Localization of Plastic Deformation in the Copper and Stainless Steels Samples, Irradiated with Neutrons

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Abstract. The reduction of ductility of austenitic stainless steels as a result of long-term operation in the nuclear reactor core is an important problem of modern radiation materials science. Understanding the mechanisms of the effect of neutron irradiation on the mechanical properties of austenitic steels is impossible without research of localization processes occurring during the deformation. In this paper, it was found that the value of the true local deformation corresponding to the onset of neck formation in face-centered cubic structured metals decreases with an increase in the radiation dose, while the true stress remains almost constant. Additional hardening of AISI 304 steel due to the intensive formation of the martensitic α'-phase increases not only the stress at which a neck is formed in this alloy, but also the true local deformation. As a result, the uniform elongation increases and remains high after neutron irradiation to 0.05 dpa. The forehanded formation of the martensitic α'-phase in sufficient quantity before the necking onset can be considered as an additional deformation mechanism that will increase the ability of the material to deform uniformly.

1. Introduction

Any metal spontaneously delaminates into actively deforming regions and regions with the close to zero deformation during the plastic flow. The most visual and vivid manifestations of plastic flow localization occur at the macrolevel such as formation of a visible neck [1], dynamic strain aging [2], the formation of Luders bands [3], autowaves of plastic deformation [4], and others. These processes form the strength and plasticity of the material, effect significantly on the ability of metals to deform without destruction [5].

In this paper, we investigated austenitic chromium-nickel stainless steels, used in reactor construction as the main material of the core internals of III and III + generations PWR, WWR and WWER pressurized water reactors. During the normal operation for 40 years, the accumulated damaging dose of these devices can reach 30-40 displacements per atom (dpa). Further operation of these devices within the framework of the current trend towards an increase of the service life of operating reactor facilities up to 60-80 years can lead to the appearance of separate elements of the internals irradiated to 100 dpa and even more [6].

Large number of radiation-unduced defects are formed in the structure of materials during the high-dose neutron irradiation [7]. Transmutation of chemical elements occurs [6] and segregation of the chemical
composition near grain boundaries [8]. As a result, austenitic steels lose their competitive advantages - corrosion resistance and good mechanical properties. The total and uniform plasticity of the material significantly decreases with a simultaneous increase in strength after irradiation with neutrons. This is one of the main problems of reactors of III and IV generations [9].

12Cr18Ni10Ti and AISI 304 austenitic steels are used in nuclear industry in metastable condition. In this materials a diffusionless transformation of the face-centered (fcc) austenite lattice into a stronger body-centered (bcc) lattice of $\alpha'$-martensite can occur during the plastic deformation at room temperature. This effect significantly on the strength and ductility of austenitic stainless steels [10].

Understanding the mechanisms of the effect of irradiation with high-energy particles on the mechanical properties of materials is impossible without research of the processes of plastic flow localization and martensitic transformation during deformation. In this article, the transition from uniform to localized deformation in copper and austenitic steels was investigated, the effect of neutron irradiation and variations in chemical composition was revealed.

2. Materials and Methods

In this paper 12Cr18Ni10Ti and AISI 304 metastable austenitic steels were investigated as well as oxygen-free copper as a ductile model metal with a stable fcc lattice. The tendency of steels to form a martensitic $\alpha'$-phase was estimated from the chemical composition through the nickel equivalent ($\text{Ni}_{\text{eq}}$) [11] and the stacking fault energy ($\gamma_{\text{SFE}}$) [12]. The chemical composition of austenitic steels and the calculated values of the nickel equivalent and the stacking fault energy are presented in table 1. Despite of the similar content of alloying elements the $\text{Ni}_{\text{eq}}$ and $\gamma_{\text{SFE}}$ values of AISI 304 steel are lower than that of 12Cr18Ni10Ti steel which indicates that more martensitic $\alpha'$-phase form in this steel during deformation.

| Material      | Fe | C  | Si | Ti  | Cr  | Mn | Ni | $\text{Ni}_{\text{eq}}$ | $\gamma_{\text{SFE}}$ |
|---------------|----|----|----|-----|-----|----|----|------------------------|------------------------|
| AISI 304      | 71.3 | 0.1 | 0.4 | 0   | 18.2 | 1.4 | 8.6 | 23                     | 20.7                   |
| 12Cr18Ni10Ti  | 70.1 | 0.1 | 0.4 | 1   | 17.7 | 0.9 | 9.8 | 23.9                   | 26.9                   |

* According to EDS analysis using Hitachi TM-4000.

