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The dynamical mechanical properties of tungsten under compression at working temperature range of divertors

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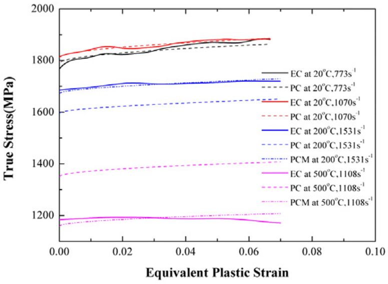
HIGHLIGHTS

- Test research on dynamic properties of tungsten at working temperature range and strain rate range of divertors.
- Constitutive equation descrbing strain hardening, strain rate hardening and temperature softening.
- A guidance to estimate dynamical response and damage evolution of tungsten divertor components under impact.

GRAPHICAL ABSTRACT



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ABSTRACT

In the divertor structure of ITER and EAST with mono-block module, tungsten plays not only a role of armor material but also a role of structural material, because electromagnetic (EM) impact will be exerted on tungsten components in VDEs or CQ. The EM loads can reach to 100 *MN*, which would cause high strain rates. In addition, directly exposed to high-temperature plasma, the temperature regime of divertor components is complex. Aiming at studying dynamical response of tungsten divertors under EM loads, an experiment on tungsten employed in EAST divertors was performed using a Kolsky bar system. The testing strain rates and temperatures is derived from actual working conditions, which makes the constitutive equation concluded by using John-Cook model and testing data very accurate and practical. The work would give a guidance to estimate the dynamical response, fatigue life and damage evolution of tungsten divertor components under EM impact loads.

1. Introduction

As an armor material, tungsten is of many good properties, such as high melting point, low sputtering rate, reasonable thermal conductivity and high strength, which make it widely used in the divertors of many fusion devices all over the world [1–4]. Nowadays, under normal operating conditions heat load on the first wall is around 2 MW/m^2, and about 15% of the total fusion power has to be removed by divertors while peak loads of 10–20 MW/m^2 have to be considered [5]. Benefitting from its high heat conduction ability and great thermal load capacity, mono-block structure has been employed in the divertors of many fusion devices to meet the serious heat transmission needs, such as ITER [6] and EAST [7]. In the mono-block structure, tungsten plays not only a role of armor material but also a role of structural material, due to huge

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electromagnetic (EM) loads besides thermal stress exerted on the tungsten structure. According to G. Sannazzaro's research, the EM force is most severe compared to other mechanical loads acting on tokamak structures, e.g. dead weight, seismic load and hydraulic pressure [8]. Besides that, thermal loads including the surface heat fluxes from plasma and the neutron heat generation are an important design driver. Thermal stress induced in thermal expansion is second stress, while EM force would generate primary stress. The effect of thermal stress on dynamic structural analysis was not considered in most articles. So the two different kinds of loads were not comparatively discussed in this paper. On one hand, eddy currents which are induced by the decay of plasma current and the change of plasma shape of disrupting plasma according to the Faraday law, would generate an electromagnetic force on the mono-block structure in the magnetic field. On the other hand, halo currents flow through the structures when vertical displacement events (VDEs) occur and the plasma current makes a contact to surrounding PFC, subsequently the currents would also generate an electromagnetic force on the mono-block structure in the magnetic field. Compared to eddy currents, halo currents is much higher and larger EM loads acted on the tungsten structure in the VDEs. The vertical force and the vertical moment are major load part for the divertor components when VDEs happen. As the property of plasma hasn't been researched very clearly, the process of VDEs cannot be quantified very precisely. Most researchers utilized DINA to simulate the plasma in VDEs in order to calculating electromagnetic loads of the vacuum vessel and the in-vessel components. By using the same method but a new method to simplify modeling process, Sunil Pak et al. have done much effective electromagnetic load calculation work on the ITER machine [9]. In their study on slow downward VDEs, it is indicated that the vertical forces exerted on the 20° sector of the divertor model get up to 5 *MN* from 0 *MN* in a linear way during about 400 *ms*, and decay to 0 *MN* in a negative exponent way during the following 700 *ms*. The duration of vertical force is very short, but the magnitude of vertical force is large, which would make the EM impact loads cause high strain rates on the divertor targets. Hence with the operation parameters constantly improved to reach the next goals of tokamak experiment device, the EM impact exerted on divertor components will be larger.

