S6-2

Properties of Tungsten and its Damaging Scenarios
タングステンの性質と損傷シナリオ

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Plasma facing material (PFM) plays an important role in the protection of both plasma and divertor devices. Worldwide fusion program is now focused on Tungsten (W) as PFM of divertor. W may suffer damages with a variety of scenarios, of which the level depens on plasma conditions and material performance of W. Physical, chemical and mechanical properties of W are summarized and its damaging scenarios are developed on the bases of the summary and plasma characteristics, such as heat load, helium implantation and displacing damages. Consideration of detailed inspection methodologies and establishment of standards of effective inspection techniques are demanded to keep an enough machine time and experimental schedule for operation of ITER..

1. Introduction

Plasma facing material (PFM) plays an important role in the protection of both plasma and devices. Worldwide fusion program is now focused on Tungsten (W) as PFM of divertor, since W features several advantageous properties for fusion application, high melting points, good thermal conductivity, high creep resistance, good high temperature strength and low vapor pressure. W has a high resistance against sputtering and low tritium retention in fusion environment and the decay time for activation is acceptable. However, there are drawbacks: low oxidation resistance, low ductility at room temperature (RT) and the high ductile to brittle transition temperature (DBTT). Furthermore, properties are sensitive to irradiation.

W-PFM may suffer from damages with a variety of scenarios, which is expected to depend on plasma conditions and material performance of W. Physical, chemical and mechanical properties of W are summarized in this symposium and its damaging scenarios are developed on the bases of the summary and plasma conditions, such as heat load, helium implantation and displacing damages.

2. Motivation

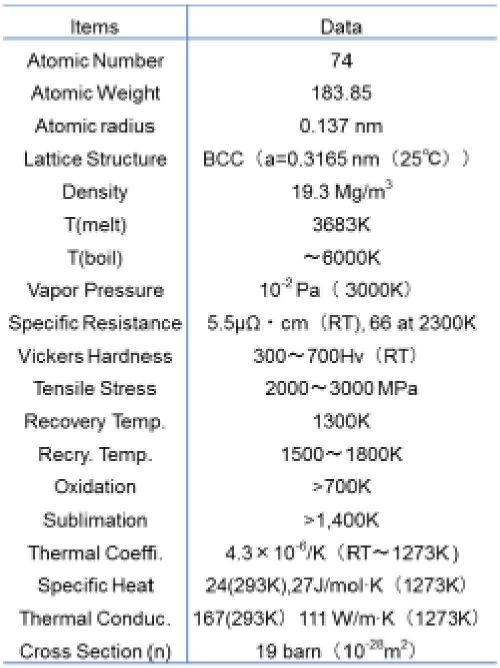
Inspection technology development of a variety of damages in W-PFM, such as cracking, melting and self-castellation is indispensable for continuous operation of divertor of fusion devices. For sound and continuous operation of the divertor, an inspection standard to evaluate damaged level of W-PFM is necessary to determine operation schedule of the divertor, which is influenced by repairing and exchanging process of W-PFM.

3. Properties of W

Specific features and basic properties of W are summarized in Table 1, indicating that the melting temperature is highest, and the vapor pressure and thermal expansion of W are the lowest in metals.

Since W is BCC metal, it has ductile to brittle transition temperature (DBTT) of fracture toughness or ductility. And, because of very high melting temperature, the DBTT of W is rather higher than 673K in impact test. Tensile test data indicates that tensile elongation becomes large enough only above 473K.

Table 1: Summary of specific features and basic properties of W.



Items	Data
Atomic Number	74
Atomic Weight	183.85
Atomic radius	0.137 nm
Lattice Structure	BCC（a=0.3165 nm（25°C））
Density	19.3 Mg/m^3
T(melt)	3683K
T(boil)	～6000K
Vapor Pressure	10^{-2} Pa（3000K）
Specific Resistance	5.5μΩ・cm（RT), 66 at 2300K
Vickers Hardness	300～700Hv（RT）
Tensile Stress	2000～3000 MPa
Recovery Temp.	1300K
Recry. Temp.	1500～1800K
Oxidation	>700K
Sublimation	>1,400K
Thermal Coeffi.	4.3×10^{-6}/K（RT～1273K）
Specific Heat	24(293K),27J/mol·K（1273K）
Thermal Conduc.	167(293K）111 W/m·K（1273K）
Cross Section (n)	19 barn（10^{-28}m^2）

