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INFLUENCING THE THIN COATING ON THE STRESS-STRAIN STATE OF THE CLADDING OF FUEL RODS OF THE VVER-1000 NUCLEAR REACTOR

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Introduction. Operability of the cladding of fuel rods significantly limits the economic effects and safety of nuclear reactors, and using the thin protective coatings is one of the ways to improve operability of the cladding [1, 2]. All researches about the thin protective coatings for cladding of fuel rods are of current interest at present including this research, which it deals with impacting the thin protective coatings on the stress-strain state of the cladding of fuel rods. Industry implementation of protective thin coatings requires substantiation for behaviour of the cladding considering with impacting that coatings. The purpose of this research is to propose the approach and to obtain some quantitative regularity about impacting the thin coating on the stress-strain state of the cladding of fuel rods used in the VVER-1000 nuclear reactors.

Interaction between the cladding and its coating. The cladding of fuel rods can be imagined as the cylinder with the central axial hole such that the average radius is about ten times more than the thickness of the wall and the axial length is about four thousand times more than the external radius. The stress-strain state of such thick-walled long cylinder can be considered using hypotheses about the plane strain [3]. We will consider the cladding with the thin coating on an external side surface only. This thin coating has the thickness about hundreds micrometres and due to it must been considered as the thin-walled shell (fig. 1-a). Due to the axial symmetry of the loading we will consider the thin coating without bending but with tensile in the own central surface with the N_θ internal forces (fig. 1-a). The equilibrium condition of the piece of the thin coating limited by the $d\theta$ angle considering with the radial stresses σ_r from the cladding, the forces N_θ and the external pressure p_b of the heat carrier (fig. 1-a) can be represented as:

$$-\sigma_r\left(R_c-\frac{h_c}{2}\right)d\theta-p_b\left(R_c+\frac{h_c}{2}\right)d\theta-2N_\theta\sin\frac{d\theta}{2}=0\,, \tag{1}$$

where h_c and R_c is the thickness and the radius of the central surface of the coating (fig. 1-a).

The thickness h_c can be neglected comparing with the radius R_c of the central surface of the coating. Besides, it is necessary to take into account the well-known relation $\sin(d\theta/2)\approx d\theta/2$ for the small $d\theta$ angle. All these circumstances transform the condition (1) to form:

$$\sigma_r=-p_b-N_\theta/R_c\,, \tag{2}$$

The circumferential force N_θ of the bending-free thin cylindrical shell can be related as [4]:

$$N_\theta=E_c h_c w/R_c\,, \tag{3}$$

where E_c is the Young's module of the coating and w is the deflection of the thin cylindrical shell, representing the thin coating.

Relations (2), (3) will be used to consider impacting the thin coating of the stress-strain state of the cladding.

Stress strain state of the cladding with the thin coating. Mathematical model of the stress-strain sate of the cladding can be represented by the well-known in the theory of elasticity [3] differential equation for the radial displacement; the boundary condition on the internal surface of the cladding are well-known too [3]. The boundary condition on the external surface of the cladding with the thin coating can be formulated using the relations (2) and (3). Thus, it is possible to propose the mathematical model of the cladding with the external thin protective coating as:

$$\frac{d^2u}{dr^2}+\frac{1}{r}\frac{du}{dr}-\frac{u}{r^2}=0,\quad a<r<b, \tag{4}$$

$$\frac{E}{1-\nu^2}\left(\frac{du}{dr}+\nu\frac{u}{r}\right)=-p_a,\ r=a,\quad \frac{E}{1-\nu^2}\left(\frac{du}{dr}+\nu\frac{u}{r}\right)+\frac{E_c h_c}{R_c^2}u=-p_b,\ r=b, \tag{5}$$

where u is the radial displacement of the cladding; r is the radial coordinate; a and b are the internal and external radii of the cladding; p_a is the internal pressure of the fission products; E and ν are the equivalent Young's modulus and the Poisson's ratio of the material of the cladding, which must be represented corresponding the hypotheses of the plane strain [3]:

$$E=E'/\left(1-\nu'^2\right),\ \nu'=\nu'/\left(1-\nu'\right), \tag{6}$$

where E' and ν' are the Young's modulus and the Poisson's ratio of the material of the cladding.

