low energy helium plasma (10 s eV). In the high temperature regime, coalescence of bubbles through the thermal migration process plays a major role for the growth of the bubbles. A similar phenomenon was dynamically observed by TEM in a Fe–Cr–Ni alloy under helium irradiation at high temperatures [5]. Due to very high binding energy with helium [6], the bubbles can survive even at such high temperatures. This type of bubble formation in the high temperature regime has not been observed for very high fluence irradiations with hydrogen plasmas [7] and hydrogen ions [8]. We note that the formation of bubbles in a wide temperature range is a distinctive phenomenon of helium irradiation.

2.4. Correlation between internal damage and surface structure

Blistering by He^+ irradiation at relatively high energies (> a few keV) was extensively studied about 20–30 years ago [1], and it was well established that inter-bubble cracking through the highly pressurized fine bubbles formed at or near the projected range of the incident ions causes blistering in the low temperature regime.

Recent helium glow discharge studies in LHD showed that blistering occurred even by helium ions with only ∼200 eV, less than the threshold energy for displacement damage. In addition to blistering, very heavy damage was accumulated in the sub-surface region; see Fig. 2 [9]. Various size bubbles (1–25 nm diameter) were formed together with dense dislocation loops. The TEM images also indicate the formation of nano-size cracks. It is considered that some of the cracks link the bubbles to the surface. After erosion by blistering at around $10^{21\sim22}$ He^+/m^2, erosion due to sputtering and the formation of bubbles progressed continuously. With increasing fluence, a thick damage layer is formed as steady state which is reached by balancing sputtering erosion and helium injection. In the case of SUS316L, the thickness of the layer was about 45 nm, which is much deeper than that of the projected range of the incident helium (∼1 nm). Some of the bubbles appear at the surfaces as holes caused by sputtering and some are linked to the surface through nano-cracks. Because of the formation of holes and cavities the effective surface area will increase. In fact, the highly damaged layer may act as good trapping sites for gas such as helium, hydrogen, oxygen, etc., and may play an undesired role for particle control of the plasma. Details of helium and hydrogen trapping in the damage layer have been discussed in [10] and [11], respectively.

The relation between the surface morphology and the internal damage in the high temperature regime is completely different. Migration and growth of bubbles play essential roles. Fig. 3 shows the surface morphology and corresponding internal damage of tungsten irradiated at 1273 K with 8 keV He^+ to the fluence of 1.5×10^{22} He^+/m^2. Comparable size surface bulges (a, b) and bubbles inside the specimen (c) indicate that the bulges are formed by the bubbles directly underneath. It is expected that such type of surface modification may change not only the optical properties such as reflection coefficient but also the thermal conductivity at the surface.

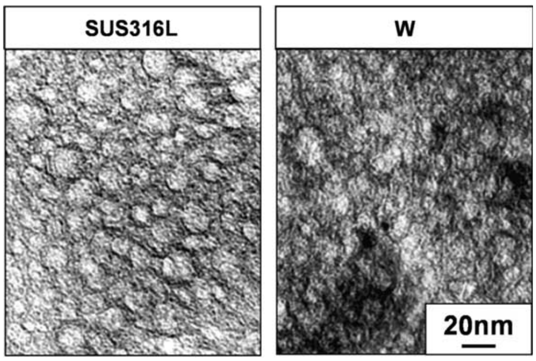

Fig. 2. Bubbles formed in SUS316L and W at room temperature irradiated by LHD helium glow discharge plasma of ∼200 eV at a fluence of $\sim4\times10^{22}$ He^+/m^2.

