STRUCTURE AND PHASE COMPOSITION OF WNb ALLOY FORMED BY COMPRESSION PLASMA FLOWS IMPACT

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The results of tungsten-niobium alloy synthesis by pulsed compression plasma flows impact are presented. The tungsten plates with a 2 μm thin niobium coating were treated with dense compression plasma flows generated by a quasi-stationary plasma accelerator. The plasma influence with the absorbed energy density of 35-70 J/cm^2 and pulse duration of 100 μs melts the niobium coating and a part of the tungsten substrate, which makes their liquid-phase mixing and WNb alloy synthesis after the crystallization possible. Simulation of the temperature distribution in the top layer of the tungsten after the plasma treatment proves the melted state. The methods of scanning-electron microscopy (SEM) as well as X-ray diffraction (XRD) were used for the structure and phase composition detection. The obtained results showed the thickness of the WNb alloy 10-20 μm where W(Nb) bcc solid solution had been found.

Keywords**:** tungsten; niobium; WNb alloy; plasma mixing; compression plasma flow; phase composition; structure.

Introduction

The operation of the thermonuclear chamber with plasma localized area surrounding by a magnetic field implies the high heat flux acting to the wall [1-5]. It provides high rate of heating and cooling of the surface that result in mechanical stress and destroying. Up to now, the improvement of thermo-mechanical properties of tungsten is still a crucial problem.

The pronounced problems of the pure tungsten can be overcome by formation of the tungsten-based alloys. The methods of tungsten-based alloys production usually use the powder technologies where fine metal particles are compacted together at high temperatures [6-7]. However, the formed powder alloys have rather high porosity and their radiation resistance is rather poor. The bulk alloys are considered as more preferable from the applied point of view. As the thin sub-surface layer plays more important role in the erosion processes, radiation effects, mechanical and wear resistance, we can suggest to make a bulk alloy just only on the surface of any other metal. In this case the system will save the physical properties of the basic metal but the surface properties will be modified.

Among the alloying elements in tungsten, niobium presents with high melting point, high corrosion resistance and low thermal-neutron absorption cross-section [8-9]. In the present work, it is proposed to use the pulsed action of compressive plasma flows on the tungsten with preliminary deposited niobium coating to form tungsten-niobium (WNb) alloy.

Materials and Methods

The tungsten samples as plates with dimensions of 10×10 mm and thickness of 2 mm were used. After the surface cleaning, the Nb coating was formed by the method of arc-vacuum deposition in inert Ar atmosphere. The thickness of the Nb coating was 2 μm. The Nb/W “coating/substrate” system was subjected to the compression plasma flows (CPF) generated in a magnetoplasma compressor of compact geometry. The plasma stream was formed in a “residual gas” mode in which a pre-evacuated vacuum chamber was filled with nitrogen up to the pressure of 3 Torr. The time of stable compression flow of 100 μs is considered as pulse duration. After this time the plasma stream is unstable and starts to dissipate. The samples were placed inside the chamber in a vertical position on the distance of 10-6 cm from the plasma source. The plasma stream was produced during the gas discharge between electrodes with the voltage of 4.0 kV. The structure and phase composition of the materials modified by the plasma flows mainly depend on the heat energy transferred to the surface layer. The used parameters of the plasma generating provide the absorbed energy density in the range from 35 to 70 J/cm^2 [10]. The CPF influence on the Nb/W samples was made by three and five pulses with a time between each of them of 20-30 s.

The varied absorbed energy density of the plasma impact allowed forming the WNb alloys with different Nb concentrations. The elemental composition of the alloys was studied by the energy-dispersion X-ray microanalysis (EDX) on Oxford MaxN analisator working at the accelerating voltage of 20 keV in the combination with scanning-electron microscope (SEM) LEO 1455 VP. This method was used for both surface and cross-sections morphologies investigation. The phase composition of the modified layers in the WNb alloys was revealed by means of the X-ray diffraction (XRD) method with Ultima IV RIGAKU diffractometer in the Bragg-Brentano geometry with parallel beams in Cu Kα radiation (with the wavelength 0.154178 nm). The error in the lattice parameters determination with XRD method was 0.05%.

