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Influence of neutron irradiation on CuNiCrSi alloy pre-implanted with helium

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Abstract

He-implanted samples were irradiated in the IVV-2M reactor at 80°C and at 300°C up to ~0.3 dpa. Samples without implantation were also irradiated at 300°C for comparison. Structural investigations were performed and mechanical properties determined after neutron irradiation as well as on unirradiated samples. Unirradiated He-implanted samples showed higher strength properties than unimplanted samples at room temperature. The plasticity of implanted samples was lower by 1.2 times. The difference of strength disappeared at 300°C and the total elongation of implanted samples decreased by 2 times in comparison with unimplanted samples.

1. Introduction

Copper alloys are being considered for applications requiring high thermal conductivity in the first wall of ITER. During operation of the reactor copper alloys will be influenced not only by neutron irradiation but also by α-particles diffusing from Be-covering. These effects may cause an unfavorable effect, such as embrittlement [1–3]. Therefore it is useful to study the influence of neutron irradiation on He-implanted copper alloys.

The purpose of the work is to study the effects of neutron irradiation on mechanical properties of CuNiCrSi alloy pre-implanted with helium.

2. Characteristics of CuNiCrSi alloy

A plate of $1 \times 65 \times 180$ mm^3 size was fabricated. The chemical composition of the CuNiCrSi plate is given in Table 1.

Thermal treatments of the alloy were as follows:
- annealed at 980–1000°C for 1 h and then quenching in water;
- cool work $\varepsilon = 70\%$;
- aging for 4 h at 460°C, following air cooling.

Flat two-bladed samples were made for mechanical tests. One part of the samples was irradiated by α-particles with an energy of 40 MeV at the JINR accelerator (Dubna) which provided penetration depth of 200 μm for He. The diameter of the irradiated region was 20 mm. Samples were irradiated in turn on both sides up to He-concentration of 30 ppm.

These samples were separated into three sets. The influence of He-implantation on the steel properties was studied using one of them. Two other sets were irradiated at 80°C and 300°C in the IVV-2M reactor (Zarechny). Other samples without implantation were simultaneously irradiated at 300°C. Damage doses of the different sets were slightly different since the irradiation was performed in different irradiation devices. Irradiation conditions are presented in Table 2.

3. Results of neutron irradiation

Mechanical tensile tests were performed on all samples. The test temperature ranges were 20–300°C for

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Table 1
Chemical composition of CuNiCrSi-alloy (wt%)

	Alloying element			Impurities					
	Cr	Ni	Si	Bi	As	Fe	Pb	Zr	Al
Element technical specifications (%)	0.4–1.0	2.2–2.8	0.5–0.9	<0.004	<0.003	<0.06	<0.005	<0.05	<0.15
Plate composition (%)	0.58	2.46	0.64	0.001	6×10^{-4}	0.005	5×10^{-4}	5×10^{-5}	0.004

Table 2
Condition parameters of samples from CuNiCrSi-alloy irradiated in IVV-2M

Irradiated samples	Reactor cell	Irradiation environment	Duration (Time) (h)	Temperature (°C)	Damage doze (dpa)
Without He	7–5	Helium	500	300	0.42
With He	9–7	Water	648	80	0.48
With He	4–8	Helium	312	300	0.26

He-implanted samples without neutron irradiation, 20–350°C after neutron irradiation at 80°C and 20–400°C after neutron irradiation at 300°C. Unimplanted samples were tested before and after neutron irradiation at room temperature and at 300°C. The temperature dependence of the ultimate strength and the total elongation of each sample conditions are shown in Fig. 1. Note, that He-implantation at under-surface layers which are 40% of the total thickness caused the increase of ultimate strength above 5% at room temperature. The strength of He-implanted samples was close to the values of unimplanted ones with temperature increasing up to 300°C.

Neutron irradiation at 300°C led to the increasing of yield strength at room temperature, and the hardening of the He-implanted samples is slightly higher than the unimplanted samples. The strength of irradiated and unirradiated samples with He was close to the unimplanted samples at 300°C. Irradiation at 80°C showed lower radiation hardening; however, it remained over the entire range of the test temperature. Changes in both conventional yield strength and ultimate strength of implanted and unimplanted samples are similar.

The total elongation decreases due to He-implantation. It was concluded that the total elongation of He-implanted unirradiated samples was about 20% lower than unimplanted ones at room temperature, but the ultimate strength reduced two times at 300°C. The relative elongation of implanted and unimplanted samples was practically the same over the whole test temperature range after irradiation at 300°C. At 250°C and 300°C, the total elongation of the implanted samples irradiated at 80°C was higher than that after irradiation at 300°C. Nevertheless, with increasing of the test temperature He-implanted samples irradiated at various temperatures had the same values of total elongation.

