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DISTRIBUTION OF PLASTIC DEFORMATION ALONG THE PERIMETER OF CIRCULAR SPECIMEN OF THIN-WALL FUEL-ELEMENT CLADDING DURING ITS EXPANSION

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Abstract. The method of measuring short-time mechanical properties of materials of cladding tubes during the process of expansion of circular specimens is conventional in reactor material science. One of the method limitations is procedure errors caused by the specimen bending on the semicylindrical supports at the initial stage of expansion. The bending induces inhomogeneous plastic deformation of the specimen working parts, which results in the inaccurate evaluation of the yield strength and the plastic properties of the material. This paper contains an analysis of the plastic strain distribution at the different stages of the expansion of the circular specimens of a cladding tube made of austenite steel. The results of the comparison between the true relative deformation and the estimated deformation of the working part are presented together with the assessment of the impact of strain hardening of the material on its mechanical properties.

Keywords: cladding tubes, circular specimen, semicylindrical supports, ovalization, mechanical properties, plastic strain, and true relative deformation

1. Introduction

In the process of operation of fuel elements of fast-neutron reactors, there occurs embrittlement of the material of cladding tubes, which leads to the degradation of the complex of stress-strain properties of this material [1,2]. Specifically, substantial degradation of plastic properties of the material is observed, which limits the service life of fuel elements [3,4]. The validation of the safe operation life and the search for the means of its extension requires the prediction of stress-strain properties of the cladding based on the results of its inspection after the different operational modes. The problem is accentuated by the fact that the cladding temperature in the meter length of the fuel element active part changes by 200–300°C, while the neutron fluence changes more than twofold. Taking into account the necessity to measure also the other properties of the material as well as to gather the statistically adequate sample of results, the length of the sections with the homogeneous irradiation conditions limits the dimensions of specimens and the methods of their testing. Therefore, one of the conventional methods of measuring stress-strain properties of the material of the fuel elements cladding after the operation within the fast-neutron reactors is the method of testing circular specimens by tension (Fig. 1).

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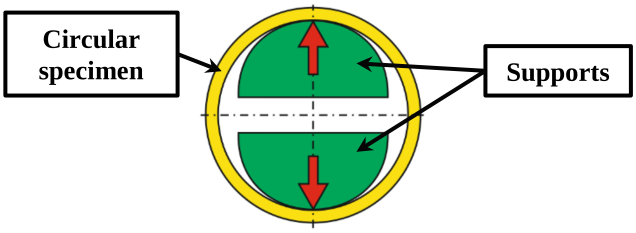


Fig. 1. Diagram of expansion of a circular specimen

A serious limitation of the method is the presence of the uncontrolled plastic deformation localized in particular areas and occurring at the stage of extension (ovalization) of the ring on the grips. This deformation is caused by bending of the ring working part on the supports and begins accumulating in the elastic range of the test diagram, not falling within the field of consideration when processing the stress-strain diagrams using a conventional method according to standard [5]. This results in an underestimation of the values of the relative elongation of the specimen working part after testing (uniform and total elongation). Moreover, for irradiated samples, incorrect information on the strength and plastic properties of the material can be obtained due to the low limit plasticity and the embrittlement of the material.

Figure 2 presents the diagram of expansion outlining the stages of deformation of a circular specimen in the initial condition when using a conventional method of diagram processing and the diagrams of expansion at different test temperatures for irradiated circular specimens with low plasticity.

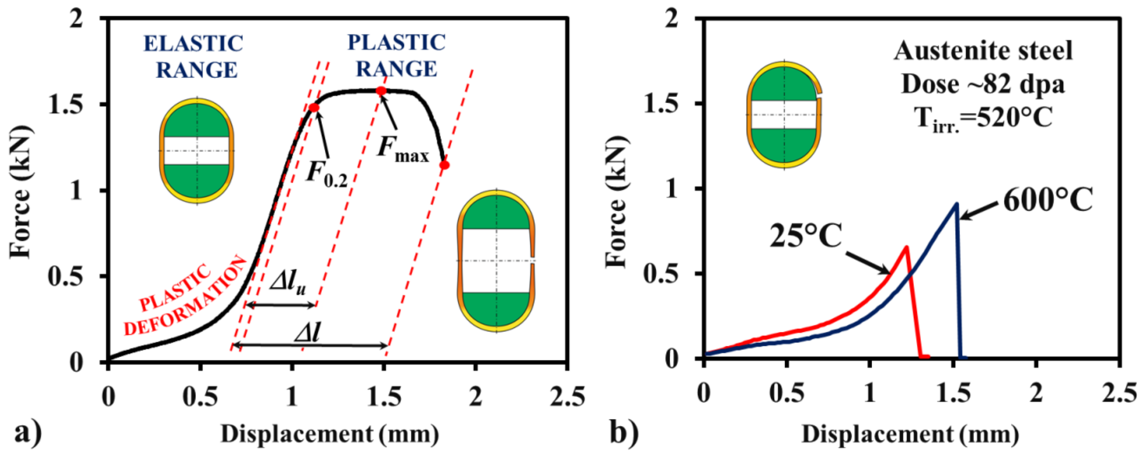


Fig. 2. Stages of deformation of a circular specimen in the initial condition when using a conventional method of diagram processing (a), and the diagrams of expansion of irradiated circular specimens at different test temperatures (b)

Figure 2a reveals that the conventional method of processing of the diagram of an expansion of a circular specimen disregards the deformation, occurring at the stage of the ring ovalization when calculating the material plastic properties because the plastic range of the diagram is only considered when determining the uniform and the total elongation.

Figure 2b shows the test diagrams for the circular specimens made of a section of a fuel element after its operation in reactor BN-600. It is seen that at an initial stage of the test, the whole residual plasticity of the material is exhausted and the specimens are destructed. A consistent assessment of the short-time mechanical properties of the material of the fuel element cladding with the use of the above diagrams seems to be impossible. Therefore, the problem of the selection of patterns and methods of testing circular specimens, as well as the selection of methods of a quantitative assessment of the plastic deformation at the stage of bending of the working part remains challenging.

The existing domestic and foreign patterns of testing circular specimens differ fundamentally. For instance, foreign authors conducting the assessment of mechanical properties of the fuel elements made of zirconium alloys use circular specimens with a specified working part and conduct the expansion both with a rigid insert within the specimen and without it [6-8]. The studies have shown that the results of the measurement of the true plastic deformation are in good agreement with the estimated values, calculated using the diagram of expansion, while the friction between the structure and the specimen internal surface leads to an insignificant overestimation of the results of the measurement of the strength properties of the material under examination [9,10]. However, the given test patterns do not help to solve the problem of achieving a consistent assessment of the mechanical properties of the material of the fuel element cladding, prone to the irradiation embrittlement after the high-dose irradiation [11].