4. W-damaging scenarios

There are several types of damages expected for W-PFM under fusion plasma exposure which causes high heat loading, helium implantation and displacement damage on W-PFM. The heat loading of 1000 cycles with 20 MW/m^2 resulted in melting the so-called iter-grade W (Fig.1(a)). Solidification after melting resulted in the formation of extremely large grains (Fig.1 (d)) that may cause embrittlelent of the materials. The loading conditions similar to ITER-ELM with 1.1 GW/m^2 (pure W: $\Delta T \approx$ 2000℃) at T_{base} = 100℃, n = 100 on a exposure area of 16 mm^2 for 1 ms caused grain boundary cracking (Fig.1(b)). Crack often initiates at the top part of the monoblock with evidence for a ductile fracture mode around the initiation site and a brittle fracture mode with typical intergranular cracks closer to cooling tube (Fig.1 (e)).

Low energy (50 eV) helium implantation with a flux above 2 x 10^{25} He^+/m^2 induced a castellation on the surface (Fig.1(c)). It was also reported that self-castellation typically appeared after several 100 loading cycles at 20 MW/m^2 but never appeared during lording 10 MW/m^2, 5000 cycles. Fatigue crack rather than crack due to brittleness might be critical. Thus, higher fatigue resistance and higher resistance to recrystallization as well as radiation tolerance are essential for W-PFM.

Since cracks influence on cooling potential of W-PFM, mechanical property databases are demanded, which are the temperature dependence of tensile properties including yield stress, ultimate tensile stress and total elongation as well as the temperature dependence of impact fracture behavior or DBTT in the temperature region from RT to 1000K. The investigation of the effect of recrystallization on the above and fatigue is necessary.

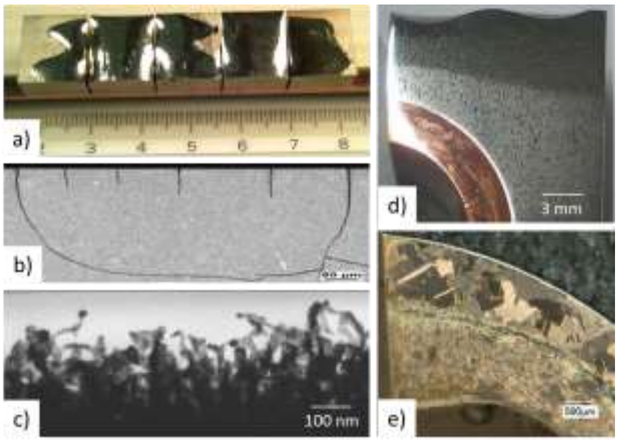


Fig.1 Damages of pure W induced by heat loading or helium implantation.

5. Inspection methodology

In order to operate fusion devices more effectively, the damaged W-PFM could be reused when the damage level is low enough to operate divertor. Even before the exposure to plasma, W-mono-blocks may suffer from damages during production. The production makers provide the mono-block under the ordering contract. In general, the importance is the contents of the specifications of the products. However, in case of consideration of product management of W-mono-blocks after practical utilization under fusion plasma, it should be sophisticate to define the specifications to reuse the W-mono-block with some damages.

ITER diverter consists of more than 300,000 pieces of W-mono-blocks which would be inspected after disruptions or ELMs, and possibly some damaged parts could be repaired or exchanged. It is expected that exchanging the damaged parts requires a rather long time and the cost is not inexpensive. It is also expected that the damaged parts could be reused even without repairing depending on the level of the critical damage. Thus, it is demanded that a standard inspection methodology would be established based on the experiments which provide information necessary to classify the damages into some levels.

Fig.2 Inspections of productions and a part(s) of W-mono-blocks for operation of fusion devices.

6. Summary

Because of the occurrence of disruptions and ELMs that generate extremely severe plasma, W-PFM is imposed requirements that overwhelm the performance of current available W. This means the W-PFM is often damaged during operation of fusion devices like ITER and beyond. Consideration of detailed inspection methodologies and establishment of standards of effective inspection techniques are demanded to keep an enough machine time and experimental schedule for operation of ITER.