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RESEARCH OF THE MECHANICAL PROPERTIES OF FUEL ELEMENT SHELLS MADE OF Zr1% Nb ALLOYS AT RADIAL STRESSES SIMILAR TO REACTOR CONDITIONS†

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When determining the mechanical properties of ring specimens, a feature of a uniaxial (standard) loading scheme is that the method of applying a load to a specimen is somewhat remote from that to which the pipe walls can be subject in real operating conditions, in particular, these are tubes of fuel element shells. As an alternative loading method, the method of strain of an ring specimen on a cylindrical rod was considered and tested. By compressing the cylindrical rod from the ends, which in this case expanded and exerted pressure on the inner walls of the ring specimen in the radial direction, the specimen was deformed. The plasticity of fuel element shells made of Zr-1%Nb alloy on ring specimens under different loading methods is evaluated: uniaxial tension on half-disk supports, on a cylindrical rod, and on a tapered rod. Uniaxial tensile strain was determined in accordance with the normative documentation for the test method. When testing on a tapered rod, a specimen with a thinned working part was used. For the proposed loading method, the radial strain was measured by the change in the sample diameter. The results of testing the samples on a cylindrical rod were compared with the previously obtained results on half-disc supports and a tapered rod. The method of deformation of a ring specimen on a cylindrical rod makes it possible to obtain higher values of plasticity in comparison with uniaxial tension. In addition, the proposed method of deformation of a sample on a cylindrical rod, in contrast to uniaxial tension, in terms of the nature of the stress state, approaches to the operating reactor conditions.
Keywords: mechanical properties, ring sample, fuel element shell (TVEL), radial stress.
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Investigations of the mechanical properties of pipes of small diameters, in particular, fuel element shells, both with and without coating, have been devoted to a lot of works [1-7]. Until now, there is extensive information on the mechanical properties of fuel element shells in the longitudinal and transverse directions at 20 °C and at elevated temperatures of ~700 ° C. However, most of the works relate to tests in the uniaxial direction of tension, like on the fragments of tubes from the fuel element shells, and on ring samples in accordance with the normative documentation [8-10]. This method of tensile strain does not fully reflect the loading conditions of the walls of the fuel element shells during the operation of reactor facilities and does not give a complete picture of the properties of the material.

At NSC KIPT, steps were also taken [4] to assess the plastic characteristics of the material by a method different from the standard uniaxial testing of ring specimens on half-disk supports, in which the tensile strain of the ring to the yield strength point is often not taken into account, which is not unimportant for comparison with reactor conditions. Since when the ring is stretched in the deformation area to the yield strength point, conditions are created for the development of microdefects, which can contribute to a decrease in plasticity. This is manifested, for example, when testing ring samples with a nanostructured chrome coating with a thickness of 5-8 microns. In this case, if the coating was applied before deformation by ring tension, this leads to a noticeable decrease in the relative elongation δ% [2, 3]. In [4], tests were carried out by distributing ring specimens on a tapered rod [11]. During these tests, significant differences in mechanical properties were noted, especially in the increase in ductility at elevated temperatures up to 350 °C. However, this method also has some nuances associated with the conditions of loading and deformation of the sample.

Taking into account the applied test methods of branch pipes and ring specimens made of fuel element shells, and noting the shortcomings of the methods about non-compliance with reactor conditions. In this work, a method of deformation of ring specimens in the radial direction is proposed. This method consists in expanding the annular specimen by compression of a metal cylindrical core, which brings this method of deformation and stress state closer to real conditions in which fuel element shells is operating.

SAMPLES AND TEST PROCEDURE

The circumference of the ring specimen $C = \pi D$, where D is the outer diameter of the ring. For the fuel tube in the initial state, $D_0 = 9.15$ mm, $C_0 = 28.73$ mm. At the yield strength point of the fuel element shell (a ring made of Zr1%Nb alloy)

$$\delta\% = ((C_1 - C_0)/C_0) \times 100 = 0{,}2\%$$

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where C_1 is the circumference at the yield strength point.
From here it is possible to calculate the increment in the value of the absolute deformation at the yield strength point on the surface of the annular specimen during radial expansion, which is equal to $\Delta C_1 \approx 0.04$ mm. The amount of deformation is recording using a contact extensometer (Fig. 1).