Domestic authors mainly use the conventional test pattern (Fig. 1), in which a circular specimen is expanded on the semicylindrical supports, the diameter of which, depending on the geometrical parameters of the specimen, is 65–95% less than the specimen inner diameter. New results have been recently obtained for the short-time mechanical properties of the existing and advanced variety of cladding tubes for the WWER type reactors [12-14]. Besides, the results have been presented, concerning the consistent assessment of the residual plastic deformation caused by the working part bending on the supports. In papers [15,16], it is shown with analytic formulas that the value of the residual plasticity, accumulated by the working part in the process of bending on the supports, exceeds the standard tolerance of 0.2% for the residual deformation when measuring the yield strength of the material. Depending on the ratio of the supports' mean diameter and the specimen wall thickness to the ring's mean diameter, this deformation can take a value falling within the range of 0.20 to 0.35%. It is also found that the value of this deformation does not depend on the nature of the material under examination [16]. The experimental results presented in paper [17] show that for the circular specimen made of the 42HNM alloy in the initial condition, the residual deformation of the inner diameter in the direction of expansion after testing at T=800°C, taken relative to the length of the working part, gives ~3.3%, and for the irradiated specimen gives ~2.6%.

The difference in values presented in papers [16] and [17] can be attributed to the methodical specifics of the measurement of the localized plastic deformation. In the first instance, [16], an analytic solution is given, which can be used for the assessment of the values of the residual deformation. However, they characterize only the lower limit of the range of values of the residual deformation occurring when bending a specimen on the semicylindrical supports. In paper [17], the authors demonstrate one of the common methods of measuring the true values of deformation: putting special equispaced marks on the specimen surface and the following measurement of distances between them after testing. Thus, it was shown that the values of plastic deformation at the stage of bending the working part of a circular specimen can be in large excess over the standard tolerance of 0.2% for the residual deformation. It may be concluded that for determining the upper limit of the range of values of the residual deformation for a specific pattern of testing a circular specimen, it is necessary to obtain information about the pattern of distribution of plastic deformation on the specimen working part.

The study of the distribution of the plastic deformation along the perimeter of a circular specimen of the thin-wall fuel-element cladding during its expansion is a vital task for making the consistent assessment of the uniform and the total elongation using the diagram of an expansion of a circular specimen, and the assessment of the impact of strain hardening, occurring at the stage of bending the circular specimen working parts, on the mechanical properties of the cladding tube material.

The prime objects of this paper are the study of the distribution of the plastic deformation along the perimeter of a circular specimen at different stages of its expansion and the comparison of the true (actual) value of the relative plastic deformation of the working part with the values of the uniform and the total elongation calculated with the use of the test diagrams. Another object of this paper is making an assessment of the impact of strain hardening, occurring at the stage of bending the circular specimen working parts, on the mechanical properties of the material of the fuel element cladding in a fast-neutron reactor.

2. Research Methodology and Material

The research material is a cladding tube made of austenite cold-shaping steel CHS68-ID 20% (06H16N15M2G2TFR) in the initial condition. The given steel grade was used as a material for the fuel element cladding in reactor BN-600, and is currently used in reactor BN-800. The outer diameter of circular specimens was equal to 6.9 ± 0.01 mm, the wall thickness was equal to $0.4^{+0.01}$ mm, and the height of specimens varied from 2.3 to 2.5 mm. On the frontal surface of the specimens, 32 marks were placed at equal distances with a laser marker, accurate to 3 µm (Fig. 3).

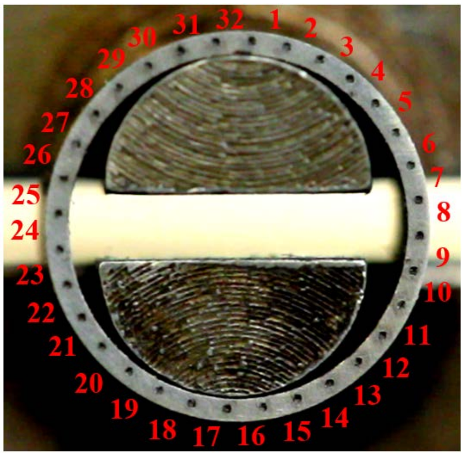
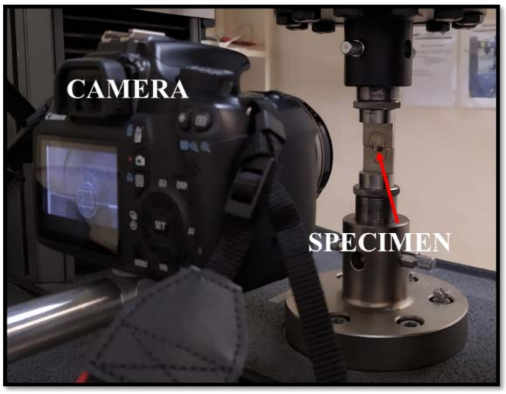


Fig. 3. Circular specimen with marks on the frontal surface

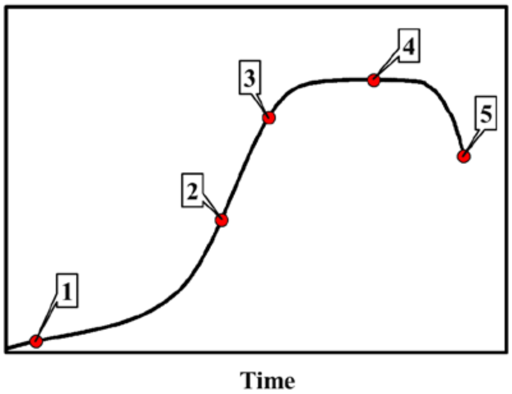
Five specimens were tested at room temperature with the speed of active grip displacement equal to 1 mm/min. The accuracy of load measurement was equal to 0.5%, while the accuracy of measurement of displacement was ±0.05%. The specimens were expanded on the grips with semicylindrical supports with a diameter of 4.8 mm.

During the process of testing, there was recorded a video file of the specimen deformation up to its complete destruction (Fig. 4a). For this purpose, a camera with a lens for macrophotography was used.

