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Helium-Ion-Implantation in Tungsten: Progress towards a Coherent Understanding of the Damage Formed and its Effects on Properties

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Abstract

Tungsten is a likely material for divertor armour in fusion reactors. We describe recent progress combining multi-technique experiments with atomistic modelling to understand how injected helium interacts with displacement damage and modifies the physical properties of tungsten. Using X-ray micro-diffraction and laser-induced transient grating measurements, we observe both a lattice swelling and modulus change after helium implantation. Surprisingly, a fraction of a percent lattice expansion is associated with an order of magnitude larger reduction in elastic modulus. These observations are interpreted using a combined elasticity and density functional theory model. We also measure a large reduction of thermal diffusivity due to helium implantation. This can be explained in terms of the underlying damage microstructure using a new atomistic kinetic theory model. Together our observations and calculations allow us to begin to form a joined-up picture of helium-implantation-induced damage in tungsten and its diverse effects on microstructure and physical properties.

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Keywords: Tungsten; Ion implantation; Helium; Laue micro-diffraction; Surface Acoustic Waves; Thermal transport

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1. Introduction

Thermo-nuclear fusion promises to be an ideal long-term energy source: sustainable, environmentally friendly and intrinsically safe. Substantial progress has been made with plasma control, and the development of new technology required to make commercial fusion a reality. ITER, currently under construction in the south of France, has the goal of demonstrating a self-sustained fusion reaction over an extended period of time. This is an essential stepping-stone towards building of a first commercial demonstration reactor (DEMO).

A major challenge for fusion reactors beyond DEMO is the lack of materials sufficiently robust to withstand the extreme conditions plasma-facing components will be exposed to[4,5]. For example armour materials in the divertor will be bombarded with 14.1 MeV fusion neutrons, receive an intense flux of helium and hydrogen ions and have to operate at temperatures up to 1500 K. Currently tungsten-based materials are most promising due to their high melting point, good resistance to sputtering, high thermal conductivity, and low tritium retention rate[6].

These extreme conditions lead to significant changes in the structure and properties of tungsten-based materials. At present it is not yet possible to exactly replicate the conditions inside future fusion reactors. Fortunately many aspects of the damage produced by ion and neutron bombardment can be replicated using ion-implantation.

Extensive studies have been carried out using tungsten self-ion bombardment to mimic the damage produced by neutron irradiation. In situ TEM observations and molecular dynamics simulations showed that defect size and frequency of occurrence are linked by a power law[7]. Interestingly the exponent of this power law remains almost the same even when the ion energy is changed, but varies strongly as a function of irradiation temperature[8].

An important question concerns the interaction of gas, produced by transmutation[9] or injected into the material from the surface[10], with irradiation damage. Gas-ion implantation has been used extensively to study this effect and we will here concentrate on the influence of helium, the waste product of the fusion reaction. Pioneering work by Kornelsen, using thermal desorption spectroscopy, showed that helium strongly binds to vacancies and vacancy clusters in tungsten[11]. This has been further confirmed by nuclear reaction analysis[12] and positron annihilation spectroscopy[13,14]. Though small, these defects have a dramatic effect on material properties, for example in tungsten implanted with 3000 atomic parts per million (appm) of helium at 573 K, large increases in hardness have been observed[15].

Interestingly TEM observations of the same sample showed no visible damage[15]. The reason is that TEM is not sufficiently sensitive to “see” the small vacancy clusters in which helium is stored. This is confirmed by image calculations of defect visibility in dark-field TEM measurements that show that only defects larger than ~1 nm can be reliably picked up[16]. This inability to observe He-V clusters in TEM makes it challenging to quantify the defect populations produced by helium ion implantation. Furthermore positron annihilation spectroscopy, thermal desorption spectroscopy or nuclear reaction analysis all only offer millimetre spatial resolution, precluding the observation of heterogeneous defect distributions, defect evolution and accumulation.

In this paper we report recent progress using synchrotron X-ray micro-diffraction to probe the population of helium-induced lattice defects via the lattice strains they cause. Changes in elastic and thermal transport properties in the ion-implanted layer are determined using laser-induced transient grating measurements. Combined with multi-scale calculations our observations allow us to shed light on the complex changes in material structure and properties that defects caused by helium-ion-implantation give rise to, and to make some progress towards a joined-up understanding of irradiation damage.

2. Experimental methodology

2.1. Sample preparation

Tungsten (W) and tungsten rhenium (W-Re) samples were prepared from elemental powders (99.9 %) by plasma arc melting. The resulting slugs had large grains, ranging from 200 to 1000 μm in size, with no preferred orientation. Samples were sectioned into ~1 mm thick slices using a diamond saw and polished mechanically using aluminium oxide paper and diamond paste, finishing with a colloidal silica mechano-chemical polishing step to produce a defect free, high quality finish.