** According to steel specification.

Miniature dumbbell-type specimens with a gauge length of 10 mm and a diameter of 1.7 mm were used for uniaxial tensile test. Heat treatment was carried out in a vacuumed tube. Austenitic steels were annealed at 1050°C for 30 minutes, while copper - at 750°C for 1 hour. The samples were irradiated in the central channels of the WWR-K research reactor core (Almaty, Republic of Kazakhstan). Temperature of irradiation was less than 50°C. Radiation damage in units of displacements per atom (dpa) was calculated using the method described in [13].

The deformation of the materials was carried out at room temperature with a tensile rate of $10^{-3}$ s$^{-1}$ using Instron 1195 universal testing facility and was accompanied by photo shooting with a high-resolution digital camera. Strength and plasticity characteristics of the of the material were determined as well as true local strains in the neck region and true stress. True characteristics were calculated from the photographs according to the change in the cross-sectional area ($S$) of the specimens. True local strains were calculated using the formula:

$$\varepsilon = \ln \left( \frac{S_0}{S_0} \right)$$

and true stress was calculated:
In equations (1) and (2) \( S_0 \) is the initial cross-sectional area, while \( \sigma \) is the engineering stress. The moment of necking was determined as the moment of intersection of the true strain hardening curves with their first derivative (Consider's ratio):

\[
\sigma_{\text{true}} = \sigma \left( \frac{S_0}{S_f} \right)
\]

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\[
\sigma_{\text{true}} = \frac{d\sigma_{\text{true}}}{d\varepsilon}
\]

## 3. Results and Discussion

Oxygen-free copper is characterized by relatively high ductility and low strength in an unirradiated state. Irradiation with neutrons to 0.4 dpa led to a significant hardening of the material. Upper yield point (UYS) appear similar to metals with a bcc lattice (figure 1, a) because of the temporary blocking of free carriers of plasticity by radiation defects. The yield point (\( \sigma_{\text{YS}} \)) increased 5 times compared to the yield point in the initial state (\( \sigma_{\text{02}} \)) (table 2). The ability of the material to plastic deformation decreased catastrophically - uniform elongation (\( \delta_{\text{UN}} \)) decreased to 3.5%, and total elongation (\( \delta \)) - to 8%. At the same time, there is almost no strain hardening - the yield stress of irradiated copper is less than the ultimate strength (\( \sigma_{\text{UTS}} \)) by only 10 MPa.

![Figure 1](image.png)

Figure 1. Engineering (a) and true strain hardening curves (b) of the copper unirradiated and irradiated with neutrons in the WWR-K reactor. Enlarged fragments of diagrams in the area of intersection of curves with their first derivative are showed in the insert on the figure (b).

### Table 2. Mechanical properties of the copper irradiated with neutrons.

| Irradiation dose, dpa | \( \sigma_{\text{02}}, \text{MPa} \) | \( \sigma_{\text{UYS}}, \text{MPa} \) | \( \sigma_{\text{YS}}, \text{MPa} \) | \( \sigma_{\text{UTS}}, \text{MPa} \) | \( \delta_{\text{UN}}, \% \) | \( \delta, \% \) |
|-----------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Unirradiated          | 57               | 297              | 285              | 295              | 27.5             | 33.5             |
| 0.4                   | 297              | 285              | 295              | 27.5             | 3.5              | 8                |

The true stress-strain curves for necking area showed on figure 1, b. One can see that the material in local micro volumes is continuously hardened (there is no stress drop, typical for engineering diagrams). The local strains in the neck are very high and exceed the total elongation of the material by 2.5 times for unirradiated copper and 6 times for neutron-irradiated copper.

After neuronal irradiation, the true local strain of the neck is dropped from ~ 30 to ~ 3% (see insert in figure 1, b). An interesting feature of neutron irradiation is that it practically does not affect the deformation of metals with an fcc lattice after localization. The relative elongation after the ultimate stress point does not change significantly with an increase in the damaging dose (figure 1, a). Figure 1, b shows the same true
local deformation in the neck ~ 45-46% in unirradiated and irradiated copper, while the total elongation was significantly higher in the unirradiated sample (33.5% versus 8%). Consequently, neutron irradiation reduces primarily the ability of metals to deform uniformly.

There is not any upper yield point on the engineering tensile curves of austenitic steels irradiated in a WWR-K reactor to 0.05 dpa. The load increase s monotonically from the yield point ($\sigma_{0.2}$) to the ultimate strength ($\sigma_B$). Significant hardening is observed during tensile test (the ratio $\sigma_B/\sigma_{0.2}$ is relatively high).

