Multi-scale mechanics of tungsten

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Introduction

Pure tungsten is proposed as armour material in plasma facing components in fusion reactors, among which the International Thermonuclear Experimental Reactor (ITER). In this reactor, the heavy hydrogen isotopes deuterium (D) and tritium (T) fuse together to form helium (He).

$$\text{^3}_2\text{D} + \text{^3}_1\text{T} \rightarrow \text{^4}_2\text{He}(3.5\text{MeV}) + n(14.1\text{MeV})$$ (1)

A high temperature ($\sim 150 \cdot 10^6 \circ C$) is required in order to overcome the natural electrostatic repulsion between the reactants. This temperature range can be obtained in a Tokamak type of reaction vessel (see top right picture), where the participating atoms are ionized and form a plasma.

In order to harvest energy, the divertor extracts both particles and heat from the plasma. The energy is extracted by means of a water flow, running through copper pipes covered in protective armour blocks of tungsten. The lifetime of the armour material is a critical element in keeping the fusion reactor operative. The tungsten endures severe loading, as it is subjected to large (pulsating) heat flows, and bombarded with a large number of ions and neutrons.

Brittle-to-ductile transition

Body Centered Cubic (BCC) metals such as tungsten typically show brittle, low energy failure behaviour at low temperatures. This type of failure generally results in cracking, and can be catastrophic for the functionality of the monoblocks. However, a much more ductile behaviour is observed at higher temperates. A sharp ($< 2 \circ C$) transition of failure mechanism can be observed, as shown in fig. 1.

$$\dot{\varepsilon} = A \cdot \exp \left( -\frac{E_{\text{BDT}}}{k_B \cdot T_{\text{BDT}}} \right)$$ (2)

where, $A$ is a constant that is dependent on the micro structure, $\dot{\varepsilon}$ is the strain rate, and $k_B$ is Boltzmann’s constant. The activation energy for the BDT ($E_{\text{BDT}}$) was found to be equal to that experimentally found for dislocation glide. The Arrhenius plot is visualized in fig. 2.

![Arrhenius plot](image)

Figure 2: Arrhenius plot [1].

The activation energy is a material parameter, which is independent of geometrical factors. The activation energy is determined to be $E_{\text{BDT}} = 1.05 \text{ eV}$ for tungsten [1].

Screw dislocation kink pairs

In BCC metals, plastic deformation occurs by nucleation and propagation of double kink screw dislocations along the dislocation line.

![Movement of a double kink screw dislocation](image)

Figure 3: Movement of a double kink screw dislocation.

At low temperatures, dislocations are almost completely suppressed, resulting in brittle failure. At intermediate temperatures, the basic process that controls the $T_{\text{BDT}}$ is considered to be dislocation mobility, and fracture becomes rate dependent [2]. The brittle-to-ductile transition plays a key role in the characterization of the relation between the microstructure of tungsten and its mechanical properties.

References