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A TUNGSTEN NEUTRON-GENERATING TARGET OF A NEUTRON SOURCE BASED ON A SUBCRITICAL ASSEMBLY DRIVEN WITH AN ELECTRON ACCELERATOR*

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Abstract

In a subcritical assembly, heavy metals are used to generate additional photo-neutrons using high-energy electrons. One of the options for a neutron-generating target is a set of tungsten plates coated with tantalum. It is promising due to the high neutron yield upon irradiation with high-energy electrons.

The operating conditions of a tungsten target exposed to electron beams with an energy of 100 MeV, a pulse beam current of 600 mA, and a power density of 2.5 kW / cm^2 impose high demands on the target's tightness, in terms of the release of radioactive products from tungsten to the target cooling water.

To protect against chemical corrosion and the ingress of radioactive products of the irradiated material into the cooling water, the tungsten target plates are coated with a protective layer of tantalum. The tungsten target worked on a high-energy electron accelerator for 6 months. No radioactive products were detected in the cooling water.

INTRODUCTION

The Subcritical Assembly (SCA) Neutron Source is under development at NSC KIPT, in which the intensity of the nuclear fission reaction of the uranium isotope ^{235}U in the core is controlled by an electron accelerator [1]. The IAEA international classification of such installations is Accelerator Driven Systems (ADS).

Target-converters of such facilities, which converts accelerated charged particles into high-intensity neutron fluxes, are a very important unit with a number of requirements and limitations caused by technical and nuclear safety requirements. Two types of targets, based on tungsten and uranium plates capable to be operated under intensive electron and neutron flux are under development in NSC KIPT. At the first stage of the facility start-up and pilot operation under 100 MeV, 1 mA average electron current with total power of 100 kW it was decided to use tungsten neutron generating target.

The design of the target was chosen on the base of numerical simulations with optimization of the target geometry, sizes and construction features to get the maximal neutron output, taking into account the effect of the neutron absorption in the target and to provide cooling of 100 kW of the electron beam power.

The target consists of the square plate set of 65.8×65.8 mm transverse sizes and total thickness of 80 mm with 2 mm gaps between target plates to provide target cooling. The thicknesses of the separate plates were chosen taking into account distribution of the heat release volume density at electron slowing-down in the target.

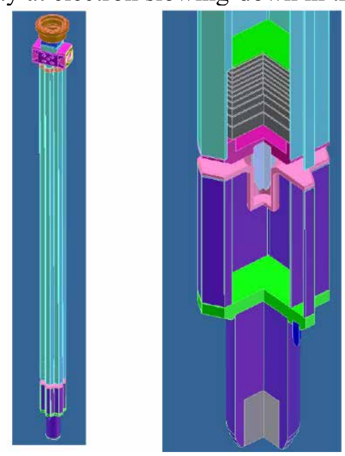

Figure 1: Layout of the NSC KIPT neutron generating target.

In order to increase tungsten corrosion resistance to aqueous coolants due to the formation of fragile tungsten hydroxide [2] and decrease high susceptibility to radiation embrittlement it was decided to clad the tungsten with a corrosion resistant material such as tantalum.

To avoid intergranular cracking of the target material target plates were manufactured from pure tungsten powder by hot vacuum pressing. High-purity tantalum powder was deposited on the side surface of tungsten plates, 1.2 mm thick, from $TaCl_5$ powder, using the *CVD* method, on a specially designed “Termit” installation.

The connection in the solid phase of flat protective surfaces of tungsten and tantalum plates, 250 μm thick, was made using an intermediate damping layer of titanium [3].

To ensure the process of joining Ta-Ti-W-Ti-Ta metals, a batch scheme for joining metals of different hardness and plasticity was used. The rolled metals were placed in a strong Nb alloy mandrel in the following sequence: a W plate of different thicknesses from 2.5 to 9.5 mm is in contact on both sides with Ti plates of 30–40 μm thickness. In turn, Ti plates are in contact with Ta plates with a thickness of 240 - 250 μm. The surface of W had irregularities in the form of protrusions and recesses, obtained during processing on an electro erosive machine. The transverse dimensions correspond to the length and width of the tungsten target. The tungsten plate had the shape of a square with a side of 65.8 mm.

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W, Ti AND Ta COMPOUND BY THE METHOD OF ROLLING IN VACUUM

In the experiments, the connection of Ta-Ti-W-Ti-Ta by hot rolling in vacuum was carried out in two stages, preliminarily by heating the package in a furnace to 1300 ˚C with an exposure of about 1 hour and feeding it under the rolls.

At the first stage of rolling, which we will call **dynamic**, Ta-Ti-W-Ti-Ta layers are installed rigidly and symmetrically with respect to the tungsten layer in a strong Nb alloy mandrel. The mandrel is moved by rolls. The movement of the mandrel is carried out in the forward, reverse and again in the forward direction. Rolling ends when the rolls are in the middle of the mandrel.

In the second stage of rolling, the rolls remain in a position in the middle of the mandrel, and this state is maintained for several hours and called **isostatic** stage.

