A use of the WWR-M research reactor for in situ investigation of the physics and mechanical properties of metals and alloys

E. Grynik, V. Revka, L. Chyrko

Institute for Nuclear Research, Kiev, Ukraine
vrevka@hotmail.com
Outline

- Background and objective
- Material tested and irradiation condition
- Experimental method
- Test data analysis
- Summary
Background

- Irradiation causes the considerable changes in mechanical properties of structural material due to radiation defect formation and evolution. As usual it is related to radiation defect formation and following evolution of damaged structure lattice.

- Most of material characterization is based on the test of irradiated specimens after irradiation not at the time of irradiation.

- Physical and mechanical properties of metal and alloys at the time of neutron irradiation differ from the characteristics of irradiated materials due to much higher concentration of radiation-induced interstitials and vacancies in materials at the time of irradiation.

- Hence a determination of physical mechanisms of material properties changes at the time of neutron irradiation has an applied importance for the application of structural material in the nuclear industry.
Objectives

- Study of key factors of radiation and thermal influence on mechanical properties of structural material under different irradiation condition
  - Remote internal friction system was developed and integrated with a test channel of WWR-M research reactor to study material properties at the time of irradiation
  - An impact of radiation defects on grain-boundary relaxation and dislocation mobility in metal and allows was studied using an analysis of internal friction parameter changes
  - Helium effect on materials sensitivity to neutron irradiation
  - An internal friction method was applied for the estimation of radiation swelling rate
Elevation drawing of reactor WWR-M

1. Reactor vessel
2. Reactor core
3. Thermal column
4. Horizontal channel
5. Spent fuel storage

Fig. 1
WWR-M research reactor at KINR

- Pool-type reactor
- Power 10 MW
- Thermal neutron flux $1.2 \times 10^{14} \text{n/cm}^2\text{s}$
- Fast neutron flux $0.7 \times 10^{14} \text{n/cm}^2\text{s}$
- Moderator & coolant: light water
- Reflector: Beryllium
- Temperature 50°C
- 25 vertical and 10 horizontal technological channels
- Criticality date: 1960
Sectional view reactor WWR-M

1 - Reactor core with control rods
2 - Beryllium Reflector
3 - Horizontal channels
4 - Thermal column
5 - Reactor tank
6 - Biological shielding
7 - Channel for moving spent fuel into storage
8 - Biological channels
9 - Channel for fuel transfer machine
10 - Thermal column protection
WWR-M reactor application

- Industry
- Medicine
- Education
- Geology
- Research
  - Nuclear Physics
  - Neutron Physics
  - Radioecology
  - Physics of Condensed Matter State
  - Radiation Physics
Experimental equipment

- Multi-detector neutron spectrometer
- System of multi-detector Ge (Li) spectrometers for neutron capture gamma-ray investigations
- $4\pi$-multi-sectional detectors from sodium iodine crystals with sections operated on base of spectrometry method of multiplicity of radiation
- Triaxial neutron spectrometer and facility for investigation of dynamic processes in fluids using the method of passing
- Neutron spectrometer on the basic of proton recoil counter for measurements of total neutron cross sections
- Neutron spectrometer for measurements of total neutron cross sections. This installation is in preparation for measurements of total, capture and scattering cross sections simultaneously
- Semiconductor differential proton recoil; spectrometer for measurements of fast neutron fission spectra up to 30MeV
- Facility for neutron transmutation doped silicon production
- High-resolution gamma and X-ray spectrometry of induced sample activity with the help of HPGe coaxial (61% of relative efficiency) and planar (1000 mm$^2$ of active area) detectors combined with Canberra high-throughput electronics.
Material test channel

- Clamping stud
- Sealing cover
- Fitting for vacuum system
- Flange and pull rods
- Shell
- Working section
- Shank
Inverse torsion pendulum system

- A torsion pendulum system is applied for the determination of energy dissipation and elastic modulus at low frequencies of 1 – 20 Hz.
- In this frequency range the diffusion processes, grain boundary and interstitial atom moving and so on can be studied.
- The torsion pendulum operation is based on undamped torsion oscillations.
- Advantage is one specimen can be tested to get a whole fluence dependence of internal friction.
Torsion pendulum specification

- Frequency range: $1 \div 20$ Hz
- This equipment enables to measure the internal friction and shear modulus in the temperature range of + 20 to + 1000°C for materials irradiated up to the fluence of $5 \cdot 10^{21}$ n·cm$^{-2}$
- The strain amplitude can be changed in the range of $5 \cdot 10^{-4}$ to $5 \cdot 10^{-7}$, where the amplitude-independent internal friction is observed
- Max shear stress on the specimen surface: 50 MPa
Torsion test parameters

- Internal friction and shear modulus
- Shear stress and torsion strain
- Stress relaxation at constant torsion strain
- Torsion creep at constant shear stress
Materials tested and specimens

- **Materials**
  - Pure metals: Fe
  - Alloys: Fe-\(^{11}\)B
  - OX16H15M3Б steel and 0X16H15M3Б steel with 0.005 mass % Boron
  - RPV steel 12ХГНМ