Results and Discussion

The depth of the layer in tungsten alloyed with niobium as well as the depth distribution of niobium depending on the absorbed energy density were analyzed in cross sections of the samples using SEM and EDX techniques. The niobium concentration profiles are presented in Figure 1.

A detailed study of the SEM-images of cross sections structure of the W-Nb alloys produced by the CPF impact made it possible to find the fine grains growth (Figure 2).

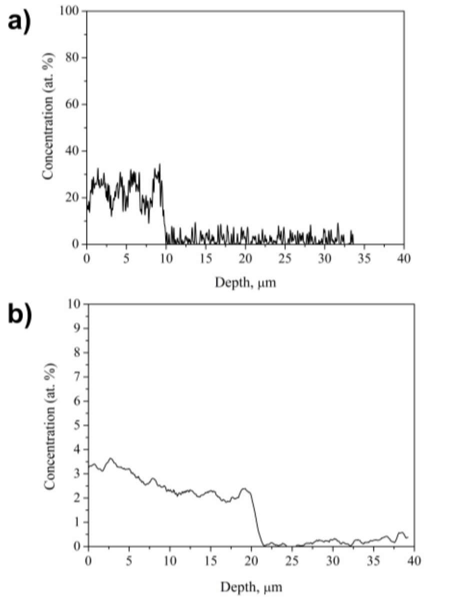

Figure 1. Niobium concentration profile over the depth in the WNb alloy formed by the CPF impact with the absorbed energy densities of (a) 35 J/cm^2 and (b) 70 J/cm^2

The SEM-image (Figure 2b) obtained on the boundary between the unmelted tungsten and the melt clearly shows the growth of columnar grains perpendicular to the interface.

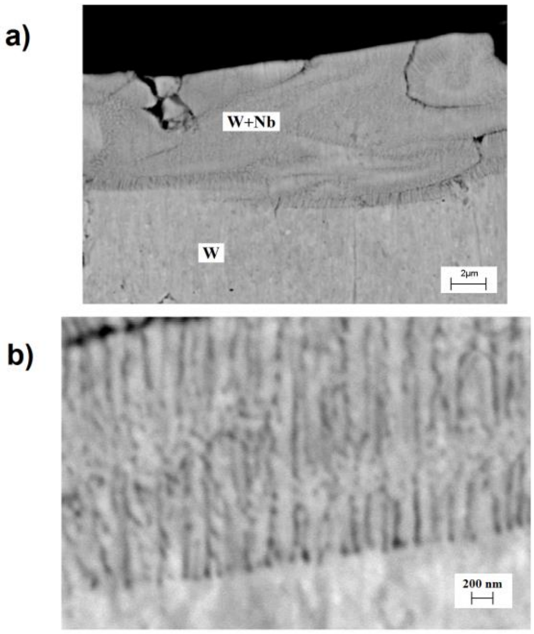

Figure 2. SEM-images of the top layer cross-section for the WNb alloy formed by the CPF impact with the absorbed energy density of 70 J/cm^2 (different magnifications)

The average thickness of the columns is 50-100 nm. The chaotic tungsten enriched areas appears in the melt because of insufficient mixing. Fine cells were revealed on the surface of the tungsten in the area where niobium atoms had been detected (Figure 3).

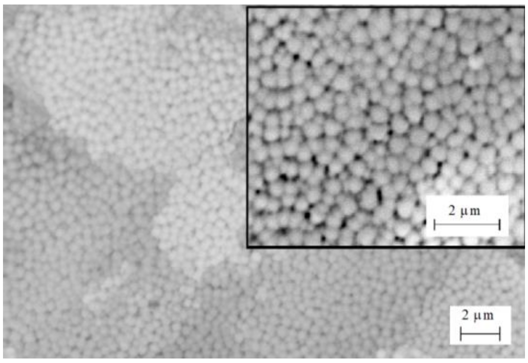

Figure 3. SEM-image of the cell structure on the surface of the WNb alloy formed by the compression plasma flows impact at the absorbed energy density 70 J/cm^2

The mean size of the cells is about 300 nm. The appearance of the cells on the surface as well as thin columns in the cross-section structure results from instability of moving crystallization front.

