STRUCTURE AND FRACTURE OF ALLOYS

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STRUCTURE AND FRACTURE RESISTANCE OF ZIRCONIUM ALLOYS FOR ATOMIC POWER ENGINEERING

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The effect of structure on the processes of deformation and fracture of zirconium alloys and on the characteristics of crack resistance and resistance to stress corrosion cracking of articles produced from them is studied. Methods for controlling fracture resistance by changing the structure of the alloys are considered.

INTRODUCTION

Zirconium alloys are the basic structural materials for parts of cores and fuel rod arrays (FRA) of power reactors.

At the present time cores of VVER reactors of the tank type with ammonia-potassium water cooling and of RBMK reactors of the pressure-tube type with boiling water coolant at atomic power plants of Russia, Ukraine, the countries of Eastern Europe, Finland, and Armenia employ articles from Russian binary alloys Zr – 1% Nb² (É110) and Zr – 2.5% Nb (É125) and a promising highly radiation-resistant multicomponent zirconium alloy Zr – 1.2% Sn – 1% Nb – 0.4% Fe (É635).

Articles from binary alloys É110 (cladding pipes, spacer grids) and É125 (pressure pipes, shroud pipes) based on a mixture of electrolytic and iodide zirconium and processes of their manufacturing have ensured reliable operation of fuel elements for three-year and four-year campaigns with fuel degradation of up to 50 MW · day/kg U and of process channels for 15 – 17 years [1]. The service life of these articles is primarily limited by aqueous corrosion and hydrogenation due to the interaction with the coolant, corrosion cracking under the action of aggressive products of fuel fission products, radiation damage, and creep under the effect of neutron irradiation and temperature.

Further increase in the economic efficiency of the use of fuel in VVER reactors with mean fuel degradation of 65 – 75 MW · day/kg U and fuel cycles of 6 – 7 years and the introduction of power maneuvering are directly connected with prolonging the life of zirconium articles and their use in FRA (fuel claddings, spacer grids, directional and central channels) [2].

Creation of construction materials with improved properties for cores of VVER-type reactors will be based on improvement of the properties of fuel claddings from alloy É110 and its modifications and on the use of alloy É635 with higher strength and creep and radiation resistances than alloy É110 [3].

In the last 15 years the department of metal science and strength physics of the Moscow Institute of Steel and Alloys headed by professor S. A. Nikulin in cooperation with the developer organization (A. A. Bochvar All-Russia Research Institute for Inorganic Materials) and producers of zirconium articles [Cherepovets Mechanical Works JSC (ChMZ)] has been studying the processes of deformation and fracture of zirconium alloys in accordance with the programs of the Ministry for Nuclear Power of the Russian Federation. A special place in the study is devoted to problems of raising the fracture resistance of articles by advancing their structure. For this purpose the effect of the structure of zirconium pressure pipes from alloys É125 and É635 [5 – 10] and of cladding pipes from alloys É110 and É635 [11] on crack resistance, stability of plastic yielding and process ductility [4, 12, 13], and stress corrosion cracking (SCC) (thin-walled pipes [14, 15]) is studied as well as the causes of the loss in ductility and of embrittlement under conditions simulating emergency cases [16]. Special methods for mechanical testing, measurement of acoustic emission (AE), and fracture studies [11, 13] have been developed. In the present work we will discuss some results of these studies.

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² Here and after, contents of elements in wt.%.
RESULTS AND DISCUSSION

Requirements on Zirconium Parts

The main requirements on the properties of zirconium articles are high corrosion resistance under conditions of oxidation and hydrogenation, ductility at sufficiently high strength, and resistance to creep and cracking.

Zirconium alloys should possess high processibility necessary for the production of domestic parts like especially thin-walled pipes for fuel cladding (4.5 m long, 8 – 10 mm in diameter, 0.3 – 1 mm in wall thickness), pipes for channels of water-moderated and boiling nuclear reactors (up to 8 m long, 80 – 130 mm in diameter, 3 – 6 mm in wall thickness), sheets and ribbons (0.3 – 1.5 mm thick) for spacer grids, and other articles.

