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# ESTIMATION OF MECHANICAL PROPERTIES OF NEUTRON-IRRADIATED 08CH18N10T STEEL FROM HARDNESS TESTING

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Abstract. Through-thickness Vickers hardness of a neutron-irradiated small segment of the core barrel made from 08Ch18N10T austenitic stainless steel was characterized experimentally and results were compared to ones simulated numerically with assumption of Ludwik's form of hardening equation and neutron dose dependent material parameters according to work of Sorokin. Simulated values of hardness trace the lower bound of scattered experimental data. Based on the same material input data and on the correlation with measured hardness profile, increase of the material yield strength of the core barrel due to reactor operation was estimated.

Keywords: 08Ch18N10T austenitic stainless steel, neutron embrittlement, hardness, yield strength, FEM, WWER-440 reactor internals.

## 1. Introduction

Radiation embrittlement of key parts of pressurized water reactors is a limiting factor for safe operation of nuclear power plants. 08Ch18N10T (chemically similar to AISI 321) is a titanium stabilized austenitic stainless steel used as the main structural material for reactor internals (namely the core barrel, the core basket and the block of guide tubes) of the WWER-440 type nuclear reactor.

Results presented in this paper are a part of a larger project with aim to monitor the degree of degradation of irradiated core internals of the WWER-440 reactor and to find the proper temperature regime to recover their mechanical properties. The effectiveness of such regenerating annealing is monitored by hardness and fracture toughness measurements and by the tests to assess stress corrosion cracking susceptibility. The size of the experimental program is highly limited by the capacity of the specialized testing facility and by the amount of disposable material. Therefore, an attempt was made to numerically simulate some tests to get additional material characteristics, to cross-check measured values against the results of other tests and against the literature data.

The paper will summarize the results of Vickers hardness measurement of the core barrel irradiated during the reactor operation and, particularly, the effect of radial distance of the indent from the reactor active zone on local hardness. Simultaneously, a finite element model of the indentation process was used to discuss the change in tensile properties of irradiated 08Ch18N10T steel, mainly the change of the yield strength.

## 2. Mechanical properties of the neutron-irradiated core barrel

### 2.1. Material

A small ring segment for material properties testing was cut from the core barrel by plasma arc. The core barrel was a part of reactor core internals in the nuclear power plant Greifswald, unit 1 (NPP Greifswald 1), which was operated for 15 cycles, i.e. 4204 full power days. Approximate irradiation damage of examined segment is 2.4 dpa (displacements per atom). The core barrel was made from a titanium stabilized chromium-nickel austenitic stainless steel 08Ch18N10T with chemical composition (see Table 1) similar to AISI 321.

### 2.2. Sample preparation

Hardness measurement was performed on surfaces of miniaturized compact tension (mCT) specimens, which were used primarily for fracture toughness measurements. All mCT specimens were fabricated from the ring segment using electro-spark wire-electrode cutting, drilling and grinding in the controlled environment of hot chamber using remote-handling systems.

### 2.3. Hardness measurement

Hardness HV5 was measured at room temperature in semi-hot chamber by the ZHV30 hardness tester from Zwick/Roell Indentec company. The thickness of 4 mm of mCT specimens allows to monitor change of hardness in 5 positions through the wall of cylindrical core barrel. At least 8 indentations were performed for each position.

| **in wt %** | **C** | **Mn** | **S** | **P** | **Ni** | **Cr** | **Ti** |
|---|---|---|---|---|---|---|---|
| 08Ch18N10T | $\leq 0.08$ | 1.0–2.0 | $\leq 0.02$ | $\leq 0.035$ | 9.0–11.0 | 17.0–19.0 | $\geq 5C \leq 0.6$ |

Table 1. Chemical composition of 08Ch18N10T austenitic stainless steel (in wt %).

### 2.4. Numerical simulation of indentation

Simultaneously, the indentation process was simulated numerically by means of nonlinear finite element program Marc 2015 within the large strain framework. Change of hardness during the neutron irradiation was simulated by the change of input material work hardening curve.

#### 2.4.1. Model tensile properties

The effect of neutron irradiation on tensile properties of 08Ch18N10T steel was studied experimentally in [1, 2]. Although the mechanical properties for the same material from different producers and for different mechanical treatments can vary, due to lack of other more relevant data the work of [1] was taken as a basis for modelling of mechanical response of material used for fabrication of the core barrel in NPP Greifswald 1. In present study, tests at room temperature only and on specimens irradiated with doses of about 2.4 dpa were performed. Therefore, original more general dependencies with the description of stress-strain curves for different test temperatures, irradiation temperatures and doses, were simplified to test temperature 20 °C and doses between 0–7 dpa.

Standard tensile test diagrams for 0 and 7 dpa are plotted in Figure 1. Neutron irradiation led to increase of yield and tensile strengths and to decrease of ductility.