Metallographic examination including microhardness measurements was performed after mechanical tests at room temperature. Microstructure was studied on the working part of He-implanted samples on longitudinal and cross microsections. It was found that the microstructure was homogeneous through the thickness. Dif-

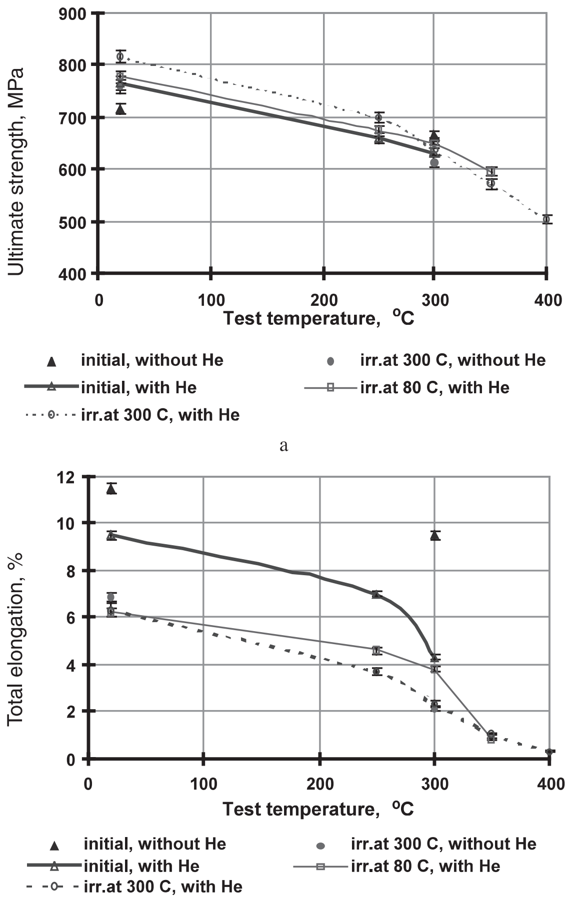

Fig. 1. Temperature dependence of short-term mechanical properties of neutron irradiated and unirradiated CuNiCrZr-alloy with and without He-content.

ferences in structure of He-implanted surface layers and central areas were not observed. It was observed that a great amount of small precipitates of less than 1 μm size were present in surface layers on one side of a sample. A smaller amount of such precipitates was in the central area and near the other surface of the sample. Irradiation at 300°C did not lead to observable changes of structure.

The Vickers microhardness was measured on a cross-section of irradiated and unirradiated He-implanted samples with two levels of loads ($P_1 = 100$ g, $P_2 = 5$ g). The following areas were studied: adjacent to damage zone, far from damage zone and location on the non-working part of a sample. We determined that microhardness on one surface is higher than the other side. This tendency remained after irradiation but it appears weaker when samples were irradiated at 80°C.

The microhardness averaged through the thickness of a sample of the areas mentioned above is shown in Fig. 2. Intragranular microhardness calculated using measurement results at lower load on the indentor was higher for a deformed area than undeformed. The highest value of microhardness was observed on the deformed area irradiated at 300°C. Integral microhardness defined using measurement results at high load on the indentor, within the limits of one standard deviation, was identical for deformed and undeformed parts.

Fractography examinations of samples after mechanical tests showed a transgranular fracture with a cup fracture formation. With increasing of the test temperature a formation of secondary cracks was observed for all conditions, Figs. 3 (a),(c) and (d). Characteristic feature of a fracture surface for irradiated samples was the formation of flat separation pits that testified to both localization of deformation and decreasing of material plasticity, Figs. 3(a),(e) and (f). Obvious evidence of the influence of a He-implanted layer on surface fracture was not revealed. Note, that separation pits became more flat in fracture area of undersurface layers than in central area and they were similar to separation pits observed in central areas of samples irradiated at 300°C, Figs. 3(b) and (e).