The most critical parts are cladding pipes, because depressurization of fuel claddings in operation causes emergencies and is impermissible. Fuel claddings serve under severe conditions of the action of temperature, irradiation, corrosive media, and stresses. Cladding materials should possess a high combination of properties at a temperature ranging from room to the operating one (300 – 380°C), withstand local heating to up to 1200°C in extreme situations, and meet numerous requirements the main of which are high corrosion resistance and resistance to radiation growth, minimum creep rate, high long-term strength, and fracture resistance. One of the most important requirements on materials of reactor cores is a low absorption of hydrogen. Hydrogen charging reduces the ductility and crack resistance of zirconium alloys, and segregation of brittle hydrides in stress concentration zones can lead to failure caused by formation and growth of hydride cracks by the mechanism of delayed fracture at operational temperatures.

Effect of Structure on the Ductility and Crack Resistance of Zirconium Alloys

The ductility in pressure treatment and the resistance to fracture toughness of zirconium alloys are determined by their capacity for steady plastic yielding under the action of tensile stresses without localization of strain. Early deterioration of stability of plastic yielding at the macroscopic level, for example in rolling and draw forming, can be the cause of reduced process ductility of alloys; at the microscopic level (under the development of a tough crack) it can lower the fracture resistance of the material.

In order to develop methods for increasing the process ductility and fracture resistance of alloys we have formulated and classified the methods used for controlling the loss in yielding stability and the development of fracture by changing the structure [4]. We used a simple and easy to interpret approach based on joint analysis of strain diagrams, acoustic emission (AE), and fractures due to uniaxial stretching. Such an analysis makes it possible not only to evaluate the ductility and fracture toughness margins of the alloys but also to determine the causes of deterioration of the stability of plastic yielding and the structural factors limiting the ductility and fracture toughness. Comparing the value of the uniform strain \( e_u \) measured under uniaxial stretching and the hardening parameter \( n \) determined from strain diagrams we can evaluate the ductility margin and the fracture resistance.

Thin-walled pipes and bars from alloys É110 and É635 and pressure pipes from alloys É125 and É635 are produced with the help of processes that include repeated cold rolling and annealing at the temperature of existence of \( \alpha_{Zr} \)-phases in parts of intermediate and final sizes and ensure, in the parts, a structural state close to a recrystallized one [2].

The microstructure of these alloys differ principally as follows:

- In alloys É110 and É125 the grains of the \( \alpha_{Zr} \)-phase and the inclusions of the \( \beta_{Zr} \)-phase (up to 0.1 μm in size) are represented by a mixture of solid solutions;
- In alloy É635 the structure is represented by grains of the \( \alpha_{Zr} \)-phase and fine dispersed particles of intermetallic compounds (0.1 – 0.3 μm in size) including Zr, Nb, and Fe.

In this connection the crack resistance of alloy É635 in the recrystallized state is determined primarily by the size of the particles of the intermetallic compounds and by their distribution in the matrix [5, 8]. The fracture resistance of binary alloys É110 and É125 primarily depends on the degree of recrystallization of the matrix and on the texture [6].

The value of the hardening parameter \( n \) in zirconium alloys is chiefly determined by the texture ensured by the deformation and heat treatment. For this reason, the uniform ductility is commonly increased (to the maximum possible level \( e_u = n \)), as well as the fracture toughness, by removing the structural causes of early degradation of the stability of plastic yielding.

In alloy É125 this is attained by increasing the degree of recrystallization \( V_r \) (the volume of the metal with recrystallized structure) by annealing after cold deformation. In stretching of longitudinal and transverse specimens of alloy É125 with nonrecrystallized structure \( (V_r < 25\%) \) the stability of yielding degrades at \( e_u < n \) due to the formation of an “internal” neck caused by microcracks in the places where twins meet slip bands and grain boundaries even at a relatively low hardening factor \( n < 0.15 \) [9]. Several strong AE pulses with an amplitude of 20 – 45 dB due to formation of microcracks are detected here before the beginning of load decrease in tests of longitudinal specimens (Fig. 1). As the volume \( V_r \) grows, the uniform strain \( e_u \) increases, attaining \( e_u = n \) at \( V_r = 50 – 74\% \).

The obtained quantitative dependences \( \sigma_{0.2} (V_r) \) and \( e_u (V_r) \) at \( V_r \) of up to 80% (Fig. 2) allow us to predict strain diagrams from the structure. Growth in the degree of recrystallization to \( V_r > 50\% \) increases the uniform strain \( e_u \), the impact toughness \( K_{CT} \), and the critical crack opening \( \delta_c \) over all directions in the pipe (Fig. 3).

While the ductility and toughness of alloy É125 can be increased substantially by creating a more recrystallized...