The reading of images obtained from the video file of deformation of the circular specimen and the measurement of distances between the marks was carried out using the COMPASS software. Previously, the different stages of deformation were localized in the diagram of expansion: 1 – the initial stage of bending a specimen on the supports; 2 – the stage of the specimen shrinkage on the supports (stage of ovalization); 3 – the stage of reaching a yield offset; 4 – the stage of reaching a maximum load; 5 – the stage of destruction of a specimen (Fig. 4b)



a)



b)

Fig. 4. Scheme of video recording of the testing process (a) and scheme of digital imaging of the stages of deformation of the circular specimen using the diagram of expansion (b)

The true relative deformation of the sections between the marks was determined from formula (1).

$$e_i = ln\left(\frac{l_{\text{f}i}}{l_{\text{ini}}}\right) \cdot 100\%, \quad (1)$$

where e_i is the true relative deformation of i-section (i = 1...32), %; $l_{\text{f}i}$ is the final length of i-section, mm; $l_{\text{in}i}$ is the initial length of i-section, mm.

The reduced error of measurement of the final and the initial length of the sections did not exceed 5%.

The uniform elongation (δ_u) and the total tension set (δ) for the circular specimens under examination were determined by the graphic method using the test diagram according to standard [5] and calculated using formulas (2) and (3).

$$\delta_u = \frac{\Delta l_u}{l_0} \cdot 100\%, \quad (2)$$

where l_0 = 6.1 mm is the initial reference length of the working part of the circular specimen; Δl_u is the length of a section of uniform elongation of the working part according to the diagram of expansion (Fig. 2a).

$$\delta = \frac{\Delta l}{l_0} \cdot 100\%, \quad (3)$$

where Δl is the absolute value of the total elongation of the working part according to the diagram of expansion, mm (Fig. 2a).

The uniform and the total elongation calculated using the diagrams of expansion were compared with the values of the actual relative plastic deformation of the working parts of the right and left halves of the circular specimens, determined at the stage of reaching the maximum load (stage 4) and the stage of the specimen destruction (stage 5), respectively. The actual relative deformation of the working part ($\varepsilon_{n\text{act}}$) was calculated by formula (4) with the use of the results of the measurement of the lengths of sections at stages 2, 4 and 5.

$$\varepsilon_{n\text{act}} = \frac{l_{n\text{act}} - l_{2\text{act}}}{l_{2\text{act}}} \cdot 100\%, \quad (4)$$

where $l_{n\text{act}}$ is the actual length of the specimen working part (index n corresponds to the numbers of stages 4 or 5), mm; $l_{2\text{act}}$ is the actual length of the specimen working part at stage 2, mm.

The actual lengths of the working parts (l_{act}) of the right and left halves of the circular specimens at different stages of the deformation were calculated by formula (5), taking into account the effects of braking and creeping of the deformation sections on the surface of the grip supports. The effect of braking of the deformation areas was understood as the deformation of the areas on the gripper supports, which was formed at the stage of ovalization of the sample and then did not participate in the deformation of the working parts of the ring sample (Fig. 5).

$$l_{act} = \sum_{i=x_0}^{x_f} e_i - (l'_g + l''_g), \quad (5)$$

where e_i is the true deformation of i-section, mm; x_0 andx_f is the start and finish positions of the sections of the deformation of the half of the sample; l'_g and l''_g are the lengths of sections of the deformation braking, mm.

$$l'_g = \sum_{i=x_0}^{x'_g} e_i; \quad (6)$$

$$l''_g = \sum_{i=x_f}^{x''_g} e_i, \quad (7)$$

where x'_g and x''_g is the number of the areas where the strain braking was observed on the upper and lower supports of the grippers.

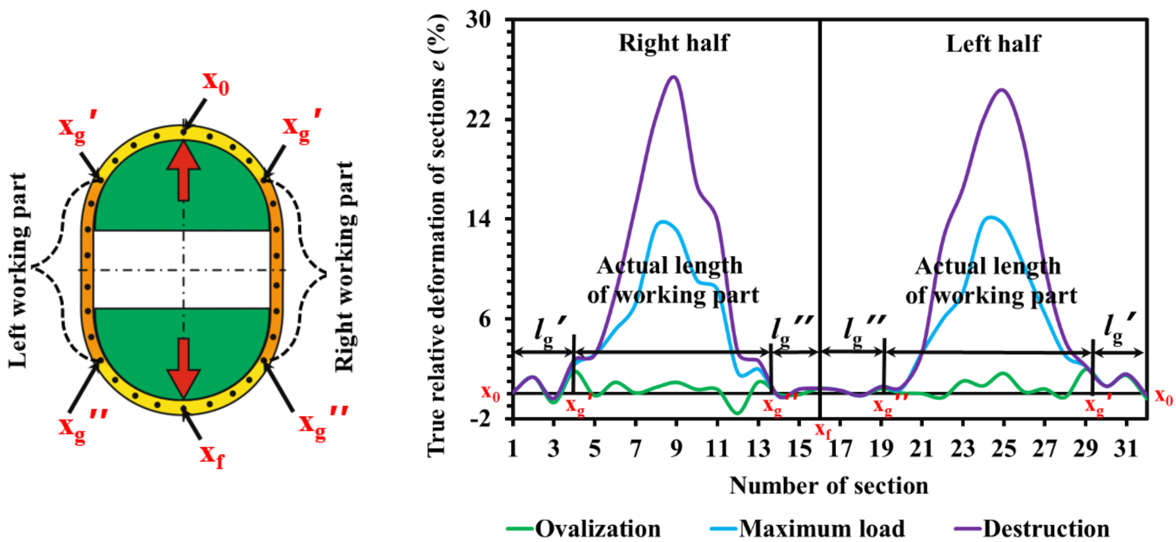


Fig. 5. Scheme of determination of the actual length of the working part

The yield offset ($\sigma_{0.2}$) and the ultimate tensile strength (σ_u) were determined by formulas (8) and (9).

$$\sigma_{0.2} = \frac{F_{0.2}}{2A_0}, \quad (8)$$

$$\sigma_u = \frac{F_{max}}{2A_0}, \quad (9)$$

where $F_{0.2}$ is the load corresponding to the deformation of the specimen working part 0.2%, kN; F_{max} is the maximum load, kN; A_0 is the initial cross-sectional area of the specimen, mm^2.