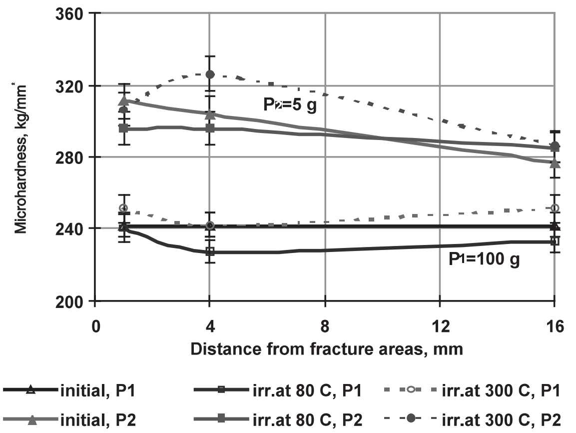

Fig. 2. Dependence of microhardness averaged through the thickness of sample from removal of areas with damage dose.

4. Discussion and conclusions

Results obtained showed that He-implantation of CuNiCrSi-alloy even to ~30 ppm increased strength and considerably decreased plasticity. The hardening (increasing of yield strength) due to a presence of He atoms in matrix can be evaluated, for example, with the help of the Orowan model [4]. Taking into consideration that a portion of a sectional area, occupied by the He-saturation material was $\beta = 0.4$ the hardening by dissolved He-atoms was expressed by the following equation:

$$\Delta\sigma_{\mathrm{He}} = \beta\alpha G b\sqrt{a c_{\mathrm{He}}}, \quad (1)$$

where α is the drag coefficient of dislocation by an impurity atom, equal to 0.1 [5]; G the shear modulus of an alloy at the room temperature, equal to 51 HPa; b the Burgers vector, equal to 0.25 nm, as dominating type of dislocations in fcc-metals are dislocations $a/2\langle 1\,1\,0\rangle$ [6]; a the lattice period, equal to 0.36 nm; c_{He} is the concentration of He atoms, 2.52×10^{24} m^{-3} for 30 ppm. The calculated value of hardening is ~15 MPa and the experimentally measured value was 49 MPa.

Such a difference was connected with the influence of concentration of He and radiation damage of undersurface layers (thickness ~200 nm) due to irradiation by He. The effect of α-irradiation-induced cascade formation at an energy of 40 MeV was not less than neutron irradiation. Therefore, together with higher He content, undersurface layers of samples were saturated by radiation defects. It appeared, in particular, that at failure separation pits were more flat in the layers as well as in the case for neutron-irradiated samples.

Outside layers of samples treated in an accelerator had a higher damage dose than the internal side one at neutron irradiation. As change dependence of mechanical properties from damage dose had saturation character for Cu-alloys outside layers would undergo smaller radiation hardening than internal one. However, at the room temperature hardening of He-implanted samples was higher than for unimplanted samples at neutron irradiation. A probable reason for such effect can be the formation of vacancy-helium complexes which are stronger stoppers than Helium atoms for moving dislocations.

Vacancies evaporate from clusters formed in samples under α-particle irradiation during deformation at 300°C. All this accelerate diffusion of substitution