The experimental conditions indicate the absence of relative motion of the rolled metals: a special mandrel does not allow the metals to move relative to each other. However, it transmits the force of the rolls in the direction transverse to the speed of movement of the metals. Due to the high pressures and rather high temperature of the samples, Ti can pass into a quasi-liquid state, while the Nb, Ta, and W alloys remain in the solid phase.

In a microscopic measurement on a thin section depicting the interface between W and Ti after the dynamic stage, one can see the incomplete connection of W and Ta through the Ti interlayer, as it is shown in Fig. 2. An increase in the load does not lead to complete filling of the formed cavities with titanium, but only to uncontrolled deformation of the mandrel and the entire package.

W, Ti AND Ta COMPOUND BY THE METHOD OF ISOSTATIC HOT VACUUM PRESSING

The W cavity filling condition was found as a result of series of experiments. To do this, it is necessary to leave the package under load in a hot state, followed by cooling. In the process of isostatic loading and when the temperature drops from 1200...1300 °C to 882 °C, within 10-12 hours, quasi-liquid Ti fills all depressions in W (see Fig. 3).

The properties of titanium $\alpha + \beta$ - alloys are such that, above a temperature of 882 °C, it has superplasticity and fluidity in the region of the β - phase.

An analysis of the phase diagram indicates that at the boundary of the solid-phase Ti - Ta compound under equilibrium conditions, the sample should consist of the α - phase of titanium and pass into the tantalum region through the two-phase region α + β, which provides superfluidity when all irregularities are filled in the solid-phase connection.

The study by scanning electron microscopy of the microstructure of the zones of the W - Ti and Ti - Ta joints (Fig. 4), as well as in the body of the constituent samples, showed the absence of defects in the form of pores, delaminations, cracks or inclusions. An X–ray electron probe microanalysis made it possible to determine the widths of the diffusion zones for Ta – Ti and Ti - W equal to 2 µm and 3 µm, respectively. The nature of the slope of the concentration curves at the boundaries of Ta - Ti and Ti - W indicates the predominant penetration of quasi-liquid titanium into both tantalum and tungsten, which is explained by the high mobility of titanium.

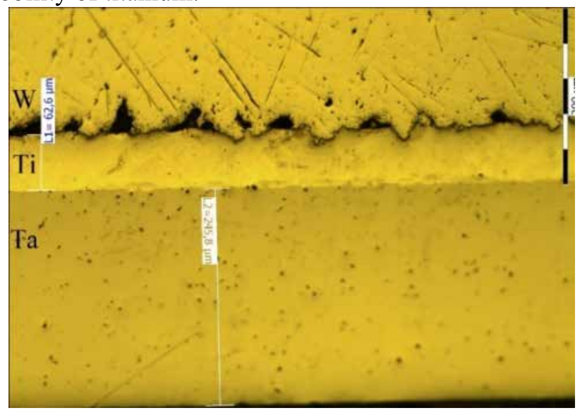

Figure 2: Microphoto of the boundaries of the W, Ti, Ta compound after the first dynamic stage. At the interface between W and Ti, one can see unfilled cavities in W.

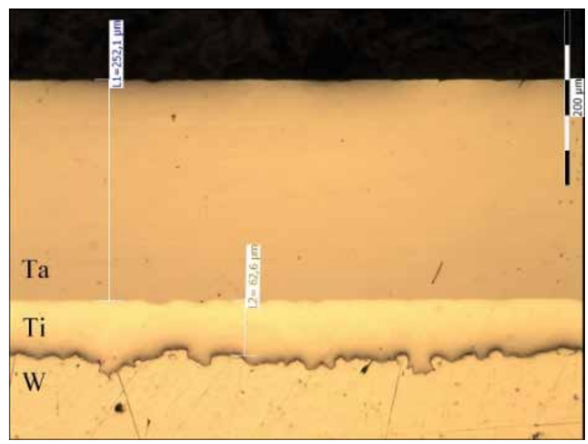

Figure 3: Microphoto of the boundary of the W+Ti+Ta compound after the second, isostatic stage of pressing. Filled cavities in W are visible at the interface between W and Ti.

When an isostatic load occurs, Ti penetrates into micro-depressions in W, and the connection in the solid phase of the surface of Ti and W occurs along the entire interface.

In addition, at this stage, we will assume that, in view of the quasi-liquid state of Ti, the metal bonding process occurs as a result of the penetration of Ti into the roughness of the tungsten boundary. Since the irregularities of tungsten are in a vacuum, the joining process will be associated with the penetration of a heavier substance (quasi-liquid Ti) into a lighter substance (vacuum). The whole system is placed in a force field, the effective acceleration of which g^* is determined by the force of volumetric compression Ti with the Ta + Nb alloy on the one hand, and W on the other, due to different coefficients of their thermal expansion.

Thus, we come to the Rayleigh - Taylor instability problem, which describes the motion of the interface between liquid media in a gravitational or other force field. In media with dissipation, which is the viscosity of liquids, such

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instabilities are called dissipative Rayleigh - Taylor instabilities (DRTI).

