Fusion Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Effects of tantalum concentration on the microstructures and mechanical properties of tungsten-tantalum alloys

Zheng Wang[a,b], Yue Yuan[b,c,*], Kameel Arshad[b,c], Jun Wang[b,c], Zhangjian Zhou[d], Jun Tang[e], Guang-Hong Lu[b,c]

[a] Sino-French Engineer School, Beihang University, Beijing 100191, China
[b] Beijing Key Laboratory of Advanced Nuclear Materials and Physics, Beihang University, Beijing 100191, China
[c] School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China
[d] School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China
[e] Institute of Nuclear Science and Technology, Sichuan University, Chengdu, Sichuan, 610064, China

HIGHLIGHTS

- Tungsten-tantalum alloys with fine grain microstructure and high mechanical properties were fabricated by spark plasma sintering.
- Effects of tantalum concentration on the basic characterization of tungsten-tantalum alloys were studied.
- 10 wt.% of tantalum was considered to be the best option compared to 5, 15 and 20 wt.% by analyzing various testing results.
- Tantalum tends to gather together if its concentration is higher than 10 wt.%, and Ta precipitate has a negative effect on mechanical property.
- Pure tungsten fractured intergranularly, while the failure mode in tungsten-tantalum alloys was predominantly transgranular.

ARTICLE INFO

Article history:
Received 30 October 2016
Received in revised form 20 April 2017
Accepted 21 April 2017
Available online xxx

Keywords:
W-Ta alloys
Ta concentration
Microstructures
Mechanical properties

ABSTRACT

Pure tungsten and tungsten-tantalum alloys with tantalum concentrations of 5, 10, 15 and 20 wt.% were fabricated by spark plasma sintering. Effects of tantalum concentration on the basic characterization of tungsten-tantalum alloys were studied. The results show that the addition of tantalum contributes to a decrease of grain size and an improvement of relative density and mechanical properties. Adding a small amount of tantalum (about 10 wt.%) increases the relative density significantly, while if the concentration of tantalum is higher than 15 wt.%, the relative density decreases apparently. The hardness of the alloy with 10 wt.% tantalum is highest, which is 508.65 HV, 42% higher than pure tungsten. The bending strength of the alloy with 5 wt.% tantalum reaches up to 742 MPa, which is 27.1% higher than pure tungsten. Pure tungsten fractures intergranularly, while the failure mode in the alloy is predominantly transgranular. SEM images show that if the concentration of tantalum is higher than 10 wt.%, tantalum tends to gather together, and this phenomenon has a negative effect on the mechanical property of materials.

1. Introduction

Plasma-material interaction is an important but very complex area in the field of fusion technology for the success operation of future fusion reactors. The hot plasma of several millions Kelvin temperature is tried to contain in a tokamak by large magnetic fields but still the plasma facing components have to face high heat flux and intense beam of different radiations such as neutron, helium and hydrogen isotopes [1–3]. Thus, plasma-facing materials for future fusion reactors have to meet many requirements such as structural integrity needs to be kept even under severe thermal loads, thermally induced mechanical stresses and cyclic loading conditions [4]. They need to be resistant against chemical, physical sputtering and erosion and must have good properties such as thermal conductivity, high temperature strength, low ductile-to-brittle transition temperature (DBTT), high recrystallization temperature even after neutron and other irradiation damage.

Tungsten (W) is chosen as the leading candidate for plasma facing material (PFM) in fusion devices due to its durability and favorable physical properties at elevated temperatures [5–8]. However, W has several disadvantages, such as high DBTT and

* Corresponding author at: School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China.
E-mail address: yuanyue880329@gmail.com (Y. Yuan).

http://dx.doi.org/10.1016/j.fusengdes.2017.04.082
0920-3796/

recrystallization brittleness [6,9]. Adding a certain amount of tantalum (Ta) into W is expected to increase ductility and reduce DBTT [10–12]. Besides, it has been reported that the addition of Ta in W can suppress surface blistering under high fluence deuterium plasma irradiation [13]. Moreover, several studies related to the thermal shock performance of W-based materials indicate that the surface cracking threshold of W-Ta alloy is higher than pure W, because the existence of Ta changes the microstructure and grain size of materials [14–16].

The different concentrations of Ta into W and their comparative analysis for the evaluation of optimized combination of Ta and W with fine microstructures and good mechanical properties has not been studied well. The aim of this work is to fabricate high quality W-Ta alloy which is expected to resist the damage caused by irradiation of fusion reactors. In this work, effects of different Ta concentrations on the microstructures and mechanical properties of W-Ta alloys are studied.

2. Experimental

Commercial powders of W (with an average particle size of 2 μm and a purity of 99.9%) and Ta (with an average particle size of 48 μm and a purity of 99.9%) were loaded in tungsten carbide mill pots in argon atmosphere. The alloy powders were mixed according to the Ta concentrations of 0, 5, 10, 15 and 20 wt.% (named W, W-5Ta, W-10Ta, W-15Ta, W-20Ta respectively). High energy ball milling (HEBM) process was operated at a speed of 380 rpm for 30 h and the weight ratio of ball to powder was 5:1. Then the powders were transferred from mill pots to a graphite die in a glove box which was filled with pure argon gas. The samples were sintered by spark plasma sintering (SPS) in vacuum under a pressure of 80 MPa, and the maximum temperature was 1800 °C with heating rate of 100 °C/min. The holding time was chosen to be 0 min in order to limit grain growth. Afterwards, the surface of all samples was mechanically polished to mirror-like finish.