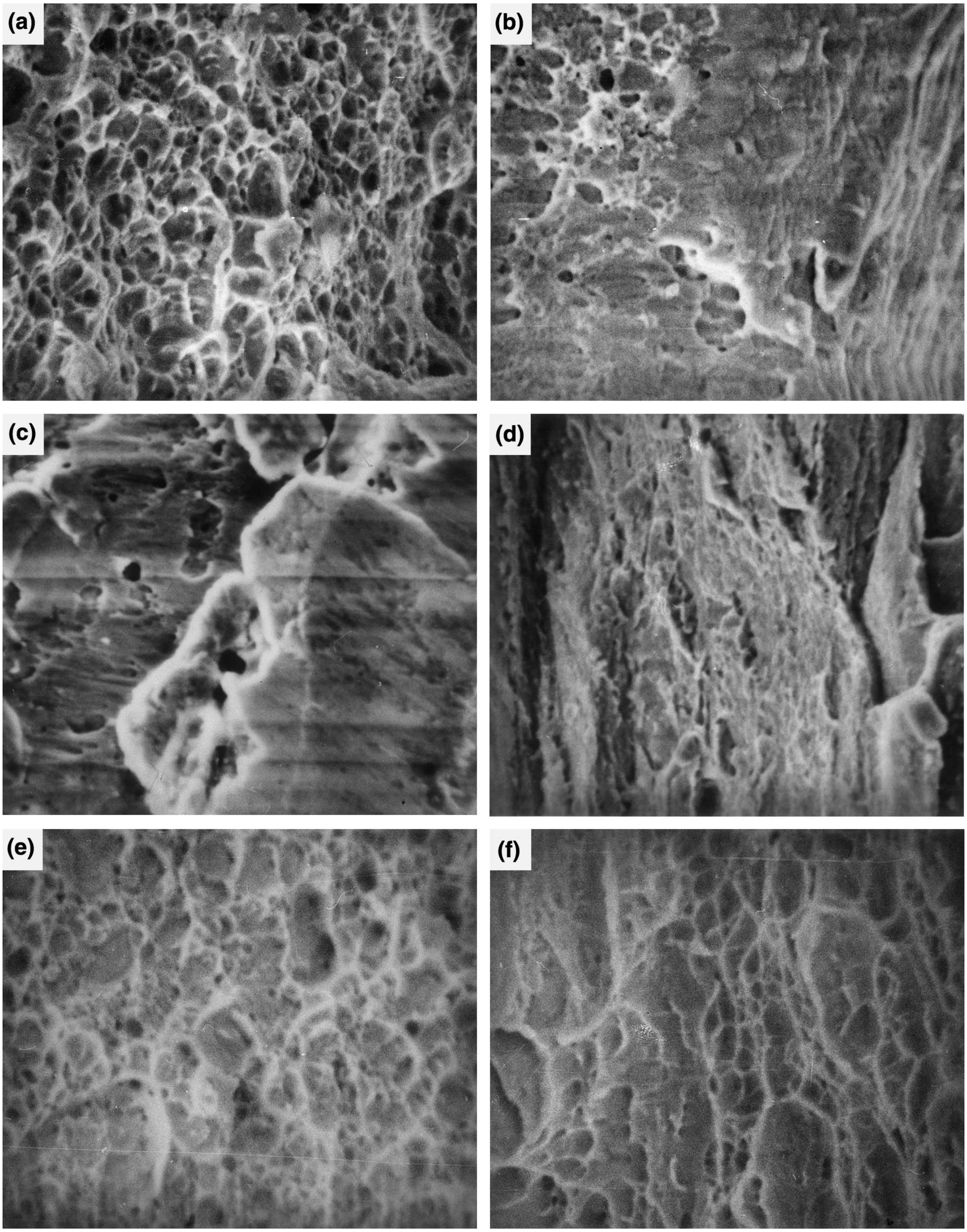

Fig. 3. A view of failure surface of He-implanted sample from CuNiCrSi-alloy: (a) an unirradiated sample tested at room temperature, central area; (b) part of the same sample, connected to edge; (c) secondary cracks formed at 300°C during fracture of an unirradiated sample; (d) secondary cracks formed at 300°C during fracture of an sample after irradiation at 300°C; (e) a neutron-irradiated sample at 300°C test at 20°, central area; (f) a neutron-irradiated sample at 300°C test at 300°C central area.

impurities and results in formation of secondary phases which stopped moving dislocations and accumulated them. Subsequently these areas become places of separation pit formation. Thus plasticity decreased. A similar process occurred at mechanical tests after neutron irradiation at the same temperature.

Injected He-atoms are traps for vacancies. It leads to both decreasing of vacancies concentration in solid solution which evaporate from clusters under heating and retardation of substitution impurities diffusion. The formation of secondary phases was lower so plasticity was reduced to a lesser degree than in samples without He-content.

It explained the fact that the plasticity of He-implanted samples after neutron irradiation decreased much less than for samples without He-content. The total elongation became equal for both types of samples at 300°C.

Thus, irradiation results in shift of embrittlement temperature of CuNiCrSi alloy to a lower temperature range. Helium injection prevented this shift that positively influenced on plasticity at temperature above 300°C.

However, it is necessary to note that helium-vacancy complexes can be void nuclei and may be a cause of vacancy swelling and other negative events at high damage doses.

References

[1] A.F. Rowcliffe, S.J. Zinkle, J.F. Stubbins et al., J. Nucl. Mater. 258–263 (1998) 183.
[2] S.A. Fabritsiev, A.S. Pokrovsky, D.J. Edwards, S.J. Zinkle, J. Nucl. Mater. 258–263 (1998) 1015.
[3] A.D. Ivanov, A.V. Kozlov et al., J. Nucl. Mater. 271&272 (1999) 139.
[4] L.P. Loshmanov, Radiation Strengthening of Metal, MRI Publishers, Moscow, 1983.
[5] I.M. Nekljudov, Radiation Strengthening of Metals and Alloys, Harkov, HPTI AS UUSR, 1978.
[6] B.N. Goshchitskii, V.V. Sagaradze, V.L. Arbusov et al., J. Nucl. Mater. 258–263 (1988) 1681.