3. Experimental Results

The study of the deformation of sections of circular specimens at different stages of loading has revealed the formation of inhomogeneous deformed areas in the process of testing. What is more, the deformation of these areas proceeds in a complex manner. At the initial stage of the specimen bending under the load of 60 N (stage 1), deformation of different types occurs in the specimen sections: some areas are subjected to compression, others to tension. Furthermore, generally, the deformation continues to accumulate in these areas as consistent with the established type of deformed condition. However, in certain instances a redistribution of deformation in the sections was observed, namely, the compressed areas began expanding or vice versa. Finally, the bending is finished, and the seating of a circular specimen on the semicylindrical supports is performed, the process of the specimen ovalization is completed, during which the two straight sections, specimen working parts, are formed (Fig. 6). It should be noted that the process of ovalization of the specimens under examination took place with the active grip displacement by 0.86 ± 0.02 mm and under the load of 750 ± 19 N.

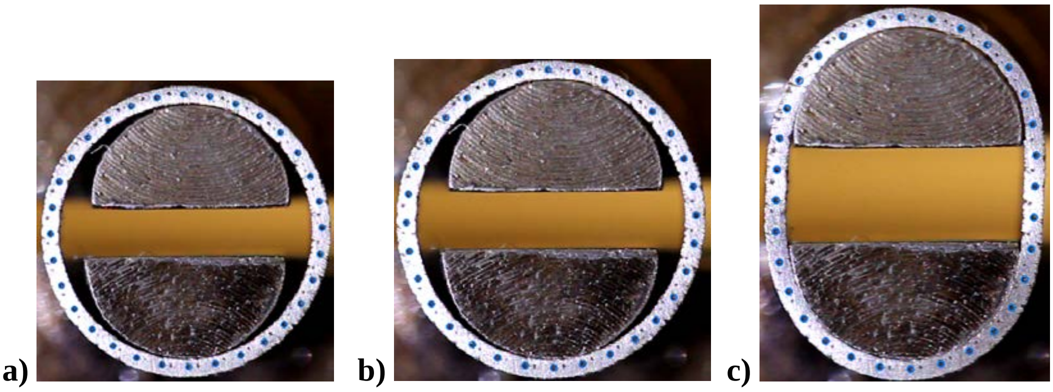


Fig. 6. Deformation of a circular specimen at different stages of expansion.
a) Before testing; b) Initial stage of bending (stage 1);
c) Ovalization on the supports (stage 2)

As an example of nonuniformity in the distribution of deformation of sections, Fig. 7a presents the diagrams of tangential distribution of the true relative deformation of sections of circular specimen 1. To demonstrate the subsequent propagation of deformation of sections of circular specimen 1, Fig. 7b presents the diagrams of distribution of the true relative deformation at different stages of the deformation process: ovalization on the supports (green line), reaching the yield point (yellow line), maximum load (blue line), and destruction of the specimen (violet line). The dotted line indicates the boundaries of the semicylindrical supports of the grips.

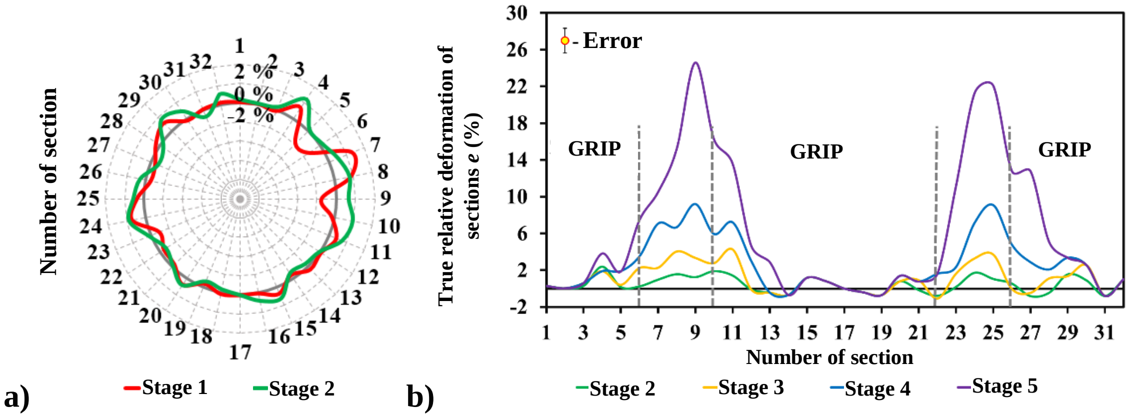


Fig. 7. Diagrams of distribution of the true relative
deformation of sections of circular specimen 1.
a) Initial stage of bending (stage 1) and ovalization stage (stage 2);
b) Ovalization on the supports (stage 2), reaching the yield point (stage 3), maximum load (stage 4), and destruction of the specimen (stage 5)

From Fig. 7a, it can be seen that at the initial stage of bending (red line) the sections with deformation of different types are formed. For instance, sections 5, 6 and 9 were compressed (strain value below 0%), and sections 4, 7, 8, 11, 24 and 29 were expanded (strain value above 0%). On reaching the stage of specimen ovalization on the supports (green line), a redistribution of deformation occurs in some sections. This effect is strongly marked in sections 5, 6, and 9.

From Fig. 7b, it can be seen that the basic plastic deformation is accumulated in the working sections between the grips (sections 6-10 and 22-26), while on the grip supports and at the apexes of the circular specimen the deformation is stabilized in the condition developed in process of the specimen ovalization. The sections of the upper grip (sections 1 to 3, 31, 32) and the lower grip (sections 14 to 19) can be considered as the sections in which the deformation braking is observed. It also should be noted that within sections 4-6, 11-13, 20-22 and 27-30, plastic deformation takes place, related to the sliding of the specimen internal surface over the surface of the grip supports.

For analyzing the reproducibility of results of the formation of localized deformation, the diagrams of distribution of the true relative deformation of sections of the other circular specimens at stages 1 and 2 are presented in Fig. 8.