X-ray diffraction (XRD) was employed to investigate the alloying behavior due to milling and sintering. The morphology and grain size distribution of sintered samples were examined by a field emission scanning electron microscope (FE-SEM) equipped with electron backscatter diffraction (EBSD) system. Element distribution was detected by Energy Dispersive Spectrometer (EDS). In order to evaluate impurity content, oxygen and carbon content in various powders were tested by infrared absorption method. The relative density of each sample was obtained by the ratio of bulk density to theoretical density. Bulk density was measured by Archimedes method in water, and theoretical density was calculated by formula (1) [17].

$$\rho = \frac{\rho_W \ \rho_{Ta}}{x\%\rho_W + (1 - x\%)\rho_{Ta}} \quad (1)$$

Vickers hardness was measured at room temperature with a load of 2.94 N for 15 s, and six different positions on polished surface were tested to obtain an average value. Three point bending tests were conducted on specimens with dimensions of 2 mm × 3 mm × 13 mm with a span of 10 mm and a crosshead speed of 0.5 mm/min. In order to get a representative value, each sample were measured three times for bending strength.

3. Results and discussion

In order to study the effect of Ta concentration (0–20 wt.%) on the basic characteristics and microstructures of W-Ta alloys, average grain size (comes from W grains), bending strength, Vickers hardness and relative density of various sintered compacts were measured. Detailed data are summarized in Table 1, and the information will be discussed in the following sections.

Table 1
Characteristics of pure W and W-Ta alloy samples.

Material	W	W-5Ta	W-10Ta	W-15Ta	W-20Ta
Average grain size (μm)	6.04	3.15	2.48	2.42	2.49
Bending strength (MPa)	584.31	741.62	706.27	647.59	586.81
Vickers hardness (HV)	358.22	414.20	508.65	466.58	489.68
Density (g/cm^3)	18.26	18.10	18.26	17.93	17.72
Theoretical density (g/cm^3)	19.25	19.10	18.96	18.82	18.68
Relative density (%)	94.84	94.73	96.29	95.27	94.89

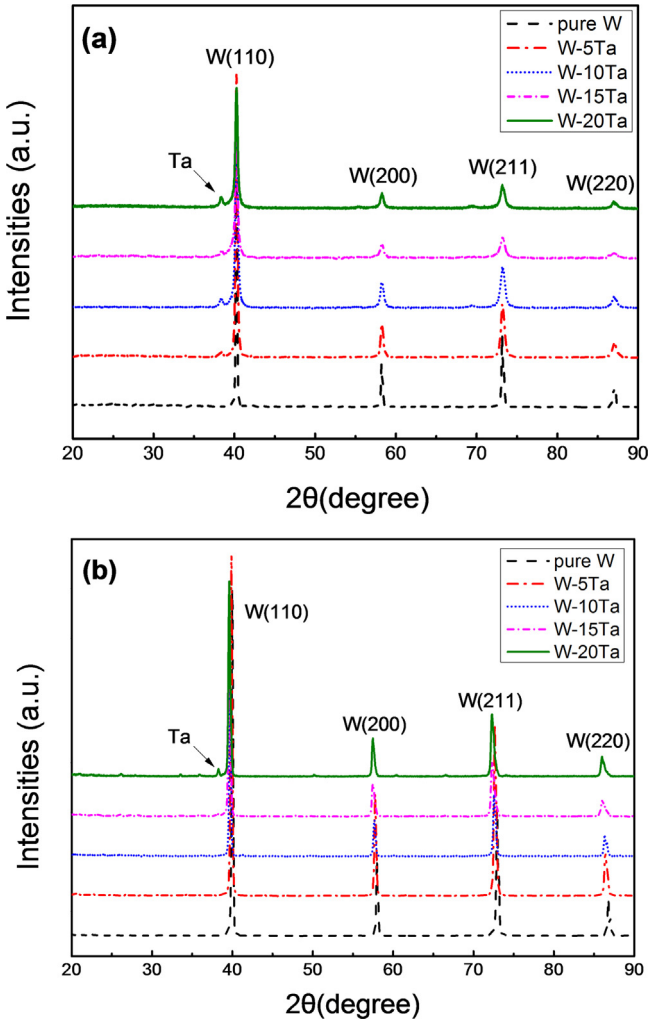

Fig. 1. XRD patterns of (a) milled powders and (b) sintered compacts.

3.1. Alloying behavior

Fig. 1 shows the XRD patterns of milled powder and sintered compacts. Small peaks of Ta can be found besides W peaks in all of the milled powders. However, for sintered compacts, small peaks of Ta only appear in W-15Ta/W-20Ta and cannot be observed in W-5Ta/W-10Ta anymore. This means that HEBM cannot effectively implement alloying when Ta concentration is more than 5 wt.%, and SPS can promote alloying behavior to some extent. When the concentration of Ta reaches 15 wt.%, a portion of Ta may aggregate and become detectable.

All the processes including powder mixing, extraction from ball miller and loading to furnace have been done in the inert environment of pure argon, thus oxygen and carbon contamination cannot be detected in XRD patterns. However, the chemical analysis shows that oxygen contents in all of these samples range from 0.13 wt.% to

Please cite this article in press as: Z. Wang, et al., Effects of tantalum concentration on the microstructures and mechanical properties of tungsten-tantalum alloys, Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.04.082