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# Effect of irradiation on the steels 316L/LN type to 12 dpa at 400 °C

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**Abstract**

The 316L type stainless steel is widely used as a structural material for the fission reactors internal structures (core, core supports, etc.) and for experimental irradiation facilities. The 316L(N)-IG type steel is proposed as a main structural material for the ITER reactor (first wall, blanket, vacuum vessel, cooling pipe lines). It is obvious that different steel grades should exhibit different reaction to neutron irradiation. The main objective of this work was to study of irradiation behaviour of three different commercial steels: AISI 316LN, AISI 316L (US grades) and 02X17H14M2 (Russian steel grade that is similar to 316L). Irradiation effect on the three commercial steels of 316L family to ~12 dpa at the temperature ~370–400 °C on the tensile properties, microstructure, swelling and susceptibility to SCC are described in the paper.


## 1. Introduction

Type 316L austenitic steel is widely used for the different components of fission reactors. Similar steel grade, 316L(N)-IG, is one of the main structural material proposed for the ITER in-vessel components and vacuum vessel. Radiation hardening and embrittlement of steel occur under irradiation. Variations in steel composition may result in different properties changes due to irradiation. The main objective of the research was to investigate the irradiation effect on the commercial steels of type 316L with some variations in composition. Since these steels are similar to 316L(N)-IG grade used for the ITER in-vessel components, the data can be used for the design analysis.

## 2. Materials, irradiation and tests conditions

Research was carried out on the samples of three different commercial grade steels AISI 316L, AISI 316LN produced in USA and 02X17H14M2 grade steel produced in Russia. All these steels belong to the same family of type 316L austenitic steel. All steels were used in the solution annealed condition. The chemical composition of the steels is presented in Table 1.

Specimens were irradiated in the BOR-60 reactor up to a fast neutron fluence of $2.4\times10^{26}$ n/m$^2$ ($E > 0.1$ MeV) that corresponds to an irradiation damage of ~12 dpa. The damage rate was ~(3–4)$\times10^{-7}$ dpa/s that is similar to estimated for ITER of $3\times10^{-7}$ dpa/s. The irradiation temperature was ~370–400 °C. Specimens were in contact with the reactor coolant – liquid sodium. Cylindrical specimens with diameter of 3 mm and a length of 15 mm were used for the tensile tests. Specimens before and after irradiation were tested on the 1794 and MM-150/1 type machines with the crosshead rate of 1 mm/min in the temperature range from 20 to 500 °C.

Fracture surfaces and microstructures have been examined using optical microscope, scanning electronic microscope P3M-101 and transmission electron microscope JEM 2000-FXII, respectively. The samples in a form of disks with diameter of 3 mm cut out from the tested tensile specimens were used for the microstructure investigation. Disks were mechanically polished and

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Table 1
The chemical composition of the investigated steels (elements content is given in wt%)

| Material | C | Si | Mn | P | S | Cr | Ni | Mo | N |
|---|---|---|---|---|---|---|---|---|---|
| 316L | 0.018 | 0.43 | 1.78 | 0.026 | 0.013 | 16.5 | 10.39 | 2.09 | 0.054 |
| 316LN | 0.009 | 0.39 | 1.75 | 0.029 | 0.002 | 18.31 | 10.2 | 2.07 | 0.11 |
| 02X17H14M2[a] | 0.02 | 0.4 | 1.5 | 0.017 | 0.01 | 17.0 | 14.0 | 2.4 | |

[a] Average values.

electrolytically thinned up to 0.1 mm. Grain boundary segregation has been studied using EDS spectrometer.

## 3. Results of investigations

### 3.1. Mechanical properties

Mechanical properties of the steels before and after irradiation are presented in Table 2. Tests of irradiated steels were carried out at temperatures of 20, 100, 200, 300, 400 and 500 °C. The stress-strain curves of irradiated steels are shown in Fig. 1. The behaviour of all steel grades under irradiation are comparable. However, the results indicate that 02X17H14M2 steel after irradiation is more prone to strain localization during deformation in comparison with another steels. The uniform elongation of irradiated 316L and 316LN steels remains above 1% in the test temperature range 20–400 °C. The strength of steels corresponds to the data of 316L family steels [1–4]. At the same time, the most significant hardening is observed for 316L and 316LN (hardening at room temperature equals to 316% and 247%, respectively), in spite of slightly lower embrittlement compared with 02X17H14M2. The higher strength of steel 316LN in comparison with 316L in unirradiated condition seems to be resulted from the higher nitrogen content.