The Figure 4 shows the X-ray pattern of the initial state of the sample, which clearly shows the diffraction reflexes of both polycrystalline tungsten (JCPDS no. 00-004-0806) and niobium (JCPDS no. 00-034-0370) coating.

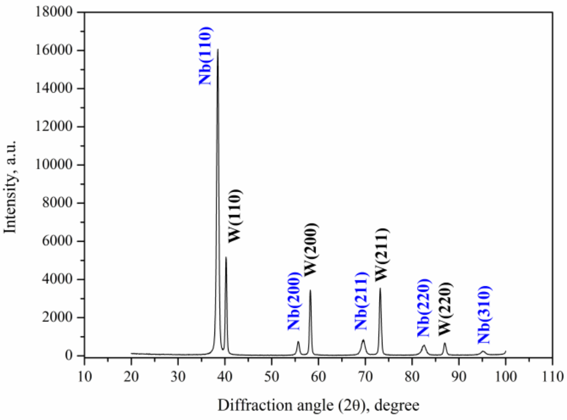

Figure 4. XRD pattern of the Nb/W system in the initial state

The diffraction reflexes of niobium phase disappear on the X-ray diffraction patterns of the samples after the plasma treatment (Figure 5).

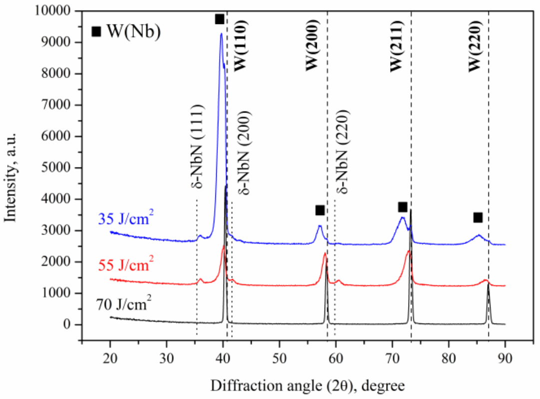

Figure 5. XRD patterns of the WNb alloys formed after three pulses of the CPF impact at different absorbed energy densities

Such niobium coating as a separate phase disappears; however, the niobium determination in the surface layer by means of the elemental analysis makes it possible to dissolve in the crystal lattice and to form solid solutions. The phase composition of the modified tungsten is controlled by the niobium concentration as well as the absorbed energy density during the plasma exposure.

However, at the absorbed energy density of 35 J/cm^2, the diffraction lines are more broadened. The deconvolution of the broad diffraction lines allowed finding the superposition of two lines corresponding to two different phases (Figure 6).

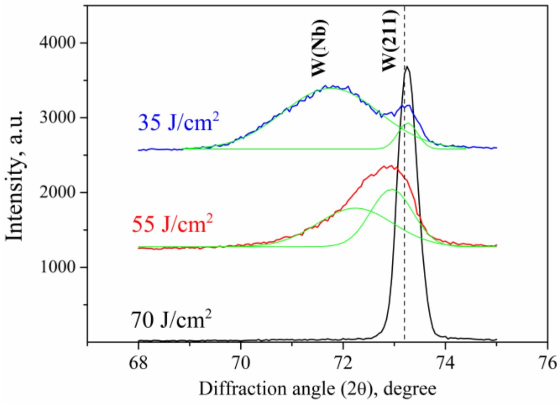

Figure 6. Deconvolution of W and W(Nb) solid solution diffraction lines

Both diffraction patterns show the presence of a relatively narrow diffraction line at higher diffraction angles which can be associated with phase of pure tungsten without any niobium atoms. Indeed, the lattice parameter equaled to 0.3175 nm is slightly higher than that of the standard value. The second line on the side of smaller diffraction angles is characterized by a large FWHM (full width on the half-maximum), and corresponds to the bcc phase with the lattice parameter of 0.3202 nm. This broadened diffraction line can be associated with the niobium solid solution phase based on the tungsten lattice W(Nb).