It is necessary to note that in the case of zero thickness (i.e. $h_c=0$) the relations (4), (5) are transformed to the case corresponded the cladding without the coating and this limiting transition substantiates correctness of the mathematical model (4), (5).

Equation (4) can be solved analytically, and the stress-strain state can be written as:

$$u(r)=C_1r+\frac{C_2}{r},\quad \sigma_r(r)=\frac{E}{1-\nu^2}\left((1+\nu)C_1+\frac{\nu-1}{r^2}C_2\right),\quad \sigma_\theta(r)=\frac{E}{1-\nu^2}\left((1+\nu)C_1+\frac{1-\nu}{r^2}C_2\right), \tag{7}$$

where σ_θ is the circumferential stress in the cladding (fig. 1-a); C_1 and C_2 are the integration constants, which are must be find from the boundary conditions (5).

The boundary conditions (5) considering the solution (7) lead to the linear equations:

$$(1+\nu)C_1+\frac{\nu-1}{a^2}C_2=-p_a\frac{1-\nu^2}{E}, \tag{8}$$

$$\left(1+\nu+\frac{1-\nu^2}{E}\frac{E_ch_cb}{R_c^2}\right)C_1+\left(\frac{\nu-1}{b^2}+\frac{1-\nu^2}{E}\frac{E_ch_c}{R_c^2b}\right)C_2=-p_b\frac{1-\nu^2}{E}. \tag{9}$$

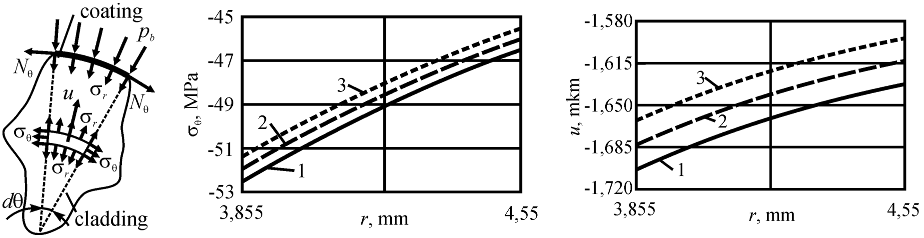
It is possible to solve analytically the linear algebraic equations (8), (9), but the resulting expressions will be cumbersome and are will not represented here.

Stress-strain state of the cladding of fuel rods used in the VVER-1000 reactor. The cladding of fuel rods of the VVER-1000 nuclear reactor is made from the Zr-1%Nb alloy and is had the well-known parameters; next we will consider the cladding with thin coatings made from the stainless 18-8 type steel [2] with the different thicknesses:

$$a=3{,}885\,\text{mm},\quad b=4{,}55\,\text{mm},\quad p_a=10\,\text{MPa},\quad p_b=16\,\text{MPa}, \tag{10}$$

$$E'=96\,\text{GPa},\quad \nu'=0{,}33,\quad E_c=210\,\text{GPa}, \tag{11}$$

Some of results for the stress-train state of the cladding of fuel rods used in the VVER-1000 nuclear reactor are shown on the fig. 1-b and fig. 1-c for the different thicknesses of the coatings.



a) b) c)

Fig. 1 Schematizing of the cladding with the coating (a) as well as circumferential stresses (b) and radial displacements (c) in the cladding made from Zr-based alloy with coatings made from the stainless 18-10 type steel with thickness $h_c = 0$ (1), $h_c = 5\text{mkm}$ (2) $h_c = 10\text{mkm}$ (3)

Obtained results (fig. 1-b and fig. 1-c) confirm the suggestion that the thin coatings must improve the operability of the cladding and show that this improvement are due to decreasing the stresses and displacements form the operating loadings. This is in agreement with the results discussed in [2].

Conclusions. It is proposed the mathematical model of the stress-strain state of the cladding of fuel rods of nuclear reactors in which the thin coating is considered. This model is represented by the differential equation and the boundary condition well-known in the theory of elasticity as well as by the modified boundary condition taking into account the thin coating. This mathematical model has the limiting transition to the well-known theory of elasticity problem when the thickness of the coating is tended to zero, which it substantiates this model. Obtained results showed that the thin protective coating leads to decreasing the stresses and displacements in the cladding of fuel rods and due to it must improve operability of the cladding. It is recommended for the further researches to consider behaviour of the cladding with the thin coating taking into account the temperature strains and the creep strains, which can lead to layering the coating from the cladding during the time.

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