### 3.2. Fracture study

Typical fracture surface of irradiated specimens after tensile tests are presented in Fig. 2. The fracture surface of unirradiated specimens for 316LN and 02XI7H14M2 steels correspond to ductile rupture, but essential differences between investigated steels were observed. Two typical sizes of the dimples (ones were close to 50 μm, another were about 5 μm) were observed in the fracture surfaces of 316LN steel. The big dimples probably were formed by the coalescence of the voids at the boundaries of the big precipitates (up to 1 μm). The small dimples formed during latest stage of extension at the locations

Table 2
Tensile properties of steels before and after irradiation up to the fluence $2.4\times10^{26}$ n/m$^2$ ($E \geqslant 0.1$ MeV) at the temperature 370–400 °C

| Material | T test (°C) | YS (MPa) | | UTS (MPa) | | UEL (%) | | TEL (%) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Unirr. | Irr. | Unirr. | Irr. | Unirr. | Irr. | Unirr. | Irr. |
| 02X17H14M2 | 20 | 315 | 980 | 565 | 1040 | 54.6 | 5.5 | 68.3 | 23.5 |
| | 100 | | 920 | | 930 | | 1.5 | | 14.1 |
| | 200 | | 870 | | 910 | | 1.1 | | 12.5 |
| | 300 | | 890 | | 890 | | 0.5 | | 11.7 |
| | 400 | 230 | 800 | 395 | 820 | 33.1 | 0.5 | 45.9 | 11.1 |
| | 500 | | 700 | | 700 | | 0.7 | | 11.5 |
| 316L | 20 | 245 | 1020 | 565 | 1095 | 84.5 | 6.5 | 84.5 | 23.7 |
| | 100 | | 1030 | | 1050 | | 2.7 | | 11.1 |
| | 200 | | 960 | | 980 | | 1.7 | | 6.7 |
| | 300 | | 930 | | 960 | | 1.4 | | 10.8 |
| | 400 | 165 | 830 | 395 | 890 | 40.5 | 1.3 | 50.1 | 6.1 |
| | 500 | | 790 | | 810 | | 0.7 | | 9.1 |
| 316LN | 20 | 360 | 1250 | 640 | 1330 | 61.6 | 3.3 | 78.7 | 19.5 |
| | 100 | | 1160 | | 1220 | | 2.3 | | 4.3 |
| | 200 | | 1110 | | 1160 | | 1.8 | | 12.9 |
| | 300 | | 1070 | | 1080 | | 1.5 | | 12.5 |
| | 400 | 125 | 1010 | 445 | 1015 | 44.0 | 0.8 | 53.3 | 11.5 |
| | 500 | | 940 | | 960 | | 1.1 | | 10.6 |

Note: UTS – ultimate tensile strength, YS – yield strength at 0.2% offset, UEL – uniform elongation, TEL – total elongation.

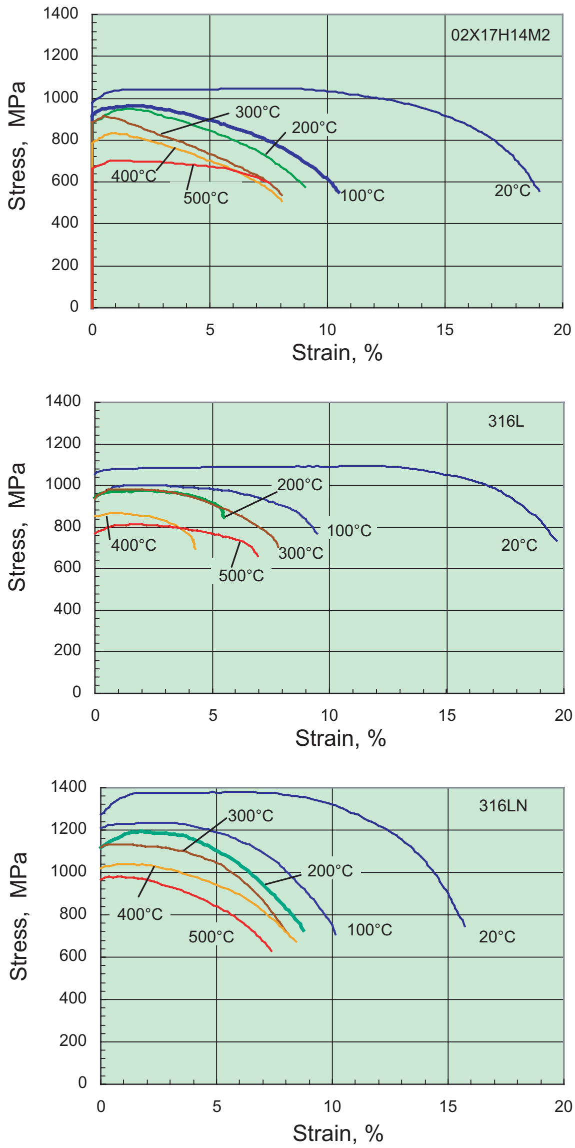


Fig. 1. Strain–stress curves of steels after irradiation at the temperature ∼400 °C by the fluence $2.4\times10^{26}$ n/cm$^2$.