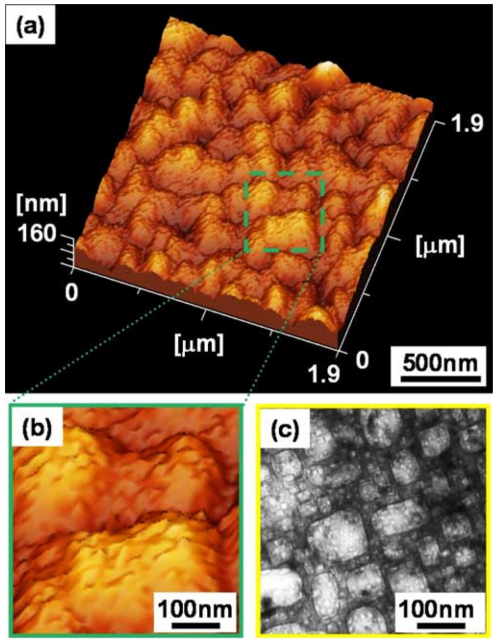

Fig. 3. Surface modification and underlying internal damage formed by 8 keV He^+ irradiation at 1273 K at a fluence of 1.5×10^{22} He^+/m^2. (a) and (b) image of surface taken with atomic force electron microscopy; (c) TEM image.

It was reported that cyclic heat loads with 14 keV He^+ cause a peculiar morphology [12]. The surface, reaching 2600 K at each cycle, is fully covered with small projections just as the inner surface of the small intestine. It is clear that migration and coalescence of the helium bubbles play an essential role for the formation of such peculiar structure.

2.5. Influence on mechanical properties and heat load resistance

Formation of helium bubbles brings changes in hardness at the sub-surface region [13]. Fig. 4 shows the surface hardening of tungsten irradiated by He^+ at 300 K and 873 K. Once the helium bubbles are formed the hardness increases remarkably. The hardness becomes

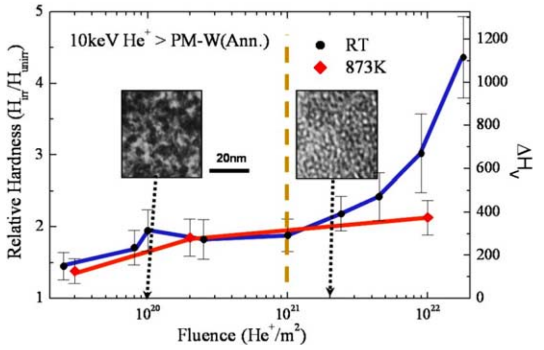

Fig. 4. Surface hardening by He^+ irradiation at room temperature and 873 K.

more than 4 times higher than that of the un-irradiated material at a fluence of $\sim 2 \times 10^{22}$ ions/m^2.

It was also reported that surface erosion by high heat loads was greatly affected by helium pre-injection [14]. Fig. 5 shows the temperature and erosion of the surface of helium pre-injected tungsten for a heat load of 13 MW/m^2 for 30 s as a function of helium fluence. The pre-injection was done at room temperature with 8 keV He^+. Once the helium bubbles and blisters are formed, the surface temperature increases due to the reduction of thermal conductivity at the surface. The weight loss at 1×10^{22} He^+/m^2 is about 0.3 mg, corresponding to an estimated erosion depth of $\sim$0.8 µm, based on the specimen size. This value is about 10 times larger than the helium ion range, indicating that the irradiation effects at very high fluence are not restricted in the narrow ion range but expand much deeper. It is likely that the helium diffused far beyond the projected range, causing embrittlement of a rather thick sub-surface area, which then exfoliated by thermal shock.

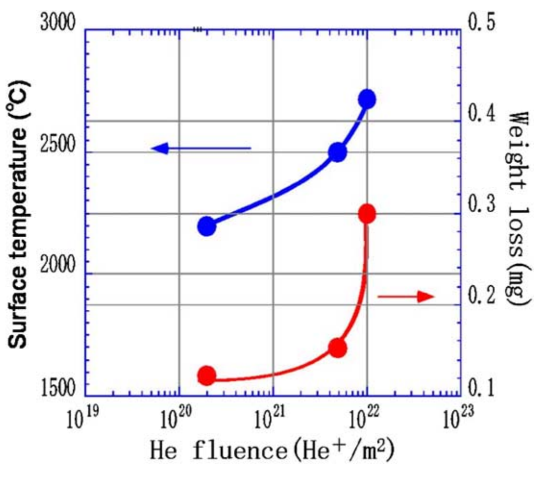

Fig. 5. Effects of helium irradiation on heat load resistance (indicated by surface temperature rise) and surface erosion measured by weight loss.