The strength of the steels (figure 2), increase after neutron irradiation, yield stress raised most significantly (by ~ 200 MPa after irradiation to 0.05 dpa, regardless of the material). This effect is associated with the accumulation of radiation defects in the structure of the material in the form of clusters and dislocation loops, which increase the stress of the onset of dislocation motion. Neutron irradiation also led to a decrease in the ductility of austenitic steels. The total elongation of steels decreased after irradiation to 0.05 dpa by 20-25% relative to the unirradiated state. With similar strength characteristics, the ductility of AISI 304 steel is almost two times higher than that of 12Cr18Ni10Ti steel (regardless of the radiation dose).

![Graph](image)

Figure 2. Mechanical properties of the AISI 304 (a), and 12Cr18Ni10Ti (b) stainless steels irradiated with neutrons in the WWR-K nuclear reactor core.

True local strain ($\varepsilon_{\text{neck}}$) and true stress ($\sigma_{\text{neck}}$) of the neck onset (table 3) were determined from the true stress-strain curves of austenitic steels. Neck formation in 12Cr18Ni10Ti steel begins at lower deformations than in AISI 304 steel. The value of $\varepsilon_{\text{neck}}$ decreases with an increase in the irradiation dose in all investigated steels. The decrease is ~10% after irradiation to 0.05 dpa of both materials.

**Table 3.** True local strain (%) and true stress (MPa) of the neck onset in austenitic steels irradiated with neutrons.

| Irradiation dose, dpa | AISI 304 | 12Cr18Ni10Ti |
|-----------------------|----------|--------------|
|                       | $\varepsilon_{\text{neck}}$ | $\sigma_{\text{neck}}$ | $\varepsilon_{\text{neck}}$ | $\sigma_{\text{neck}}$ |
| Unirradiated          | 61       | 1356         | 37            | 998        |
| 0.001                 | 65       | 1264         | 37            | 1010       |
| 0.005                 | 56       | 1319         | 34.5          | 998        |
| 0.01                  | —a       | —a           | 32            | 999        |
| 0.05                  | 52       | 1330         | 27.5          | 987        |

* No data available.
The true stress of the onset of neck in the studied materials did not significantly changed with an increase in the radiation dose. The $\sigma_{\text{neck}}$ value of AISI 304 steel, is significantly higher than that of 12Cr18Ni10Ti steel. This effect is because much more of strong martensitic $\alpha'$-phase is formed during deformation in the austenitic matrix of AISI 304 steel.

Additional hardening of the material compensates for geometric softening and increases the true local deformation. As a result, the uniform and total elongation of the alloy increases (figure 2, a). The ductility of AISI 304 steel decreases with an increase of the neutron radiation dose to a lesser extent. The $\varepsilon_{\text{neck}}$ value remains quite high - ~52% even after irradiation to 0.05 dpa. Consequently, the relative decrease in the true local deformation after neutron irradiation of AISI 304 steel is significantly less than that of 12Cr18Ni10Ti steel (~14 and ~27% of the $\varepsilon_{\text{neck}}$ value after irradiation to 0.05 dpa relatively to the value of the unirradiated material).

Certain forms of strain localization during deformation of highly irradiated (> 50 dpa) austenitic steels at room temperature, make it possible to obtain high values of total elongation [14, 15]. The authors of the papers associate the obtained results with the intense martensitic transformation after necking. On the other hand, the formation of a sufficient amount of the martensitic phase before the onset of localization can be considered as an additional deformation mechanism [10], which will increase the ability of the material to deform uniformly.

4. Conclusions

This paper presents the results of mechanical tests of oxygen-free copper and 12Cr18Ni10Ti and AISI 304 industrial stainless steels, irradiated with neutrons. Photographing the samples during the tensile tests made possible to build true tensile curves and determine the parameters of necking.

It has been shown that the true local deformation of neck formation decreases in all studied materials after neuronal irradiation, to the greatest extent in copper samples, while the true stress of the onset of localization changes little with an increase in the radiation dose.

It was shown that even small variations in the chemical composition lead to a change in the metastability of the austenitic matrix sufficient for a significant increase in uniform elongation. The ductility of AISI 304 steel, in which more of the martensitic phase formed during deformation, is not only significantly higher than that of 12Cr18Ni10Ti steel, but also decreases to a lesser extent with increasing neutron radiation dose. The $\varepsilon_{\text{neck}}$ value remains quite high - ~52% even after irradiation to 0.05 dpa. The formation of a sufficient amount of a martensitic phase in the structure of a deformed material not only increases the plasticity, but also the strength (true stress of the onset of localization) of the material, which allows us to consider this process as an effective deformation mechanism in irradiated metastable steels.

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