Conclusions

The presented results showed the possibility of WNb alloy synthesis with high-energy pulsed plasma stream influence on the tungsten with 2 μm Nb coating. The plasma treatment melts the niobium coating and a part of the tungsten substrate that makes it possible to mix both liquid layers and produce WNb alloy. The composition of the alloy is determined by the relation between the thicknesses of the melted layers and, as a result, by the absorbed energy density. The plasma flow with the absorbed energy density in the range of 35-55 J/cm^2 predominantly melts the niobium coating and pro-duces the solid solution W(Nb) in the areas contacting with the tungsten. The lattice parameter of the bcc solid solution W(Nb) depends on the niobium concentration. The thickness of the WNb alloy synthesis increases from 10 to 20 μm with absorbed energy density rising from 55 to 70 J/cm^2. The highest absorbed energy density of 70 J/cm^2 provides the uniform niobium distribution in the modified layer with the niobium concentration of 4 at.%.

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References

1. Nogami S., Watanabe S., Reiser J., Rieth M., Sickinger S., Hasegawa A. A Review of Impact Properties of Tungsten Materials. *Fusion Engineering and Design* 2018; 135: 196-203.
2. Fukuda M., Hasegawa A., Nogami S. Thermal Properties of Pure Tungsten and Its Alloys for Fusion Applications. *Fusion Engineering and Design* 2018; 132: 1-6.
3. Coenen J.W., Mao Y., Almanstötter J., Calvo A., Sistla S., Gietl H., et al. Advanced Materials for a Damage Resilient Divertor Concept for DEMO: Powder-Metallurgical Tungsten-Fiber Reinforced Tungsten. *Fusion Engineering and Design* 2017; 124: 964-968.
4. Bhuyan M., Mohanty S.R., Rao C.V.S., Rayjada P.A., Raole P.M. Plasma Focus Assisted Damage Studies on Tungsten. *Applied Surface Science* 2013; 264: 674-680.
5. Wang K., Bannister M.E., Meyer F.W., Parish C.M. Effect of Starting Microstructure on Helium Plasma-Materials Interaction in Tungsten. *Acta Materialia* 2017; 124: 556-567.
6. Gong X., Fan J., Ding F. Tensile Mechanical Properties and Fracture Behavior of Tungsten Heavy Alloys at 25-1100°C. *Materials Science and Engineering: A* 2015; 646: 315-321.
7. Daoush W.M., Yao J., Shamma M., Morsi K. Ultra-Rapid Processing of High-Hardness Tungsten-Copper Nanocomposites. *Scripta Materialia* 2016; 113: 246-249.
8. Chen J.-B., Luo L.-M., Zhao M.-L., Xu Q., Zan X., Wu Y.-C. Investigation of Microstructure and Irradiation Behavior of W-Nb/Ti Composites Prepared by Spark Plasma Sintering. *Fusion Engineering and Design* 2016; 112: 349-354.
9. Xu M.-Y., Luo L.-M., Zhou Y.-F., Zan X., Xu Y., Xu Q., Tokunaga K., Zhu X.-Y., Wu Y.-C. Helium Irradiation Behavior of Tungsten-Niobium Alloys Under Different Ion Energies. *Fusion Engineering and Design* 2018; 132: 7-12.
10. Shymanski V.I., Uglov V.V., Cherenda N.N., Pigasova V.S., Astashynski V.M., Kuzmitski A.M., et al. Structure and Phase Composition of Tungsten Alloys Modified by Compression Plasma Flows and High-Intense Pulsed Ion Beam Impacts. *Applied Surface Science* 2019; 491: 43-52.