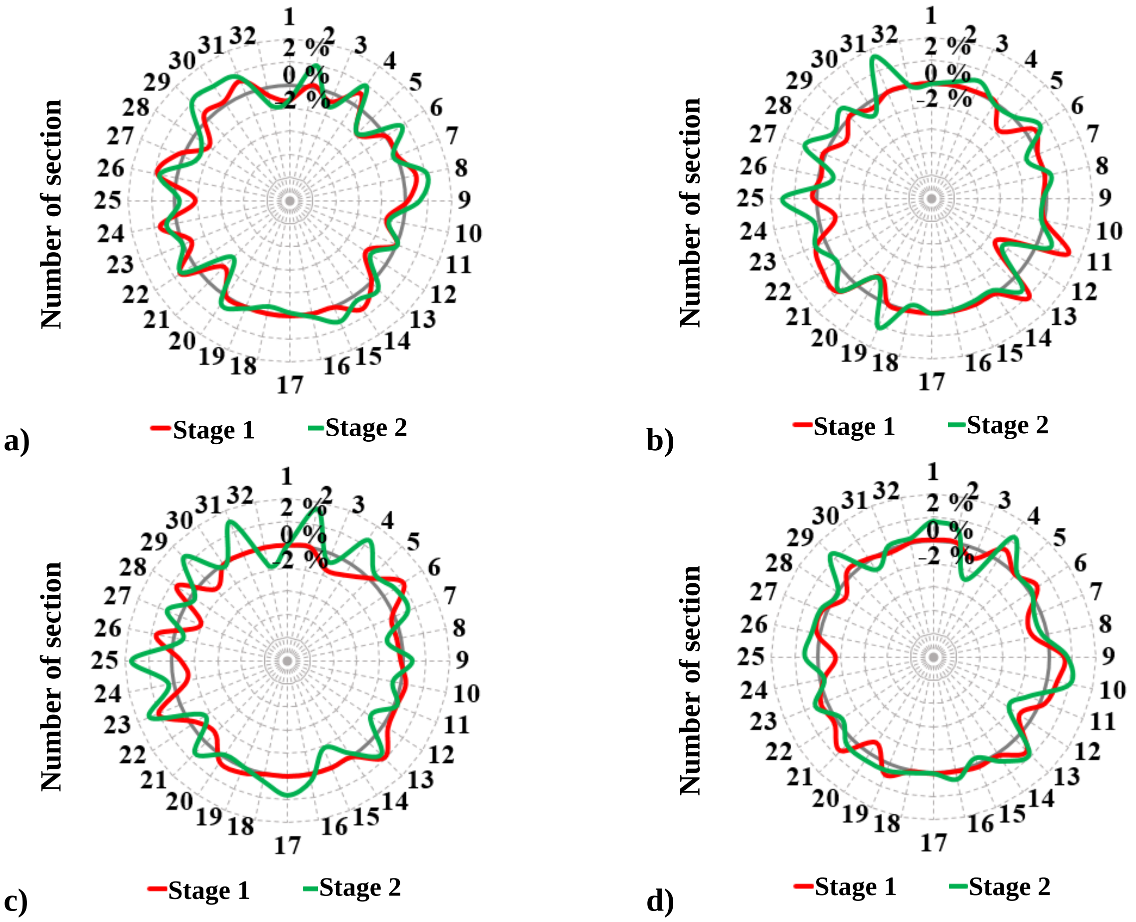


Fig. 8. Diagrams of distribution of the true relative deformation of sections.
a) Specimen 2; b) Specimen 3; c) Specimen 4; d) Specimen 5

During the analysis of the experimental data of testing the five specimens, low reproducibility of values of deformation of sections was revealed. From Fig. 8, it can be seen that the sections of plastic deformation of the specimens were formed in different ways, namely the numerical values of deformation in the same section on different specimens were different, except for the sections at the apexes of the grips (sections 1 and 17) in certain instances. The complex and uncontrolled process of deformation of sections at the stage of ovalization affects the formation of actual lengths of the right and left working parts of a circular specimen. For instance, the difference between the values of the right and left working parts of specimens 1–3 amounted to ~0.61 mm, and of specimens 4 and 5 – to 0.08 and 0.06 mm, respectively (Table 1).

Table 1. Values of the actual length of the working part of the right and left halves of the circular specimens under examination

Specimen	Actual length of working part l_{act}, mm		Absolute difference Δl_{act}, mm
	Left half	Right half	
1	6.37	5.75	0.62
2	5.70	5.09	0.61
3	5.79	6.40	0.61
4	5.79	5.71	0.08
5	5.12	5.06	0.06
Average	5.75	5.60	0.05

The pattern of distribution of the true relative deformation of the specimens under examination at the stage of destruction was found identical: the maximum values lie between the supports of the grips. The maximum value of deformation of sections of specimen 4 is observed in the right working part and amounts to ~30%. The maximum values of deformation of specimens 2 and 3 reached ~27%, and of specimens 1 and 5 – 24 and 22%, respectively. Figure 9 presents the diagrams of the distribution of deformation of sections of circular specimens at the stage of destruction (stage 5).

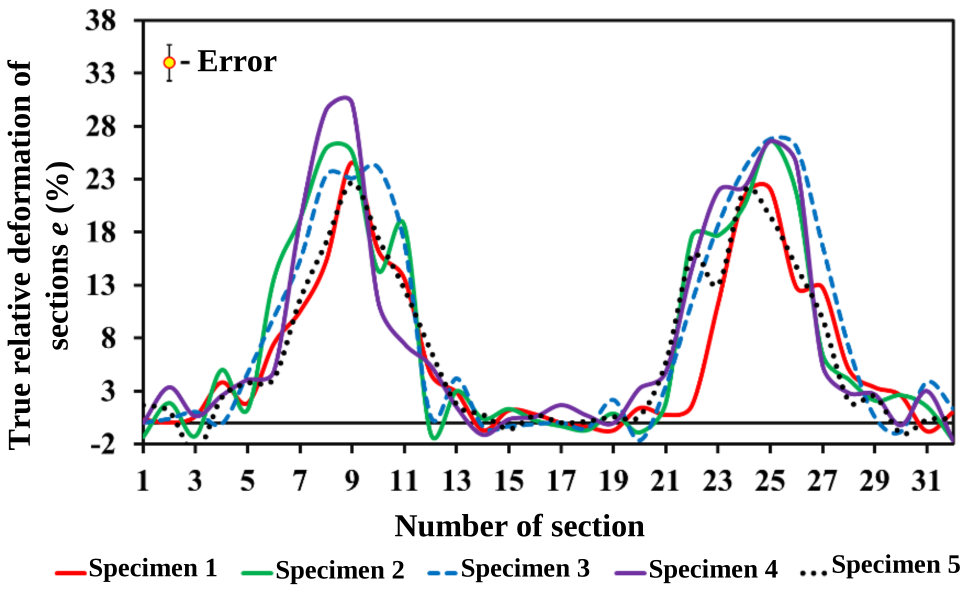


Fig. 9. Diagrams of distribution of the true relative deformation of sections of circular specimens at the stage of destruction

4. Discussion

Comparison of the values of the actual relative deformation of the working parts with the values of the relative elongation calculated using the diagram of expansion. Figure 10 presents the distribution of the values of the actual relative deformation of the working parts of the right and left halves of the circular specimens under examination at different stages of the deformation process as a function of the active grip displacement.

