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Use of tungsten single crystals to enhance nuclear reactors structural elements properties

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ABSTRACT

This paper demonstrates advantages of using tungsten single crystal as structural material in science absorbing industry in comparison with polycrystalline material. High-temperature short-term static strength and creep resistance characteristics of polycrystalline tungsten and single crystal alloy were obtained and compared. The results of comparative studies of the mechanical properties of polycrystalline and monocrystalline tungsten – 4% tantalum alloy are presented.

It is shown that monocrystalline tungsten based materials have both high-temperature strength and plasticity which makes them most suitable for use under high temperatures and high mechanical stresses. Use of monocrystalline tungsten as a structural material makes it possible to prolong the service life and avoid the failures resulting from embrittlement and strain. Moreover, thermo mechanical treatment of monocrystalline tungsten enhances its high-temperature strength. However, it is necessary to carry out additional experimental research to choose the appropriate thermo mechanical treatment conditions.

Introduction

Tungsten, molybdenum and their alloys are perspective structural materials of modern technical facilities, such as nuclear power installations, fast and high-temperature reactors, ITER metal mirrors, cathodes of powerful X-ray tubes etc. [1] The basic requirement for such facilities structural materials is the ability to operate at high temperature (1500–2500 °C) and mechanical stress, in contact with aggressive media and radiation exposure. Structural materials of high-temperature and high-loaded systems must have such properties as high tensile strength, high ductility and low creep at elevated temperatures. It means that tungsten based materials can be used as high temperature materials in many fields of science and technology due to the high rates of long-term strength and creep resistance. However, increasing temperature and operation time lead to deterioration of properties of polycrystalline tungsten, so it is needed to enhance the material creep strength.

Almost all materials are naturally polycrystalline. Grain boundaries pose the weakest point of the polycrystalline materials: they accumulate the most harmful impurities and defects and cause cracks formation, resulting in destruction of

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the material. Use of monocrystalline refractory metals leads to significant increase of commercial properties due to their crystallographic and dimensional stability, plasticity, compatibility with nuclear fuel [2,3].

Monocrystalline tungsten has a number of advantages in comparison with polycrystalline material [1,4]. Pure single crystal has:

- no grain boundaries, so it has a number of unique physical properties that are absent in metals and alloys with polycrystalline structure;
- the absence of recrystallization and grain boundary fracture at room and high temperatures;
- stability of structure and properties up to the pre-melting temperatures (polycrystalline grain growth promotes the release of impurities on the surface, which leads to sharp degradation of mechanical properties);
- low temperature brittle–ductile transition (providing good machinability);
- high corrosion resistance in contact with nuclear fuel (oxides, carbides and nitrides of uranium and plutonium), plasma and coolant (liquid metal – Li, Na, K or gas – H_2, Cs);
- anisotropy of the thermal, mechanical and chemical properties (ability to control the properties);
- high resistance to radiation and laser damage (concentration of impurities in monocrystalline materials is up to 2–3 orders of magnitude lower than polycrystalline);
- low level of gas impurity release at high temperatures;
- phenomenal heat resistance at working load above 10 MPa and temperature over than 1500 °C (creep rate of the single crystal to 3–4 orders of magnitude lower than polycrystalline material);
- low – flow of fuel components and fission products through the fuel element jacket (the monocrystalline jacket serves as a diffusion barrier).

FSUE SRI SIA “LUCH” has a long-term experience in development of thermionic fuel elements with nuclear and non-nuclear heating. A great volume of researches has been carried out to develop a new class of structural materials for structurally functional parts including monocrystalline refractory metals and nuclear fuel. Now FSUE SRI SIA “LUCH” possesses a unique complex of modern technologies on a basis of single-crystal and high-temperature materials. It produces series of large-size rolled refractory metal products for atomic power engineering and aerospace industry. A unique method of growing oriented single crystals of refractory metals with practically no limitations on sizes and cross-section profile by plasma-induction zonal technology (Fig. 1) has been developed and makes it possible to grow large and super-large single crystals (about 800 mm length) [4].

To forecast the capability of a technical object (e.g. nuclear power plants) the ultimate strength or yield strength of structural materials are extremely important. Main parameters which determine the strength of the structures are the tensile strength, yield strength and the curve of probability of failure under loading obtained on the basis of experimental data on the tensile, bending, breaking, etc.

Therefore, the main aim of this study is to obtain experimental data on the comparative study of mechanical properties: high-temperature short-term static strength, creep resistance and high-temperature deformation of tungsten with poly- and monocrystalline structure (tungsten – 4% tantalum alloy).

Moreover, obtained data are valuable for investigation of the impact of high-temperature deformation processing on improvement of high temperature strength. It is very desirable that thermo mechanical treatment with subsequent annealing would improve the high-temperature strength of the material preserving its monocrystalline structure and consequently – its plasticity. This paper presents the results of comparative studies of the mechanical properties and deformation behavior at short-term loading of monocrystalline and polycrystalline tungsten.

Materials and methods

All researches were conducted using materials produced by FSUE SRI SIA “LUCH” [5].

To investigate short-term strength and creep flat samples were used. Appearance of the samples is shown in Fig. 2. The dimensions of samples are given in Table 1. Single-crystal W–Ta samples were cut along the <110> direction with an inclination angle less than 4°, the working part of the plane is close to the {111} with a deviation less than 4°.

Load direction was corresponded to the rolling direction of a polycrystalline tungsten and the <110> axis – for a single crystal. Before testing all samples have been annealed in vacuum 5×10^{-5} Pa at 2000 °C for 1 h. Short-term strength tests were performed at active grip movement velocity 2 mm/min in a vacuum, under constant direct loading. Deformation of the specimen was measured by cathetometer. The total error in determining the characteristics of strength does not exceed 5%, the creep rate – 20% of the coefficient of linear expansion – 10%. Creep tests were carried out in load range about 0.7–0.9 of the material yield strength.

To study the deformation behavior of W–4%Ta monocrystalline alloy and W polycrystalline cylindrical specimens were prepared. The diameter of the sample was about 25.0 mm, height – 20.0 mm. The deposition was carried out by loading the upper plunger of press. Furnace temperature was about 1100 °C, the temperature of samples surface was 450–500 °C. Tools for extrusion: cylindrical container with a drawing die at the bottom. Work pieces (samples of polycrystalline and single crystal in molybdenum jacket) underwent preliminary heating in vacuum to 1200 °C and were placed into a steel casing preheated to 800–900 °C, the punch descended and the pressing machine performed the compression stroke (Fig. 3). Extrusion was carried out in molybdenum containers located below the drawing die. Preform is heated in vacuum up to 1200 °C and then the assembly is placed in a container on top of the punch descends and makes working stroke of the press.

Results and discussion

The results of polycrystalline and monocrystalline tungsten short-term strength testing are presented in Fig. 4 and Table 2.