It is supposed, that elastic-plastic behavior of 08Ch18N10T steel follows the power equation in the form

$$\sigma_{eq} = \sigma_y(D) + A(D) \cdot (\varepsilon^p_{eq})^n, \qquad (1)$$

where $\sigma_{eq}$ and $\varepsilon^p_{eq}$ are equivalent values of the true stress and the accumulated true plastic strain, respectively, and dose $D$ dependent material properties yield strength $\sigma_y$ and coefficient $A$ are expressed as follows:

$$\sigma_y(D) = 280 + \Delta\sigma_y(D)\ \mathrm{MPa}, \qquad (2)$$

$$A(D) = 943 - 0.158 \cdot \Delta\sigma_y(D)\ \mathrm{MPa}, \qquad (3)$$

where

$$\Delta\sigma_y(D) = 612\sqrt{1 - \exp\left(-0.143 \cdot D\right)}\ \mathrm{MPa}, \qquad (4)$$

is the yield strength increase due to neutron irradiation. Strain hardening exponent $n$ is 0.55 for studied irradiation up to 7 dpa. Model power law hardening curves in true stress – true (logarithmic) plastic strain coordinates for 0 and 7 dpa are plotted in Figure 2 together with tensile curves from Figure 1 converted from engineering (eng) to true values using following relations:

$$\sigma_{true} = \sigma_{eng}(1 + \varepsilon_{eng}), \qquad (5)$$

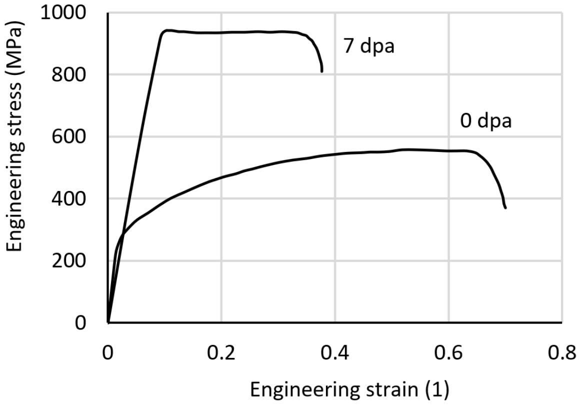

Figure 1. Tensile diagrams at 20 °C for 08Ch18N10T steel in original and neutron-irradiated state (7 dpa) [1].

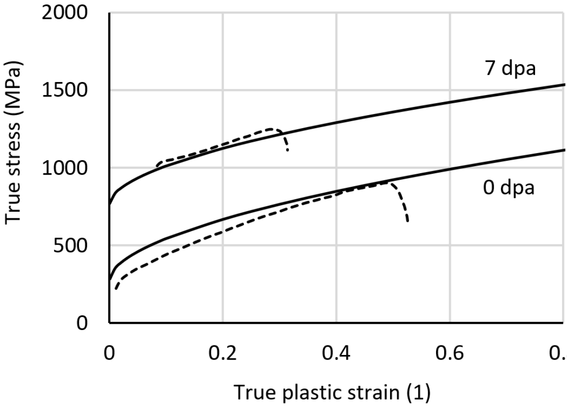

Figure 2. Comparison of model work-hardening curves (full lines) with tests (dotted lines) at 20 °C for 08Ch18N10T steel in original and neutron-irradiated state (7 dpa).

$$\varepsilon_{p,true} = \ln\left(1 + \varepsilon_{eng}\right) - \frac{\sigma_{true}}{E}. \qquad (6)$$

Elastic properties are characterized by the Young's modulus $E = 196\,000$ MPa and Poisson's ratio $\nu = 0.26$.

#### 2.4.2. FE mesh and boundary conditions

Due to symmetry of Vicker's indenter, only one fourth of the indenter and material were modelled. The rigid indenter was pushed against the deformable material by the maximum force of 12.2575 N, which corresponded to one fourth of 5 kgf during HV5 measurement. Coulomb type friction with friction coefficient 0.16 was supposed according to general recommendation in [3] for contact with diamond indenter. Fine mapped mesh under the indenter (see Figure 3 and Figure 4) consists of 8-noded hexahedral elements with size of 2 µm in material surface direction. Nodes

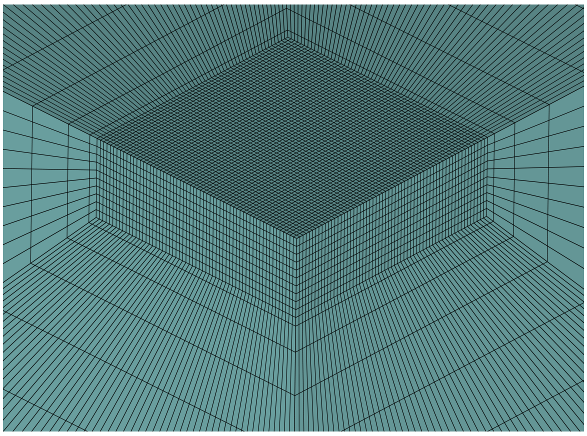

Figure 3. Finite element mesh under the indenter before the indentation.

