Int. Journal of Refractory Metals and Hard Materials 61 (2016) 61–66

Contents lists available at ScienceDirect

Int. Journal of Refractory Metals and Hard Materials

journal homepage: www.elsevier.com/locate/IJRMHM

Thermal fatigue mechanism of recrystallized tungsten under cyclic heat loads via electron beam facility

Liang Wang, Bo Wang *, Shu-Dan Li, Dong Ma, Yun-Hui Tang, Hui Yan

School of Materials Science and Engineering, Beijing University of Technology, Beijing 100124, China

ARTICLE INFO

Article history:
Received 18 May 2016
Received in revised form 3 July 2016
Accepted 27 July 2016
Available online 5 August 2016

Keywords:
Tungsten
Cyclic heat loads
Thermal fatigue
Extruded flake structures

ABSTRACT

Thermal fatigue resistance of plasma facing materials (PFMs) is an inevitable concern for component lifetime and plasma operations, since the temperature fluctuations will always exist in future nuclear fusion facilities and reactors. Accordingly, experiments were performed in the electron beam facility to investigate the thermal fatigue behavior under operational loading conditions. The tungsten is investigated in its stress relieved and fully recrystallized state for a better understanding of the thermal fatigue process when exposed to cyclic heat loads. The heat loads range from 24 to 48 MW/m^2 and the number of cycles increases from 100 to 1000 times. The results indicate that the thermal fatigue damage (surface roughening) due to plastic deformation strongly depends on the loading conditions and the cycle index. As the power density and the number of cycles increase, the density of the intragranular shear bands in each grain becomes higher and the swelling of grain boundaries becomes more pronounced. The shear bands are generally parallel to different directions for varying grains, showing strong grain orientation dependence. Additionally, extruded flake structures on shear bands were observed in these damaged areas. It found that the shear bands are generally parallel to the traces of {112} slip planes with the surface. The results suggest that slip plastic deformation represent the predominant mechanism for thermal fatigue and a set of schematic diagram is presented to explain the formation of thermal fatigue damage morphology (extrusion and intrusion structures).

1. Introduction

One of the key concerns for future nuclear fusion devices is the development of plasma facing materials (PFMs). These FPMs should be able to withstand the severe and complex environmental conditions especially in the divertor region. Tungsten (W) has multiple favorable thermal properties, which makes it a most promising plasma facing material [1]. Nevertheless, a PFM will be subjected to steady-state heat loads and several types of short transient events during plasma operation in fusion reactors, which can cause unacceptable material damage, such as cracks, surface melting, evaporation, droplet ejection and fatigue fracture [2–4]. Therefore, different experimental set-ups to simulate these environmental conditions are essential to determine behavior and damage mechanisms of tungsten. Recently, a series of experiments have been conducted using pulsed laser and electron beams to reproduce fusion relevant transient and steady state heat loads. Based on these results, it is concluded that the damage types, such as surface roughening, cracks and melting, evolve as function of transient heat loads, number of pulses and the base temperature of W [5–8]. However, few studies focused on the detailed microscopic analysis of the thermal fatigue damage (surface roughening) caused by cyclic heat loads. W as a plasma facing material (PFM) would be exposed to a variety of cyclic heat loads and subjected to stress under temperature changes due to different strain rates. Therefore, thermal fatigue resistance of W is an inevitable concern for component lifetime and plasma operations, since the temperature fluctuations will always exist in future nuclear fusion facilities and reactors. Y·Yuan [9] has focused on surface roughening and conjectured that it is mainly caused by twin plastic deformation. Unfortunately, the microscopic images of the Yuan's papers showed only the images of overall deformation features without local details.

In this work, W is investigated in its stress relieved and fully recrystallized state to ascertain a better understanding of the thermal fatigue process under cyclic heat loads. Thermal fatigue resistance is assessed by changing the power density and cycle index. Additionally, we study on the potential mechanism of surface deformation (typically the extruded flake structures) observed in loaded areas.

2. Experimental

Thermal fatigue tests were performed in the electron beam facility with 8 kV rated voltage. All samples were mounted on carbon crucible placed on a water-cooled Cu block. To ensure a good contact for heat conduction, a small amount of metal gallium was added between the samples and the crucible. The thermal fatigue tests were conducted out with 100, 300, 500 and 1000 pulses at an absorbed power density

---

* Corresponding author.
E-mail address: wangbo@bjut.edu.cn (B. Wang).

http://dx.doi.org/10.1016/j.ijrmhm.2016.07.022
0263-4368/

of 48 MW/m^2 with a duration of 1 s and followed by a 9 s interval to cool the loaded area to the base temperature. In addition, the thermal fatigue tests were carried out at two other absorbed power densities of 24, 36 MW/m^2 with 500 pulses. In the tests, the maximum current was observed to be 107, 160 and 214 mA during a pulsed loading, and the electron beam deposited area is a circle with a diameter of 5 mm. Thereby, the absorbed power densities are 24, 36 and 48 MW/m^2, respectively (the electron absorption coefficient of W is 0.55 [9]).