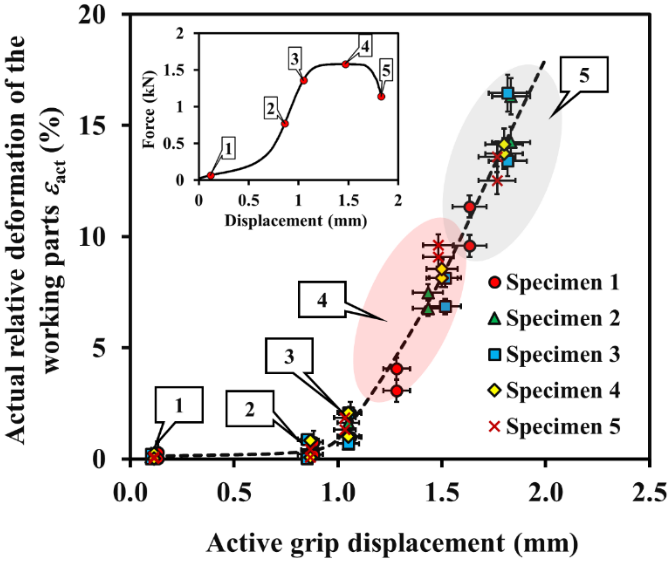


Fig. 10. Distribution of the values of the actual relative deformation of the working parts of the right and left halves of the circular specimens under examination at different stages of the deformation process as a function of the active grip displacement

From Fig. 10, it can be seen that in the process of testing the working parts of the circular specimens began yielding at the initial stage of expansion. The values of the actual relative deformation of the left and right working parts at stage 1 vary within the range of 0.1 to 0.3%. At the stage of ovalization (stage 2), the maximum values of the actual relative deformation amounted to ~0.9% (specimens 3 and 4 – left halves of the specimens) and ~0.8% (specimen 1 – right half of the specimen), while the other values fell within the range of 0.2 to 0.5%. At the stage of reaching the yield point (stage 3), the values of deformation of the working parts fell within the range of 0.7 to 2.1%. Tables 2 and 3 contain the values of the actual relative deformation of the working parts of the specimens under examination at stages 4 and 5 and the values of the uniform and the total elongation determined from the diagrams of expansion.

Table 2. The values of the actual relative deformation of the working parts at stage 4 and the values of the uniform elongation

Specimen	Actual relative deformation of the working parts at the stage of maximum loading (ε_{4act}), %		Uniform elongation (δ_u), %
	Left half	Right half	
1	3.1	4.1	3.1
2	6.8	7.5	5.7
3	8.1	6.9	6.1
4	8.5	8.1	5.8
5	9.6	9.1	5.6
Average	7.2	7.1	5.3

Table 3. The values of the actual relative deformation of the working parts at stage 5 and the values of the total tension set

Specimen	Actual relative deformation of the working parts at the stage of destruction (ε_{5act}), %		Total tension set (δ), %
	Left half	Right half	
1	9.6	11.4	10.3
2	14.2	16.3	14.0
3	16.5	13.4	13.9
4	14.2	13.7	13.4
5	13.6	12.5	13.4
Average	13.6	13.5	13.0

From the above Tables 2 and 3, it can be seen that the values of the actual relative deformation of the left and right working parts differ from each other. The maximum absolute difference between the values is observed with specimen 3 and amounts to ~1.3 and ~3.1% at stages 4 and 5, respectively. The minimum difference between the values of the left and right halves is observed with specimen 4 and is equal to 0.4% at both stages of expansion under consideration.

The comparison of the values of the actual relative deformation of the working parts with the values of the uniform and the total elongation shows that the values of plasticity calculated by the diagram are lower than the actual relative values (Fig. 11).

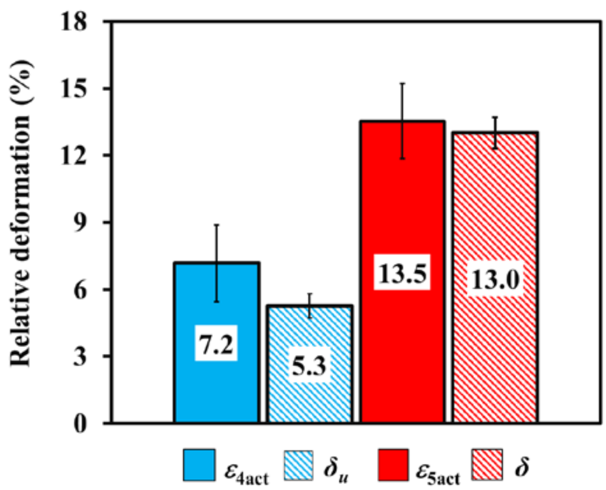


Fig. 11. Comparison of the average values of the actual relative deformation (ε_{act}) with the values of the uniform (δ_u) and the total elongation (δ)

A considerable absolute difference is observed when comparing the average values of the actual relative deformation at the stage of reaching the maximum load (stage 4) with the values of the uniform elongation. This amounts to ~1.9%, which can be explained by several reasons.

The first and the most objective reason is related to the accumulation of plastic deformation at the stage of bending of the working parts, which does not fall within the field of observation when processing the diagrams with a conventional method (Fig. 2a). The average value of deformation at the stage of ovalization (stage 2) is equal to ~0.5%.

The second procedure error is to be sought in the determination of the initial reference length of the working part of the circular specimen, calculated by formula (10).

$$l_0 = \frac{\pi}{2}\left(D_{\mathrm{av}} - k\left(d_{\mathrm{g}} + a\right)\right), \quad (10)$$

where D_{av} is the average diameter of the specimen, mm; d_{g} is the diameter of the grips, mm; a is the thickness of the specimen wall, mm; k is the coefficient of deformation.

With $k = 0.5$, as specified for steels, l_0 takes on the value of 6.1 mm, which is above the average value of the actual length of the working part (l_{act} = 5.7 ± 0.2 mm), determined by the scheme presented in Fig. 5. It means that the coefficient of deformation k must take on another value. A number of questions concerning the correct determination of the initial reference length of the working part of the circular specimen are argued in papers [16–19].

The most considerable contribution to the difference between the average values $\varepsilon_{4\mathrm{act}}$ and δ_u is made by plastic deformation occurring between the stages of deforming 2 and 3 (Fig. 4b). The analysis of the diagrams of distribution of the true relative deformation along the perimeter of circular specimens (Fig. 7b) has revealed that the braking of the deformation sections on the supports occurs at the stage of ovalization (stage 2), while the accumulation and the localization of plastic deformation in the formed working parts of the specimen occur during the subsequent expansion up to the stage of reaching the yield point (stage 3). This deformation does not fall within the field of observation when processing the diagrams with a conventional method, as well as the deformation accumulated at the stage of bending the working parts. The average value of the difference of the actual relative deformation of the working part between stages 2 and 3 amounts to ~1.1%.