- **Specimen tested**
  - Wire with 1 mm diameter and 50 to 100 mm length
Irradiation condition

- Neutron fluence rate:
  \[10^{13} \div 10^{14} \text{ n}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}\]

- Neutron (E > 0.1 MeV) fluence:
  \[10^{19} \div 10^{21} \text{ n}\cdot\text{cm}^{-2}\]

- Irradiation temperature:
  \[350 \div 400^\circ\text{C}\]
Internal friction parameter calculation

- Internal friction Q-1 is calculated using the following expression:

\[ Q^{-1} = \frac{1}{2\pi} \cdot \frac{\Delta W}{W} \]

- Where \( \Delta W \) – a loss of energy per cycle, 
  \( W \) – total energy of forced oscillations.

After the simple conversions taking into account the excitation parameters and specimen stiffness we can derive a formula for the determination of internal friction from the test:

\[ Q^{-1} = \frac{4 \cdot i_b \cdot C_2}{\pi \cdot C_1 \cdot e_0} \]

- Where \( C_1 \) and \( C_2 \) – device constants, \( e_0 \) – a parameter which correspond to specified strain amplitude and \( i_b \) – an excitation current is only parameter which is recorded. As a result the internal friction values are plotted against the test temperature in the temperature range of grain boundary relaxation.

- The height and temperature of grain boundary peak of internal friction are considered in the analysis.
Investigation of He diffusion on grain boundaries for pure Fe

- Irradiation temperature for tested specimens was 350°C
- The internal friction peak is related to grain boundary relaxation
- At the time of irradiation the temperature of internal friction peak is lower than under reactor shutdown condition in the whole range of neutron fluence. This effect is related to radiation vacancy flux towards the grain boundaries.
- Change of height and temperature of internal friction peak with neutron fluence increase is related to He formation due to \((n, \alpha)\) reaction and following He diffusion towards grain boundaries
- For platinum the \((n, \alpha)\) – reaction and He formation do not occur. In this case the changes of internal friction peak parameters have not been revealed.
Investigation of He diffusion on grain boundaries for structural steel 0X16H15M3Б

- It was found out that a grain boundary peak of internal friction reaches a maximum at fluence of $2 \cdot 10^{20}$ n/cm$^2$ for 0X16H15M3Б steel and $8.7 \cdot 10^{20}$ n/cm$^2$ for 0X16H15M3Б steel with 0.005 mass % B and then decreases.

- Maximum of internal friction peak value is related to the saturation of grain boundaries with Helium.

- Boron micro alloying of structural steel considerably increases neutron fluence at which the saturation of grain boundaries with He occurs.

- Internal friction method can be successfully used to estimate relaxation stability of grain boundaries in the relation to helium embrittlement.
Radiation-induced swelling for Fe – $^{11}$B

- Internal friction method was applied for the estimation of radiation swelling.
- A large increase of a grain boundary peak after the neutron fluence of $5 \cdot 10^{20}$ n/cm$^2$ was revealed in the temperature range of grain boundary relaxation.
- It is known that in materials the effects related to a formation of vacancy voids and interstitial dislocation loops occur at the neutron fluence of $\sim 10^{21}$ n/cm$^2$.
- An anomalous growth of internal friction can be explained by micro void nucleation in the Fe – $^{11}$B alloy.
- Since the micro void nucleation leads to a swelling the method of internal friction allows to estimate a radiation swelling rate.

Fluence (E > 0.1 MeV), n/cm$^2$

Open symbols – reactor shutdown
Closed symbols – at the time of irradiation
Influence of radiation damage on dislocation mobility: pure Fe

- Method of internal friction was used and a change of shear modulus due to irradiation was investigated.
- Shear modulus is much lower at the time of irradiation then when a reactor is shutdown at the same neutron fluence.
- This modulus decrease is fully reversible and observed only at the time of irradiation.
- Revealed effect is related to interstitials to mobile dislocations interaction.

Fluence (E > 0.1 MeV), n/cm²

- Open symbols – reactor shutdown
- Closed symbols – at the time of irradiation
Influence of radiation damage on dislocation mobility: structural steels

- For a structural steel 0X16H15M3Б the decrease of shear modulus at the time of irradiation is observed only in the initial period of irradiation.

- The reversible decrease of shear modulus is not revealed at all for the RPV steel 12ХГНМ in the whole range of neutron fluence.

- In steel the mobile dislocations are strongly locked by alloying elements and precipitates.
Summary

- Remote internal friction system integrated with a test channel in the research reactor was successfully applied to study material property changes at the time of and after irradiation.
- Boron micro alloying of structural steel considerably increases neutron fluence at which the saturation of grain boundaries with He occurs.
- Internal friction method allows us to estimate parameters of material void swelling at early stage ($\sim 10^{-2}$ %).
- Reversible decrease of shear modulus was revealed for pure Fe at the time of irradiation. This effect was not observed for the structural and RPV steels.