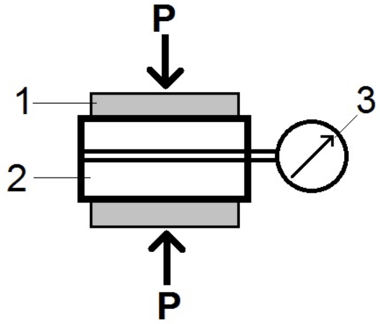

Figure 1. Test scheme
P - load (in compression), 1 - a rod made of ductile metal (alloy), 2-ring specimen of fuel element shell, 3-pin extensometer

It should be note that research of the mechanical characteristics of ring specimens made from fuel element shells can be performe on any mechanical testing facility, and testing on an Instron-5581 facility makes it possible to expand and simplify research.

One should take into account the limited possibility of deformation of a ring specimen on a compressive cylindrical rod (made of copper), which may not achieve destruction due to the significant plasticity of the Zr1%Nb alloy. Therefore, to compare the ductility of ring specimens made of Zr1%Nb alloy during standard uniaxial tests on half-disk supports and in deformation of rings on a compressing cylindrical rod (rod cooper), the achieved ductility of the specimen at the maximum level of core compression can be used. If the destruction of the ring specimen is not achieved, the obtained value of δ% will be conditional.

The proposed deformation method makes it possible to test ring specimens of fuel element shells in the radial direction, which brings the stress state of the specimen walls closer to the conditions that arise during the operation of fuel element shells.

EXPERIMENTAL PART

When studying the strength and plastic characteristics of ring specimens from various materials using the device in Fig. 1 for loading, it is necessary to take into account some of the features that exist for brittle and ductile materials. The main difference is that brittle materials reach destruction and the characteristics of strength and ductility have finite values, for example, samples from chromium alloys. For plastic materials, which include the Zr1% Nb alloy and its δ (%) uniaxial tensile strain at normal temperature is $\delta \approx 27\%$, the samples may not reach destruction (when loaded according to the scheme in Fig. 1), therefore, determine the final values of δ (%) does not seem possible.

In this case, it is advisable to consider the values of δ (%) in stages, for example: at the first stage - deformation to the conditional yield strength $\sigma_{0.2}$ (the most significant in the deformation of the fuel element shell under reactor conditions), and then at the second stage - above the value of the conditional yield strength $\sigma_{0.2}$. In this case, the values $\sigma_{0.2}$ and δ (%), with uniform deformation, and other values obtained on this alloy under uniaxial tensile strain of ring specimens (on 2 half-disk supports) can be used. In such comparisons, some “conventional” values of δ (%) can be obtained at various points on the stress-strain diagram.

As an example, we can consider the tests carried out on an ring specimen made of Zr1%Nb alloy with a diameter of D = 7.70 mm and a height of h = 4.0 mm, into which a cylindrical rod (made of copper) with parameters D = 7.65 mm and h = 12.37 mm. Compressive strain of the rod was carried out on an Instron-5581 setup at normal temperature at a rate of 0.1 mm / min.

At the first stage, with a load P_1 = 1335 kg, the outer diameter of the ring specimen was D_1 = 9.16 mm and ΔD_1 = 0.06 mm. At the second stage of deformation with a load P_2 = 2100 kg D_2 = 9.77 mm, and ΔD_2 = 0.62 mm, which corresponds to δ_2 = 24.2%.

When comparing δ_2 = 24.2% of the deformation obtained at the 2nd stage with the value of δ_{max} (%) for ring specimens tested according to the standard method uniaxial tensile strain, which reached $\delta_{max} \approx 24\%$ at destruction, it can be seen that with radial deformation using the loading scheme in Fig. 1, the plasticity is much higher, since the value δ_2 = 24.2% already exceeds $\delta_{max} \approx 24\%$ for uniaxial tension. With further deformation of the ring on the rod, δ_2 (%) will increase significantly. It should be note that under the applied loads, the specimen was not brought to destruction.