2.6. Synergistic effects with neutron irradiation

Some of the injected helium, which can successfully evade the trapping sites such as vacancies and bubbles localized in the damaged zone, will migrate into the bulk until it gets trapped. For the simulation of radiation damage of plasma-facing materials in reactors, accumulation of helium and point defects under simultaneous irradiations by helium and neutrons has been calculated based on rate theory by considering the diffusion of the point defects and helium. The probability that one vacancy located deep in the material meets with a helium atom diffusing from the incident surface is comparable to the probability of interstitials and vacancies – produced homogeneously by the neutron irradiation – meeting [15]. This means that the behaviour of the vacancies, which result in void swelling and radiation hardening for example, must be strongly controlled by the helium from the plasma. Fig. 6 is an example showing the synergistic effect of diffusing helium. In case of (a), tungsten was irradiated at 1073 K by only Cu^{2+} at 2.4 MeV for 3 dpa, while in (b) it was simultaneously irradiated by $Cu^{2+}$and He^+ at 0.25 keV (1×10^{22} He^+/m^2); here 0.25 keV He^+ ions cannot form displacement damage. Both dense interstitial loops (black images) and fine voids (white images) were formed in (a) but only sparse interstitial loops are seen in (b). The absence of visible voids in (b) indicates that the vacancies cannot form the voids, because they become immobile by absorbing helium. Though this is only one example demonstrating a synergistic effect, it is likely that other synergistic effects may change the scenario of neutron irradiation damage of the plasma-facing materials.

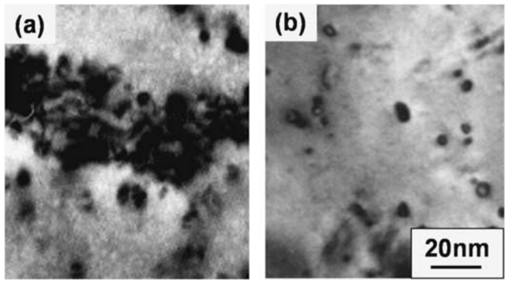

Fig. 6. Comparison of damage by (a) irradiation with high energy Cu^+ only, and (b) simultaneous irradiation with high energy Cu^+ and low energy He^+.

3. Damage in large-size plasma confinement devices

To further study the phenomena of plasma-wall interactions in large-size plasma confinement devices, metallic specimens were exposed to helium plasma discharges in the scrape-off layer in TRIAM-1M [16]. Remarkable formation of dislocation loops and dense fine bubbles was observed in tungsten facing the core plasma after being exposed for only 125 s. It was concluded that the defects are formed mainly by the bombardment of charge- exchanged helium neutrals ejected from the core plasma. According to recent experiments in LHD, interaction with the divertor helium plasma causes serious blistering for tungsten [17].

4. Summary

The most distinctive irradiation effect of helium in tungsten is the formation of helium bubbles for very wide conditions, i.e., above a few 10 eV, from very low dose about 10^{19} He^+/m^2 and up to very high temperatures near the melting point. It is remarkable that self-aggregation results in bubble formation without pre-existing vacancies such as radiation induced ones.

Dense and fine bubbles and dislocation loops are formed at low temperatures, where thermal migration of vacancy-helium complex and bubbles are rather low. They form the thick damaged layer beneath the surface and change the retention of gaseous atoms very much. The helium bubbles induce serious hardening and reduction of thermal conductivity which enhances erosion under high heat load. At high temperatures, internal structure such as large bubbles determined the wavy and peculiar morphology of the specimen surface. It was also pointed out that the synergistic irradiation effects of neutrons and helium plasma would play important roles for radiation damage of the plasma facing materials. These recent results indicate that helium irradiation is a serious issue for tungsten as a plasma facing materials in the burning plasma condition.

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