ASSESSMENT OF BRITTLE FRACTURE STRENGTH OF WELDED CONTROL RODS IN THE WWER-1000 NUCLEAR REACTORS

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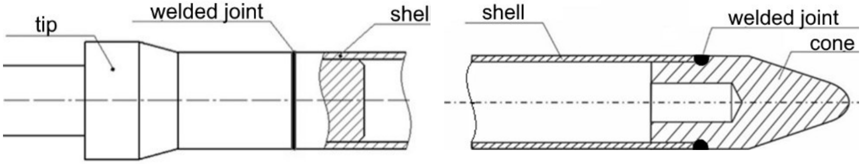
The strength of welded control rod joints in the WWER-1000 Control Rod System was assessed using finite element modeling and the postulated defect method. Residual and operational stresses, irradiation effects, and subsurface crack behavior were considered. Results show that even under conservative assumptions, the minimum safety factor exceeds 2.14, ensuring structural integrity over 10 years of extended service.

Keywords: Control Rod system, WWER-1000, nuclear reactor, control rod, weld, 42KhNM, finite element modeling, brittle fracture, safety factor, postulated defect

The Control Rod System is intended for control of power release distribution in the core, changing reactor power, providing preventive and emergency reactor protection. In the WWER-1000 there are 61 control rods (CR). Each control rod consists of 18 absorber elements, which move inside fuel assemblies in special channels and which have individual drives.

To investigate the interaction between residual and operational stresses in the CR shell made of nickel-based alloy 42KhNM and their impact on reliability, finite element modeling (FEM) of the circumferential weld process and operational loading was carried out. This was followed by an analysis of brittle strength based on the postulated defect method [3].



a b

Fig. 1. Welded joints of the tip (a) and the cone (b) with the CR shell.

In determining the welding residual stresses, the problem of numerically predicting the temperature field kinetics and the development of elasto-plastic strains was considered using the FEM within the framework of a boundary value problem of non-stationary thermoplasticity. The non-stationary heat conduction equation [1]:

$$c\rho\left(r,\beta,z,T\right)\cdot\frac{\partial T\left(r,\beta,z\right)}{\partial\tau}=\nabla\left[\lambda\left(r,\beta,z,T\right)\cdot\nabla T\left(r,\beta,z\right)\right], \quad (1)$$

where λ and cρ are the thermal conductivity and the volumetric heat capacity of the material, respectively.

The heat source is a normally distributed surface heat flux from the welding arc in the area of the assembly joint. The boundary conditions are related to convective heat transfer and infrared radiation:

$$-\lambda\left(T\right)\cdot\frac{\partial T}{\partial n}=-q_{I}+\alpha_{T}\cdot\left(T-T_{C}\right)+\varepsilon\cdot\sigma_{SB}\cdot\left(T^{4}-T_{C}^{4}\right). \quad (2)$$

The increment of the strain tensor is the sum of the increments of the elastic strain tensor, instantaneous plastic strain and thermal strain, respectively:

$$d\varepsilon_{ij}=d\varepsilon_{ij}^{e}+d\varepsilon_{ij}^{p}+\delta_{ij}\cdot d\varepsilon_{T}. \quad (3)$$

The tensors of mechanical stresses σ_{ij} and elastic strains $d\varepsilon^{e}_{ij}$ are related by the generalized Hooke's law [2]:

$$\varepsilon_{ij}^{e}=\frac{\sigma_{ij}-\delta_{ij}\cdot\sigma}{2\cdot G}+\delta_{ij}\cdot(K\cdot\sigma+\varphi),$$

where σ is the mean value of the normal components of the stress tensor σij.

The modeling of the thermal and stress-strain state was carried out in a two-dimensional axisymmetric formulation. The physical nonlinearity associated with the formation of plastic deformations was determined using the von Mises yield criterion. The thermophysical and mechanical properties of the chromium-nickel alloy 42KhNM were considered as temperature-dependent.

The development of the thermomechanical state during the welding of the cone to the shell leads to the formation of a stress-strain field dominated by circular and axial residual stresses (Fig.2 c, d). After reactor shutdown and cooldown (TTO mode), the external pressure of the coolant decreases while the internal pressure of the rod filler is maintained, resulting in a rise of maximum stresses above 500-600 MPa (Fig. 2, d). This situation creates the most unfavorable conditions for the strength of the CR welds, increasing the risk of defect development during operation.

To quantitatively assess the strength of the welded joints "cone-shell" and "tip-shell," a calculation of the brittle strength safety factor distribution *n* in the weld area was carried out using the postulated crack method [3]. For this purpose, an isolated subsurface crack was introduced at various locations of the cross-section of the structure. Then, an algorithm was used to calculate the stress intensity factors and reference stresses to evaluate the acceptability of the postulated defect within the framework of fracture mechanics and the two-parameter criterion of brittle-to-ductile fracture.