Figure 2 shows the dependence of the plasticity δ_2 (%) of the Zr1%Nb alloy on the loading method. With uniaxial tensile strain of the ring specimen on half-disk supports until destruction - item No.1 in Figure. 2.

Under radial tension of specimens on a cylindrical rod (made of copper) during its compression, the load P reached 1335 ... 2100 kg (without destruction of the specimen, since with this method of loading the plastic alloy cannot reach destruction, and in this case δ_2 (%) is a conventional value - item No.2 in Figure 2). Ring specimens (item No.3 in Figure 2) refer to the method of expansion in the radial direction on a tamper rod [4] until destruction, while δ_2 = 40%.

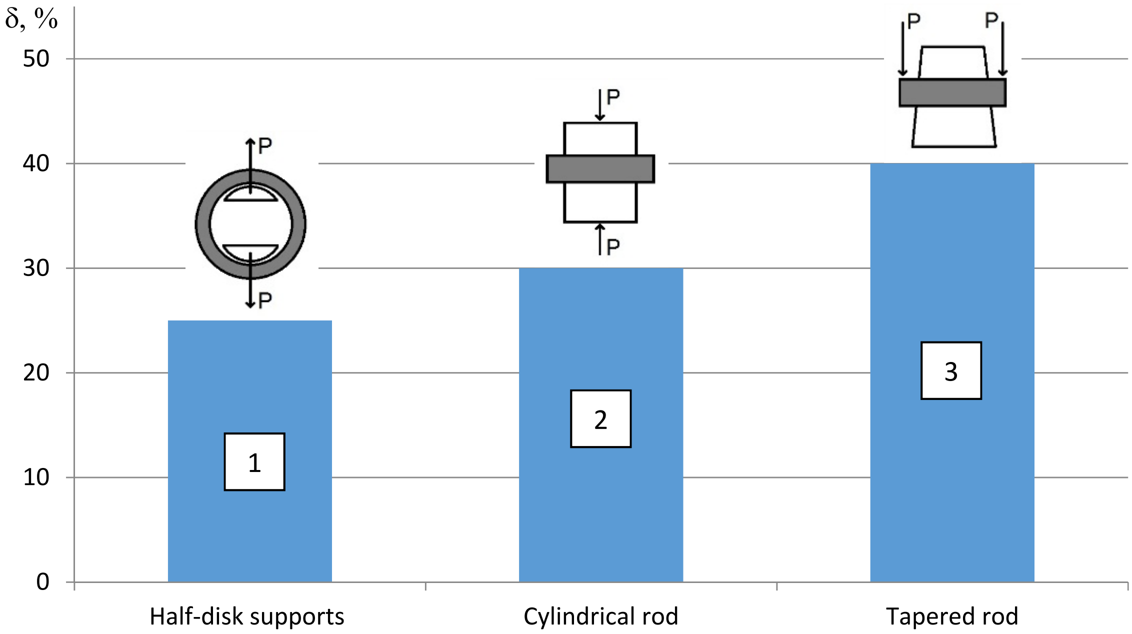

Figure 2. The dependence of plasticity δ_2 (%) of the Zr1%Nb alloy on the loading method.

From the presented results, it can see that under uniaxial tensile strain of ring specimens on half-disk supports, the maximum plasticity is the lowest in destruction (item No.1 in Figure 2). In the second case (item No.2 in Figure 2), the plasticity increases and even in the stress range $\approx\sigma_{0.2}$ it already exceeds δ_2 (%) in comparison with uniaxial tension. With the loading method (item No.3 in Figure 2) on a tamper rod, δ_2 (%) of the ring specimen at destruction is maximum in comparison with the plasticity for the first two cases (item No.1, No.2 in Figure 2). The stress in the ring specimen in the radial direction is determine by the formula

$$\sigma = \frac{E_t}{1-\nu^2}\left(\frac{1}{d_0} - \frac{1}{d_1}\right),$$

where σ is tensile stress, E_t is Young's modulus, ν is Poisson's ratio, d_0, d_1 are the initial and final diameters of the specimen [4].