of the dislocation accumulations. The sizes of dimples in the 02X17H14M2 steel were more homogeneous and

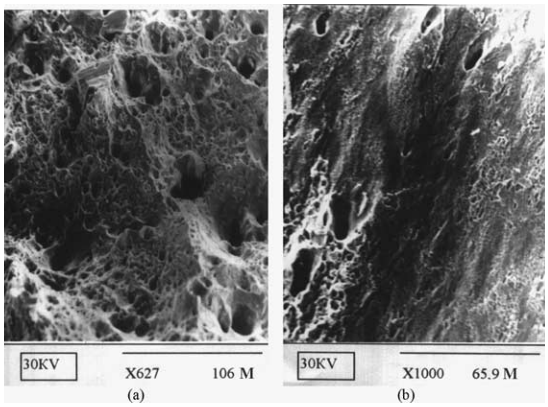


Fig. 2. Typical fracture view of irradiated and tested at 20 °C steels 316LN (a) and 02X17H14M2 (b), respectively.

equal of about 5 microns that resulted from the absence of big precipitates.

The fracture surface of both 316LN and 02XI7 H14M2 steels remained ductile, in spite of the significant hardening. However, the formation of the secondary cracking was observed for the both irradiated steels.

### 3.3. Microstructure examinations

Main characteristics of microstructure of irradiated steels are presented in Table 3. It can be concluded from the presented data that the larger diameter of dislocation loops resulted in faster lost of strain hardening capability of 02X17H14M2 steel due to irradiation, and the bigger values of hardening observed for 316L and 316LN steels are connected with the bigger vacancy pores density and swelling.

The values of swelling connected with voids were estimated on the bases of data presented in Table 3. The following estimated values of swelling have been received: $(0.08\pm0.03)$% for 316L steel, $(0.14\pm0.05)$% for 316LN steel and $(0.03\pm0.01)$% for 02X17H14M2. These results confirm the numerous data received for similar steels after irradiation [1,5]. It is known that for solution annealed steels type 316 the maximum value of swelling are observed in the temperatures range 425–525 °C. At

Table 3
Radiation defects in 316LN, 316L and 02X17H14M2 steels after irradiation in BOR-60 reactor up to dose ∼12 dpa at the temperature 370–400 °C

| Steel | Vacancy voids | | | | Dislocation loops | |
|---|---|---|---|---|---|---|
| | Diameter (nm) | Volume ($10^{-19}$ cm$^3$) | Density ($10^{13}$ cm$^{-3}$) | Swelling (%) | Diameter (nm) | Density ($10^{16}$ cm$^{-3}$) |
| 316L | $7.8\pm1.2$ | $4.0\pm0.8$ | $1.9\pm0.6$ | $0.08\pm0.03$ | $11.6\pm2.3$ | $4.8\pm1.5$ |
| 316LN | $7.2\pm1.0$ | $3.1\pm0.6$ | $4.5\pm1.3$ | $0.14\pm0.5$ | $10.4\pm2.0$ | $4.2\pm1.3$ |
| 02X17H14M2 | $7.2\pm1.0$ | $3.4\pm0.6$ | $0.9\pm0.3$ | $0.03\pm0.01$ | $14.4\pm3.0$ | $4.8\pm1.5$ |

the temperatures below 400 °C, swelling of 316LN type steel is relatively small.

Redistribution of alloying elements on the grain boundary may resulted in susceptibility to stress corrosion cracking (SCC) [6]. The Straus method and Electrochemical Reactivation method were used for revealing susceptibility of steels to SCC [7,8]. Both methods did not reveal the susceptibility of all austenitic steels to the SCC both before and after irradiation.

## 4. Conclusion

Result of examinations of stainless steels 316L, 316LN and 02XI7H14M2 types show just minor differences in the different steels behaviour both before and after irradiation. This conclusion is based on investigation of tensile properties, microstructure and SCC of steels before and after irradiation to dose of ~12 dpa at the temperature 370–400 °C. However, an additional investigation of irradiation behaviour of steels at lower temperature, ~200–300 °C, is advisable, because of this temperature range is more critical for irradiation embrittlement.

Steel with addition of nitrogen (316LN) exhibits slightly better resistance to embrittlement after irradiation compared with another steels, low swelling and is not susceptible to IASCC. The strength of this steel is slightly higher due to the addition of nitrogen.

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