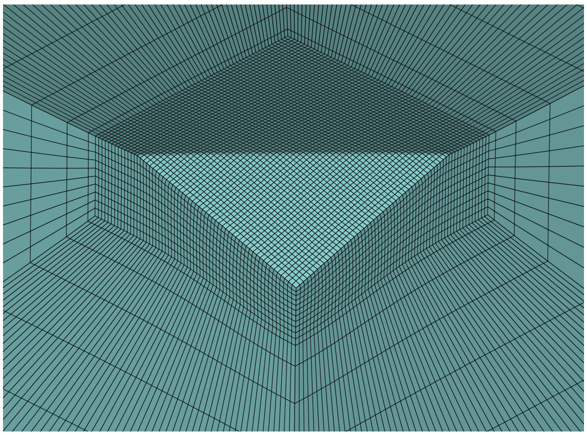

Figure 4. Finite element mesh under the indenter after the indentation.

in both symmetry planes were constrained in normal directions, nodes in bottom surface of the material specimen were fixed in all directions. The size of the specimen was more than 100× higher than expected impressions depths.

As in the real measurement, numerical hardness was calculated from the length of the diagonal $d$ left by the indenter after unloading according to formula

$$\mathrm{HV5} = \frac{1.8544 \cdot 5}{d^2} \quad \left[\frac{\mathrm{kgf}}{\mathrm{mm}^2}\right]. \tag{7}$$

The length of the diagonal was evaluated from the coordinate after unloading of the last node in contact with indenter.

# 3. Results and discussion

## 3.1. Computed hardness

Increase of Vickers hardness during the neutron irradiation up to 7 dpa in 0.2 dpa steps were simulated numerically and plotted in Figure 5. As can be seen, the numerical results form a stepwise curve rather than a smooth one due to the discrete nature of the contact used in the finite element method. The length of the diagonal of the impression can increase only by the length of one element which is 2 µm. This step in length leads to step of about 5 and 12 units of HV5 for 0 and 7 dpa respectively. Therefore, the numerically determined values of hardness were fitted by the formula similar to the one for yield strength in Eq. 2. Smooth dependence of the hardness on neutron dose has the final form

$$\mathrm{HV5}\,(D) = 160 + 174.3\sqrt{1 - \exp\left(-0.143 \cdot D\right)}. \tag{8}$$

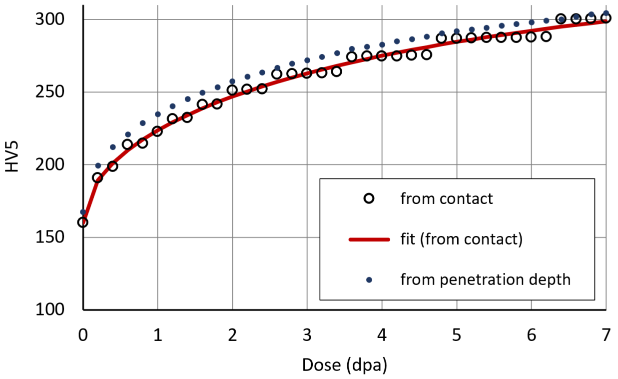

Figure 5. Computed dependence of Vickers hardness on the dose.

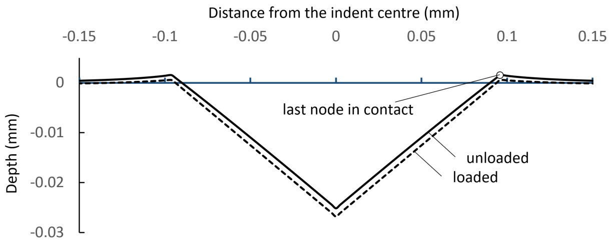

Figure 6. Computed indent profile along its diagonal at 2.4 dpa.

Alternatively, as a rough estimate for studied steel, the length of the diagonal can be determined also as the seven times the size of the maximum penetration depth, which comes from the shape of the Vickers indenter. This approach is valid for indentations, for which the elastic recovery is negligible and the surface around the indenter remains flat. As can be seen in Figure 6, both conditions are almost fully satisfied – the unloading led to only small displacement of the indenter tip and the material surface exhibits only mild pile-up. Slightly shorter diagonals determined from penetration depths led to slight overestimation of hardness but the dependence on dose is now smooth and justifies the used fit.