Considering all the error values, the difference between the average values $\varepsilon_{4\mathrm{act}}$ and δ_u will be reduced from ~1.9% to ~0.2%.

When comparing the average values of the actual relative deformation at the stage of destruction (stage 5) with the values of the total tension set, it was found that the absolute difference amounted to 0.5%. It is evident that such a difference is attributed to the accumulated plastic deformation at the stage of bending the working parts.

Assessment of the impact of strain hardening on the mechanical properties. The results presented above show that during the process of bending of a circular specimen on the supports, the accumulation and the localization of plastic deformation proceed in the working parts at the initial stage of testing. This leads to a strain hardening of the material, which affects the values of the mechanical properties, and specifically, this leads to an increase in the yield strength of the material [20].

The average values of the yield offset and the ultimate tensile strength determined from the diagrams of expansion of circular specimens amounted to $\sigma_{0.2}$ = 702 ± 4 MPa and σ_u = 799 ± 5 MPa.

With an account for the progressing process of material hardening, it is necessary to determine the actual value of the stress intensity with a standard tolerance of 0.2% for the residual deformation when measuring the yield offset and to compare it with the value $\sigma_{0.2}$, available from experiments. The given problem can be solved by calculation. Thus, to assess the impact of strain hardening on the mechanical properties with empirical Equation (11), a power-law hardening diagram was constructed in the coordinates of stress intensity (σ_i) – strain intensity (ε_i) [20].

$$\sigma_i = \sigma_y + A\varepsilon_i^m, \quad (11)$$

where σ_y is the yield stress, MPa; A and m are the coefficients of approximation.

To solve Equation (9), the numerical values of tensile strength and uniform elongation were used, as these are characteristics defining the material hardenability [21]. Instead of the uniform elongation, however, the values of the actual relative deformation of the working parts at the maximum load stage (stage 4) were used, as these values characterize the true strain of the circular specimen. From Fig. 10, it can be seen that the values of the actual relative deformation of the left and right working parts of circular specimen 1 at stage 4 differ considerably from the common. Therefore, using the criterion for revealing and excluding a crude error from the small series of measurements, introduced in paper [22], the above values obtained for specimen 1 were considered as crude errors and disregarded when averaging the relative deformation of the working part at stage 4 (δ_{4av}).

When using the values $\sigma = \sigma_u = 799$ MPa and $\varepsilon = \varepsilon_{4act} = 0.0808$, the following solutions of Equation (9) were obtained: $\sigma_y = 582$ MPa, $A = 522$, and $m = 0.3493$.

As far as the uniform elongation δ_u of the circular specimens under examination does not exceed 10%, then the values of the relative deformation of the working part were used instead of the logarithmic strain, commonly taken as an X-axis when constructing the diagrams of strain hardening of the material [20]. Figure 11 presents the schematic diagram with a power-law hardening of the material of circular specimens, constructed with the computed solution of Equation (9).

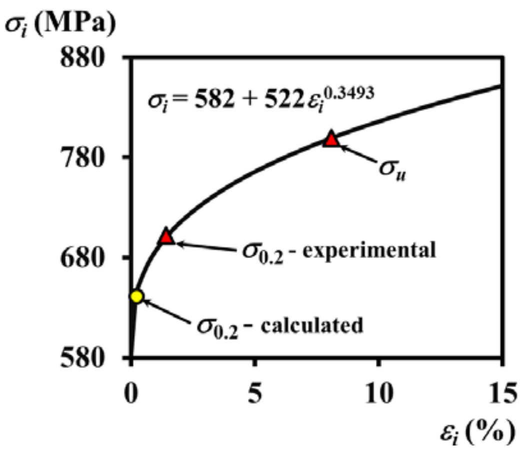


Fig. 11. Schematic diagram with a power-law hardening of the material of circular specimens: ○ – calculated stress value σ_i with a tolerance for deformation equal to $\varepsilon_i = 0.2\%$; ▲ – experimental values of the yield strength and the tensile strength

From Fig. 11, it can be seen that the calculated stress value ($\sigma_{0.2} = 642$ MPa) with a tolerance for deformation equal to $\varepsilon_i = 0.2\%$ is considerably lower than the value $\sigma_{0.2}$ available from experiments with the expansion of circular specimens; the percentage difference between them makes ~9%, which is equal to 60 MPa in absolute terms. The tolerance for the residual deformation for the experimental value $\sigma_{0.2}$ amounted to ~1.4%.

From all that has been said, it follows that the diagrams of expansion give overestimated values of the yield offset because when processing the diagrams using a conventional method, these values get into the field of consideration with tolerance being in large excess over the standard tolerance of 0.2%. In fact, the value of the material yield strength is reached at the initial stage of testing of the circular specimens (stage 1), since it has been established that at stage 1 the residual deformation amounts to ~0.2% (Fig. 10).

4. Conclusion

The study of the distribution of the localized plastic deformation in the working parts of a circular specimen during its expansion on the semicylindrical supports has been completed. It has been established that at the initial stage of testing the deformation in particular areas proceeds in a complex manner and has an uncontrolled and inhomogeneous nature. Low reproducibility of values of the localized deformation of sections in the working parts of a circular specimen has been also revealed.

The values of the true relative deformation of the working part of a circular specimen have been obtained. The comparison of these values with the values of the uniform and the total elongation, calculated by the diagrams of expansion using a conventional method, has shown that the true values are higher than the calculated ones. This is because a portion of important information about the plastic deformation, occurring at the stage of bending of the specimen working parts, does not fall within the field of observation when processing the diagrams. The underestimating of the results of determination of the relative elongation from the diagram of expansion is caused, besides the accumulated residual deformation at the stage of bending, by the error related to the calculation of the initial reference length of the circular specimen.

The conducted assessment of the impact of strain hardening of the material on the mechanical properties of the material of the specimens under examination has shown that the diagrams of expansion gave overestimated values of the yield offset $\sigma_{0.2}$. The calculated stress value with a standard tolerance for deformation equal to 0.2% is lower by 60 MPa than the experimental value $\sigma_{0,2}$, and is reached at the initial stage of testing of circular specimens.