In the study of radial deformation in the range below the yield strength point, it is possible to compare δ(%), $\sigma_{0.2}$ and σ_B when removing an ring specimen from a cylindrical rod (copper), and performing a test. This makes it possible to compare the effect of uniaxial and radial loading on the strength uniaxial tensile strain and plastic properties of ring specimens. Thus, when using and comparing stress-strain diagrams by new and other methods, the plastic and strength characteristics that are closest to the reactor conditions can be obtained.

DISCUSSION

It is necessary to note the influence of the stress state scheme on the results of mechanical tests, which is especially significant in the region of elastic and uniform deformations occurring under reactor conditions in the fuel element shells made of Zr1% Nb alloy.

To assess the "softness" of the stress state circuit, the "softness" coefficient is used - (coefficient according to Ya. B. Fridman): $\alpha = t_{max} / S^n_{max}$, where t_{max} is the maximum shear stress, S^n_{max} is the maximum reduced principal normal stress. Hence it follows that the more t_{max} and less S^n_{max} (i.e., more α), the better the conditions for the development of plastic deformation. In practice, for example, in experiments with taper loading [4] or when loading in the radial direction in the fuel element shell, a noticeable increase in plasticity occurs in comparison with uniaxial loading, when the coefficient = 0.5, which is a significantly low indicator.

Thus, when using and comparing stress-strain diagrams during deformation of a ring on a rod with other methods, plastic and strength characteristics can be obtained that are closest to reactor conditions.

CONCLUSIONS

In order to assess the plasticity of the metal of thin-walled pipes of small diameters, in particular, of the fuel element shells, an alternative to the standard method of deformation of the ring specimen was used. By compressing the cylindrical rod from the ends, which expanded and exerted pressure on the inner walls of the ring specimen in the radial direction, the specimen was deformed.

The results of the plasticity characteristics of ring specimens of fuel element shells under different methods of deformation are compared.

It is shown that under deformation of a ring specimen on a cylindrical rod, the value of plasticity is characterized by a large value, in contrast to the standard, uniaxial test method.

In the process of deformation of ring specimen on a cylindrical rod, the nature of the stress state of the specimen walls is close to the state that arises during operation of a fuel element shells under reactor conditions.

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ДОСЛІДЖЕННЯ МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ ОБОЛОНОК ТВЕЛ З Zr1%Nb СПЛАВІВ ПРИ РАДІАЛЬНИХ НАПРУЖЕННЯХ, АНАЛОГІЧНИХ РЕАКТОРНИМ УМОВАМ

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При визначенні механічних властивостей кільцевих зразків особливість одновісної (стандартної) схеми навантаження полягає в тому, що спосіб прикладання навантаження до зразком кілька віддалений від того, яким можуть піддаватися стінки труб в реальних умовах експлуатації, зокрема це трубки ТВЕЛ. В якості альтернативного способу навантаження було розглянуто і випробувано спосіб деформації кільцевого зразка на циліндричній стрижні. Шляхом стиснення циліндричного стержня з торців, який при цьому розширювався і тиснув на внутрішні стінки кільцевого зразка в радіальному напрямку, відбувалася деформація зразка. Проведено оцінку пластичності оболонок ТВЕЛ зі сплаву Zr-1%Nb на кільцевих зразках при різних способах навантаження: одновісне розтягнення на напівдискові опорах, на циліндричній стрижні і на конусної оправі. Деформація при одновісному розтягуванні визначалася відповідно до нормативної документації на метод випробування. При випробуванні на конусі застосовувався зразок з стоншеною робочою частиною. Для запропонованого способу навантаження радіальна деформація вимірювалася зі зміни діаметра зразка. Результати випробувань зразків на циліндричному стрижні були зіставлені з раніше отриманими результатами на напівдискових опорах і конусній оправі. Спосіб деформації кільцевого зразка на циліндричному стрижні дозволяє отримати великі значення пластичності в порівнянні з одноосьовим розтягуванням. Крім того, запропонований спосіб деформації зразка на циліндричній стрижні на відміну від одновісного розтягу за характером напруженого стану наближається до експлуатаційних реакторних умов.

Ключові слова: механічні властивості, кільцевий зразок, оболонка ТВЕЛ, радіальні напруження.