## 3.2. Measured hardness

Measured Vickers hardness in 5 various distances from the inner surface of the core barrel, together with error bars indicating one standard deviation, are plotted in Figure 7. Both the hardness and hardness scatter decrease with increasing distance from the inner wall as the neutron fluence decreases across the thickness.

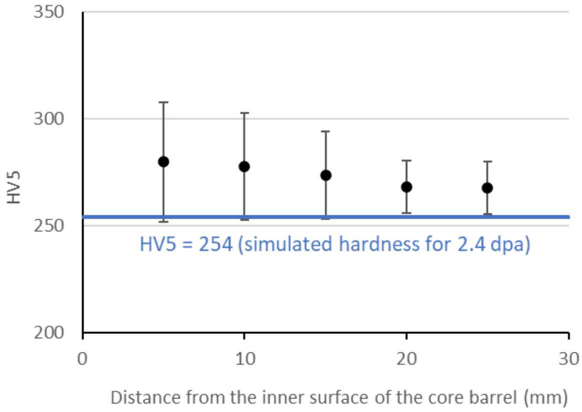

Figure 7. Measured Vickers hardness in the wall of the core barrel.

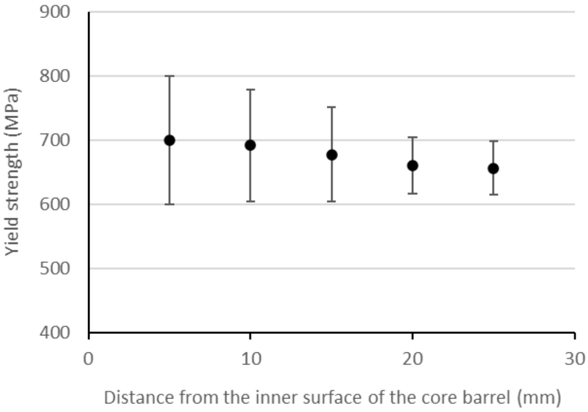

Figure 8. Estimated yield strength through the wall of the core barrel.

If we suppose the dose of the measured segment of the core barrel 2.4 dpa then from Eq. 8 follows HV5 $(D = 2.4\,\mathrm{dpa}) = 254$. This value is lower than average measured values across the thickness of the core barrel but is within the scatter of measured data at the lower boundary given by the standard deviation. Here are a few ideas why the simulation underestimated measured average hardness 277 by 9 %:

- 18Cr–10Ni–Ti steel used in the study [1] has slightly different mechanical properties than the steel of rings used for the fabrication of the core barrel in NPP Greifswald 1.
- Deformation response of material under the indenter did not follow the power law used in Eq. 1 in the whole range of plastic strains.
- In contrast to the stiff but deformable real indenter, the rigid indenter in the simulation leads to a slightly lower prediction of the impression area and thus to a slight overestimation of the calculated hardness.
- Hypothetically, the segment of the core barrel was exposed to higher neutron fluence which led to higher hardening. According to Eq. 8, necessary dose to achieve HV5 277 should be 4.6 dpa in average.

There are many empirical relationships (eg. [4] for irradiated austenitic steels) between hardness and yield strength. In this study, yield strength profile across the wall of the core barrel was estimated assuming that hardening of neutron-irradiated 08Ch18N10T steel follows Eqs 1–4 and the hardness comes from Eq. 8. All unknown material parameters in these equations are related to neutron dose and, therefore, solution is unique. Estimated yield strength in Figure 8 decreases from 700 MPa close to inner surface of the barrel to 660 MPa 20–25 mm under the inner surface. Coefficient $A$ varies only slightly between 877 and 883 MPa and exponent $n$ is 0.55.

## 4. Conclusions

The paper deals with the characterization of the tensile material properties of the neutron-irradiated segment of the core barrel from the reactor internals of NPP Greifswald 1, which was shut down after almost 16 years of its operation. Due to small amount of material, values of measured hardness together with finite element simulation of the indentation was used instead of the standard tensile test. The results can be summarized as follows:

- Ludwik's form of hardening equation Eq. 1 and neutron dose dependent material parameters in Eqs 2–4 according to work of Sorokin [1] can be used for the description of the tensile properties of neutron-irradiated 08Ch18N10T austenitic stainless steel used for fabrication of the core barrel. Although these material properties underestimate the measured hardness by 9 %, computed hardness lies within the scatter of experimental data.
- Numerically determined dependence of the hardness on the neutron dose is expressed by the equation $\mathrm{HV5}\,(D) = 160 + 174.3\sqrt{1 - \exp\left(-0.143 \cdot D\right)}$.
- Tensile properties of the examined segment of the core barrel vary across the wall thickness. Yield strength reaches 700 MPa close to the inner surface and then gradually decreases to 660 MPa. Strength coefficient is about 880 MPa and strain hardening exponent is 0.55.

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