The tests were performed on fully recrystallized W plate manufactured by AT&M Co., Ltd. (China). The internal stresses induced by rolling deformation were completely released after full recrystallization [10]. Thereby, for the loaded recrystallized W, the stress distribution largely depends on the thermal stresses induced during loading. All samples were cut from the recrystallized W plate with the dimensions of 10 × 10 × 2 mm^3 for thermal fatigue tests. In order to obtain a stress-free and a well-defined reference surface, the surface of the samples was electro-polishing in a 2 wt.% NaOH solution to a low roughness of Ra < 0.1 μm. After the thermal fatigue tests, the surface morphology and microstructure were observed by a scanning electron microscope

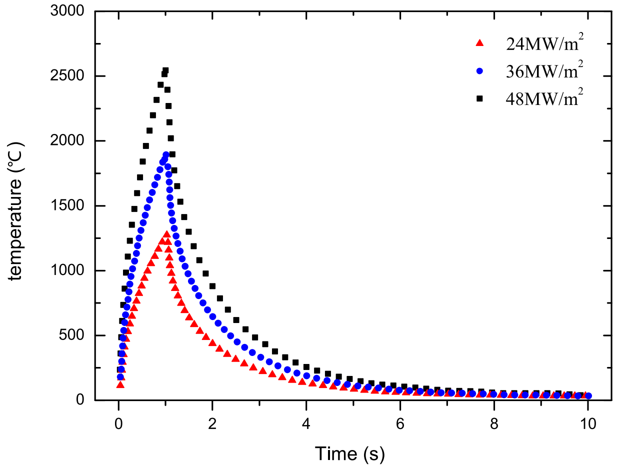

Fig. 1. The maximum temperature evolution of electron beam deposited area simulated by FEM during one cyclic heat loads.

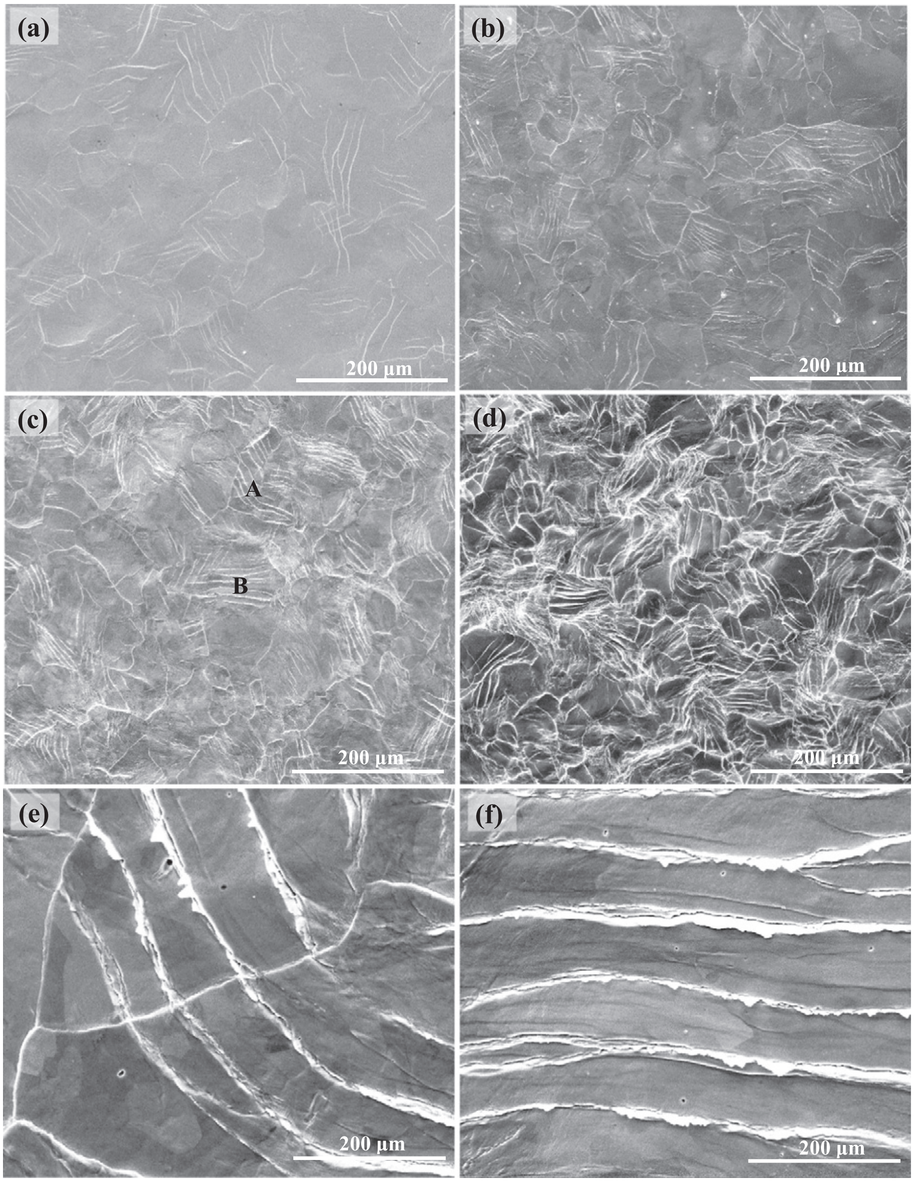

Fig. 2. SEM images of the electro-polished recrystallized W after exposure to cyclic heat loads (absorbed power density 48 MW/m^2) in different cycle indexes. (a) 100 pulses, (b) 300 pulses, (c) 500 pulses and (d) 1000 pulses. (e and f) is higher magnification of grains A and B shown in (c).