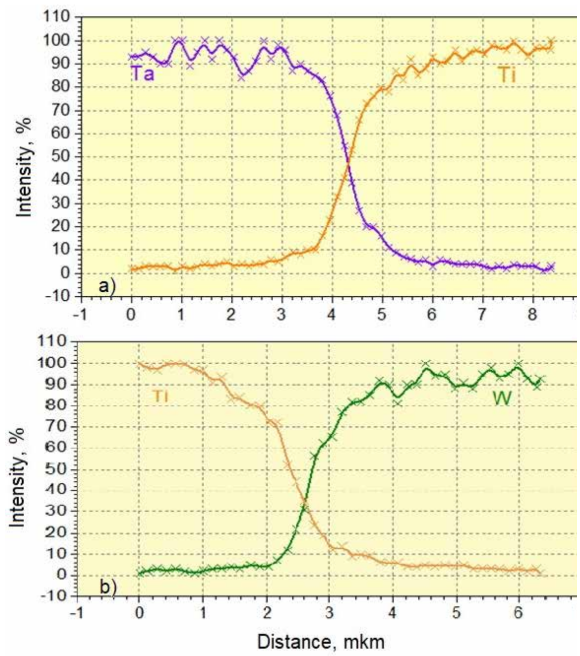

Figure 4: Electron probe X-ray spectral analysis of Ta-W-Ta samples (Ti interlayers) through the boundaries of the connection: a) tantalum-titanium and b) titanium-tungsten.

Based on the use of the DRTI model, the estimate of the characteristic connection time turns out to be about 40 s. The validity of the model is confirmed by the experimentally measured relative change in the diameter of the rolls at the dynamic and isostatic stages of rolling. The relative change in the roll gap is the difference between the current convergence of the rolls and the initial one, which in the experiment was chosen to be 100 μm. The initial convergence of the rolls during rolling or isostatic hot vacuum pressing is determined by the difference between the thickness of the Nb - $H_{As}(t)$ and the vertical distance between the generatrixes of the upper and lower rolls - $H_{Rolls}(t)$, where t is time.

Due to the small, applied stresses during rolling, we will assume that all metals, except for Ti, obey Hooke's law, i. e. when stress is removed, they return to their original shape. Therefore, a change in the dimensions of rolled metals can occur as a result of linear expansion / contraction of the samples when their temperature changes.

From the experimentally obtained relative temperature change in the gap between the rolls at the dynamic and isostatic stages of rolling follows that during the dynamic stage, during rolling in the forward and reverse directions for about 9 s, the massive rolls were in contact along the generatrix line with the surface of the heated assembly over a rolling length of 10 cm, which corresponds to the rolling of the rolls clockwise and in the opposite direction by angle 67.44°. The assembly, in preparation for rolling, is preheated in the furnace to 1300°C. During rolling, the rolls are heated, because of plastic deformation of the rolled package, so that the relative convergence with an external increase in the diameters of the rolls at the isostatic stage will increase to 20 μm. The increase in the assembly temperature in this case is estimated at about 25 – 30 . Then, at the isostatic stage, the rolls are heated through the area of contact with the package assembly, and the assembly of Nb+Ta+Ti+W+Ti+Ta+Nb metals is cooled in accordance with their thermal conductivity coefficients.

Thus, because of the cooling process of the assembly and heating of the rolls and, accordingly, their increase in diameter, during the isostatic stage, volumetric thermal compression of the assembly is observed, and a decrease in pressure in Ti, which is still in a quasi-liquid state for a certain time. This stage, as shown by experiment and numerical evaluation, lasts on the order of several tens of seconds. During this time, the tungsten cavities are filled with quasi-liquid titanium because of the development of DRTI.

After that, the rolls continue to heat up, and as a result of their volumetric thermal expansion, the force of isostatic vacuum pressing of the package assembly is increased. After a long period of cooling (about 12 hours) of the entire system, Ti passes into the solid phase, and the process of joining Ti + W is completed. The experimentally measured time for changing the gap between the rolls and decreasing the pressure in Ti corresponds to the characteristic time for the development of DRTI.

CONCLUSION

The technology of the tungsten target-converter manufacture of a for the NSC KIPT RNF is described. The process of joining W with Ta in the solid phase with the help of a Ti interlayer by the vacuum rolling method is considered. To facilitate the process of joining these metals, it is proposed to use the previously developed batch scheme for joining metals of different hardness and plasticity. The combination of W and Ta by rolling in a vacuum is carried out in two stages. The first is the dynamic stage of rolling. The second is the isostatic stage of pressing the W and Ta compound by rolling in vacuum, controlled by nano-mechanisms with the appropriate temperature-force parameters. A scheme has been developed for rolling a mandrel made of niobium with joined metals in the solid phase. An electron-probe X-ray spectral analysis of the boundary between the titanium-tungsten and titanium-tantalum junctions has been carried out. The predominant diffusion penetration of titanium into tantalum and tungsten is shown. The stages of the physical foundations of nano-mechanisms of joining in the solid phase of tungsten and tantalum at the dynamic and isostatic stages of hot vacuum pressing are determined. Experimental data on the relative temperature convergence of the rolls at these stages have been obtained.

One set of the target plates was loaded to the facility core and was used during tuning and facility physical start-up. During start-up any mechanical damages or material leakages were registered.

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