As the vertical force is major load exerted on the tungsten components, the compressive impact is a great threat to the durability of tungsten divertors. In order to figure out the dynamical mechanical property, an experiment on tungsten employed in the EAST divertor was performed using a Kolsky bar system (also known as a Split Hopkinson pressure bar, SHPB) [10]. As supplementary, a quasi-static compression test with a strain rate of $10^{-3}\ s^{-1}$ at the room temperature was carried out to acquire basic stress-strain relationship using an MTS hydro-servo system. The experiment is introduced in Section 2. The respective effects of the strain rate and temperature on the stress-strain characteristics of the impacted specimens are identified and discussed in Sections 3.1 and 3.2. In Section 3.3, a constitutive equation involving five material constants was built by using John-Cook model to describe the effects of strain hardening, strain rate hardening and temperature softening [11]. The predicted curves at various cases calculated by the constitutive equation were compared with the experimental curves to evaluate the reliability. The two kinds of curves fit very well at room temperature, but there is an obvious difference between the two kinds of curves. As a result, the thermal softening exponent m was corrected by a negative exponential function and the error was greatly reduced. Some conclusions have been made in Section 4. The model can be used to estimate the dynamic response of the tungsten divertor under the electromagnetic impact, which is very important to design and optimize the divertor structure in the future fusion power reactors.

2. Experimental

Currently, commercial purity tungsten produced at Advanced Technology & Materials Co., Ltd. (AT&M) is employed for the EAST divertor application. The EAST project chose powder metallurgical methods utilizing mechanical alloying (MA) for the manufacture of Ultra-fine grained (UFG) W compacts. Microstructural modification by hot plastic working has been applied to the compacts processed by MA in a purified Ar or H_2 atmosphere and hot isostatic pressing (HIP) [12]. The modified compacts exhibit a very high fracture strength and appreciable ductility at room temperature. The commercial purity tungsten meets ASTM B760-86 (1999) Standard Specification for Tungsten Plat, and the chemical composition of pure W is shown in Table 1.

A quasi-static compression test with a strain rate of $10^{-3}\ s^{-1}$ in the room temperature was carried out by using an MTS hydro-servo system. While pure tungsten is of a very high yield strength, it is quite important to reduce the draw ratio instead of normal values (they are 0.5, 1, 1.5) for getting high strain rates and forbidding Pressure-Bending effect of the incident bar and transmission bar. Therefore, cylinders of 4, 5 or 6 *mm* diameter and 8 *mm* height were chosen as the dynamic compression test specimens. Considering that W has a very high strength, the stress rate of W at 400 s^{-1} is approximately estimated to reach a great value of 16000 GPa per second. Referring to the testing work about pure W of Z. Pan et al. [13], high strain rates ranging from 400 to 1600 s^{-1} were chosen to assess the effect of strain rate hardening to W. Because the heating temperatures below 800 °C were accurately provided by the heating furnace in the lab and mechanical properties at high temperature above 700 °C could be extrapolated by researching the trend of testing curves, Dynamic tests were performed at room temperature, 200, 300, 500, 700 °C by means of a spilt Hopkinson pressure bar. Schematic diagram of the apparatus is given in Fig. 1. A specimen was cemented with artificial butter between the incident bar and transmitter bar. A heating furnace completely surrounding the specimen was employed to ensure experiment temperatures. The reflected and transmitted pulses are recorded by strain gauges bonded to the middle of two bars. And two cooling systems were respectively installed at the ends of the incident and transmission bars near the specimen, which could protect the strain gages from heat flow transported from the heating furnace because strain gages are very sensitive to heat flow. Based on data recorded through the strain gages on the incident bar and transmitter bar, specimen strain, strain rate and stress can be obtained according to the following formulas which are derived from the one-dimensional stress wave theory:

$$\dot{\varepsilon}(t) = \frac{2c}{l_0}\varepsilon_r(t) \tag{1}$$

$$\varepsilon(t) = \frac{2c}{l_0}\int_0^t \varepsilon_r(t)dt \tag{2}$$

$$\sigma(t) = \frac{A}{A_0}E\varepsilon_t(t) \tag{3}$$

where *E*, *c*, *A* refer to the elastic modulus, the elastic wave velocity and the cross-sectional area of the pressure bar, respectively. A_0 and l_0 are the cross-sectional area and the length of the specimen, respectively.