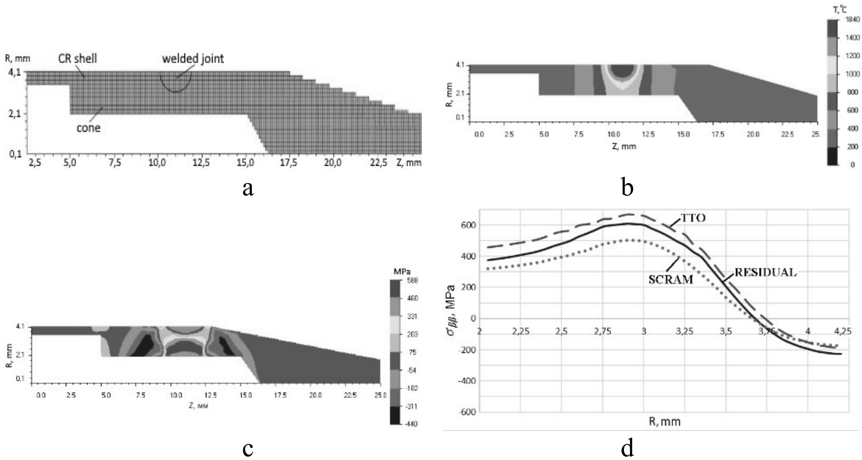


Fig. 2 FE model of the "cone-shell" welded joint (a), distributions of maximum temperatures (b), residual circular stresses (c), total residual and operational circumferential stresses through the thickness of the welded joint (d)

The wall thickness of the CR shell is 0.5 mm, this value was adopted as the minimum linear size of the elliptical subsurface crack 2a. The other dimension (2c) was considered in two variants: with aspect ratios 2a/2c=0.7 (i.e., 2a×2c=0.5×0.71 mm) and 2a/2c=0.3 (i.e., 2a×2c=0.5×1.6 mm7) (Fig. 3). The orientation of the subsurface cracks was defined in both circumferential and axial directions, with the lowest safety factor selected for each spatial location.

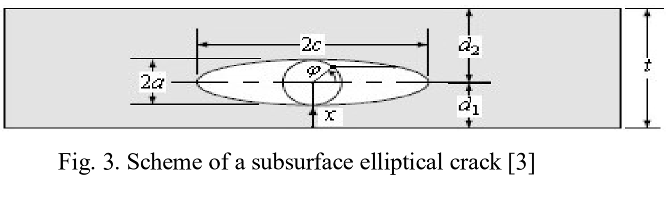


Fig. 3. Scheme of a subsurface elliptical crack [3]

The reduction of K_{Ic} of the chromium-nickel alloy as a result of irradiation (12 dpa) can reach up to 3.66 times. That is, while the initial fracture toughness of the 42KhNM alloy was taken as K_{Ic} = 189 MPa·m$^{1/2}$ [4], after irradiation this value may decrease to K_{Ic} = 51.6 MPa·m$^{1/2}$.

The results of the brittle fracture strength assessment of the welded joints "cone-shell" and "tip-shell", taking into account the effect of irradiation on the material's resistance to brittle fracture, showed that under maximum emergency loading conditions (31g, SCRAM), the minimum safety factor for the "cone-shell" joint with an aspect ratio of 2a/2c = 0.3 is n_{min}=2.14, and for the "tip-shell" piece joint it is n_{min}=2.4. Under the TTO mode after reactor shutdown, the minimum safety factor for the "cone-shell" joint with 2a/2c=0.3 is n_{min}=2.2, and for the "tip-shell" joint it is n_{min}=2.8. Thus, despite the significant conservatism of the brittle fracture strength calculation, the minimum safety factor is guaranteed to be no less than n_{min}=2.14, which is sufficient for structures of this class.

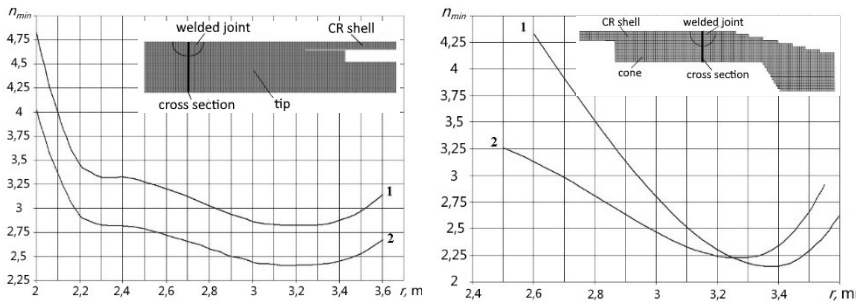


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Fig. 4. Distribution of the minimum brittle fracture safety factor n_{min} across the cross-section of the welded joint as a function of the radial coordinate *r* of the centre of the postulated defect; subsurface elliptical crack 2a=0.5 mm, a/c=0.3: a) "tip-shell" joint; b) "cone-shell" joint; 1 - SCRAM mode; 2 - TTO mode.

Conclusions. The lower and upper welded joints of the control rod are operable during an extended service life of up to 10 years, provided that the previous operating conditions are maintained, accounting for residual stresses and potential discontinuities, and confirming that the integrity of the CR is ensured under dynamic loads (e.g., drops) and under maximum degradation of the mechanical properties of the material due to radiation exposure.

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