In general, the determination of plastic properties of the fuel elements cladding of the fast-neutron reactor is satisfactory for the material in the initial condition. The difference between the actual and the estimated values of the relative deformation of the working part does not exceed the statistical error. The situation becomes critical when testing the circular specimens with low plasticity, specifically after the irradiation, as it’s established that the true residual deformation, accumulated when bending on the grip supports, is less than 1.4% and does not fall within the field of observation when processing the diagrams with a conventional method.

The development of methods of removing shortcomings and the improvement of the methods of measuring stress-strain properties of the material of cladding tubes during the expansion of circular specimens remains a vital task.

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References

[1] Ershova OV, Shcherbakov EN, Yagovitin PI, Evseev MV, Shikhalyov VS, Kozlov AV. Relation between the physicomechanical properties of an austenitic ChS-68 steel and its swelling during high-dose irradiation. *Phys. Met. Metall*. 2008;106: 624-629. (In Russian)

[2] Porollo SI, Ivanov AA, Konobeev YV, Shulepin SV. High-Temperature Radiation Embrittlement of Neutron-Irradiated Austenitic Stainless Steels 08Kh18N10T, Ei-847, EP-172, and ChS-68. *Atom. En.* 2020;128-2: 75-81. (In Russian)

[3] Mosin AM, Evseev MV, Portnykh IA, Shcherbakov EN, Shikhalyov VS, Mitrofanova NM, Kozlov AV. Change of physical and mechanical property of pin cladding of EK164 and CHS68 steels afterexploitation at reactor BN-600 during four microcampaigns. *Izvestiya vuzov, Yadernaya Energetika.* 2011;1: 224-229. (In Russian)

[4] Barsanova SV, Kozlov AV, Shilo OB. The effect of fast neutron irradiation on changes in mechanical properties of EK-164 and CHS-68 austenitic steels. *Voprosy atomnoi nauki i tekhniki, Materialovedenie i novye materialy.* 2018;5(96): 4-12. (In Russian)

[5] State Standard 1497–84. *Metals. Methods of tensions test*. Moscow; 2006. (In Russian)

[6] Arsene S, Bai J. A new approach to measuring transverse properties of structural tubing by a ring test. *Journal of Testing and Evaluation*. 1996;24(6): 386-391.

[7] Grigoriev V, Jakobsson R, Josefsson B, Schrire D. Advanced techniques for mechanical testing of irradiated cladding materials. *Advanced post-irradiation examination techniques for water reactor fuel: IAEA.* 2002: 187-193.

[8] Macdonald V, Le Boulch D, Menibus AH, Besson J, Auzoux Q, Crépin J, Le Jolu T. Fracture of Zircaloy-4 fuel cladding tubes with hydride blisters. *Procedia Materials Science*. 2014;3: 233-238.

[9] Cohen AB, Majumdar S, Ruther WE, Billone MC, Chung HM, Neimark LA. Modified ring stretch tensile testing of Zr-lNb cladding. *Argonne National Laboratory*; 1997.

[10] Daum RS, Majumdar S, Tsai H, Bray TS, Koss DA, Motta AT, Billone MC. Mechanical Property Testing of Irradiated Zircaloy Cladding Under Reactor Transient Conditions, Small Specimen Test Techniques. In: *ASTM STP 1418*, *American Society for Testing and Materials*. 2002.

[11] Desquines J, Koss DA, Motta AT, Cazalis B, Petit M. The issue of stress state during mechanical tests to assess cladding performance during a reactivity-initiated accident (RIA). *Journal of Nuclear Materials*. 2011;412(2): 250-267.

[12] Fedotov PV, Loshmanov LP, Kostyukhina AV. Vliyanie kratkovremennoi termoobrabotki na mekhanicheskie svoistva splava E110. *Fizika i khimia obrabotki materialov*. 2014;5: 67-73. (In Russian)

[13] Izmalkov IN, Loshmanov LP, Kostyukhina AV. Mekhanicheskie svoistva splava E110 pri temperaturakh do 1273 K. *Izvestiya vuzov, Yadernaya Energetika.* 2013;2: 64-70. (In Russian)

[14] Sheldyakov AA, Yakovlev VV, Obukhov AV. Mekhanicheskie svoistva i struktura obluchennogo splava 42HNM. *Sbornik trudov GNTS NIIAR*. 2011;2: 3-7. (In Russian)

[15] Loshmanov LP, Kostyukhina AV, Fedotov V P, Murkhazanov GKh, Baskanov AV. Opredelenie predela tekuchesti stali EK-181 pri ispytanii na rastyazhenie koltsevykh obraztsov. *Zavodskya laboratoriya, Diagnostika materialov*. 2016;82(10): 56-61. (In Russian)

[16] Leontieva-Smirnova MV, Kalinin BA, Morozov EM, Kostyukhina AV, Fedotov PV, Taktashev RN. Metodicheskie osobennosti ispytanii na rastyazhenie koltsevykh obraztsov. *Fizika i khimia obrabotki materialov*. 2019;6: 62-71. (In Russian)

[17] Gurovich BA, Frolov AS, Maltsev DA, Kuleshova EA, Fedotova SV, Fedotov IV. Fazovye prevrasheniya v obluchennom splave 42HNM posle otzhigov pri povyshennykh temperaturakh, a takzhe posle bystrogo otzhiga, imititiruyushchego uslovia maksimalnoi proektnoi avarii. In: *Doklad. XI Konferentsiya po reaktornomu materialovedeniyu*. Dimitrovgrad; 2019. (In Russian)

[18] Prokhorov VI, Finko AG, Mineev RI. Eksperimentalnoe opredelenie rabochei dliny koltsevykh obraztsov iz obolochek tvelov pri poperechnom sechenii. *Dimitrovgrad*; 1977. (In Russian)

[19] Neklyudov IM, Ozhigov LS, Savchenko VI, Stukalov AI, Gritsina VM, Vakhrusheva VS, Kovalev VV, Bukhanovskij VV. Determination peculiarities of plasticity characteristics of ring-type zirconium alloy specimens in the lateral direction. *Strength of Materials*. 2001;2: 137-141. (In Russian)

[20] Malinin NN. *Prikladnaya teoriya plastichnos'ti i polzuchesti.* Moscow: Mashinostroenie; 1975. (In Russian)

[21] Tomlyonov AD. *Teoriya plasticheskogo deformirovaniya metallov*. Moscow: Metallurgy; 1972. (In Russian)

[22] Kassandrova ON, Lebedev VV. *Obrabotka rezultatov nablyudenii.* Moscow; 1970. (In Russian)