ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 1312–1318

journal of nuclear materials

Influence of operation conditions on structure and properties of 12% Cr steels as candidate structural materials for fusion reactor

A.G. Ioltukhovsky [a,*], M.V. Leontyeva-Smirnova [a], Y.I. Kazennov [a], E.A. Medvedeva [a], A.V. Tselishchev [b], V.K. Shamardin [b], A.V. Povstyanko [b], S.E. Ostrovsky [b], A.M. Dvoryashin [c], S.I. Porollo [c], A.N. Vorobyev [c], V.S. Khabarov [c]

[a] *SSC RF, A.A. Bochvar All-Russia Research Institute of Inorganic Materials (VNIINM), P.O. Box 369, Moscow 123060, Russian Federation*

[b] *Scientific Research Institute of Atomic Reactor, 433510 Dimitrovgrad, Russian Federation*

[c] *SSC RF Institute of Physics and Power Engineering, Obninsk 249020, Russian Federation*

Abstract

The Russian experience in the development and operation of the nuclear core components in fast reactors with a sodium coolant demonstrates that 12% Cr steels may be successfully used at temperatures of 270–650°C and at high neutron damage dose (up to 100 dpa and above). The priority of the temperature but not of dose of the irradiation is noted for the steels at 270–350°C. In addition, the following may take place: a sharp decrease in the ductility of material, a change in the mechanism of fracture with which the ductile–brittle-transition-temperature (DBTT) shift is associated. With an increase in irradiation temperature to 350–500°C and the irradiation dose (up to 100 dpa) chromium steels are observed to strengthen; their ductility increased monotonously, and embrittlement does not show up. With the irradiation temperature increased above 500°C (up to 650–690°C), the material becomes plastic and some of its strength properties are decreased. The high level of the irradiation resistance of 12% Cr steels is a result of their structure and phase transformations. The properties of the welded joints of 12% Cr steels under the conditions of the neutron irradiation are slightly inferior to the properties of the base metal.

In the previous work [1] the authors demonstrated the general feasibility of using 12% Cr steels as a structural material for the first wall and fusion reactor blanket, specifically the DEMO reactor. This work deals with the specificity of the structure transformations and mechanical behaviour of the steels under discussion at different temperatures and fluences.

The current investigations were focused on steels that have already demonstrated the high serviceability as structural materials of fuel rod claddings, fuel assembly wrappers and other components of experimental and commercial reactors of BN type (BN-600, BN-350, BOR-60 and other). These are primarily heat resistant 12% Cr steels EP450 and EP823 (Table 1).

The results of BN-350 and BN-600 irradiation point to the most dangerous and high stress low temperature region of 270–350°C for 12% Cr steels [2,3]. The effect of neutron irradiation within 270–350°C makes this temperature range most critical in terms of the irradiation-induced strengthening, reduction in ductility, impact property changes in steels. Nonetheless, as is shown by the experience gained in the operation of Cr steels and experimental results the priority influence of the temperature but not the irradiation dose is evident in this range [4].

---

[*] Corresponding author. Tel.: +7 095 190 2375; fax: +7 095 196 6591; e-mail: ira1@bochvar.ru.

0022-3115/98/$19.00 © 1998 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(98)00396-1

Table 1
Chemical composition of ferritic–martensitic steels

Grade of steel	Content of elements, % mass									
	C	Si	Mn	Ni	Cr	V	Mo	W	Nb	B
EP450	0.10	<0.5	<0.8	0.05	11.0	0.1	1.2	–	0.3	0.004
1Cr12Mo2NbVB	0.15			0.30	13.5	0.3	1.8		0.6	calc.
EP823	0.14	1.1	0.5	0.5	10.0	0.2	0.6	0.5	0.2	0.006
16Cr12MoWSiVNbB	0.18	1.3	0.8	0.8	12.0	0.4	0.9	0.8	0.4	calc.

The strengthening effect is most noticeable at low irradiation doses of 10–30 dpa in the narrow temperature range (300–365°C); with the irradiation dose increased there takes place a partial recovery of the initial strength, Fig. 1. A similar dependence is also observed for the impact toughness. After an appreciable reduction at 20–30 dpa with an increase of the dose the impact toughness starts increasing, Fig. 2. The recovery of the percent elongation is observed to a lesser extent. This mechanical behaviour of Cr steels removes the acute problem of their likely brittleness under high dose irradiation.

Of 12% Cr steels examined by the authors, steels of 05Cr12Ni2Mo, 16Cr12MoWSiVNbB and 1Cr12Mo2 NbVB types are least prone to a low temperature embrittlement [5,6]. Their propensity for embrittlement proved to be substantially affected by the contents of the δ-ferrite and the harmful impurities [1]. This is particularly manifest in weldments with joints having the chemical composition of the steel welded. The metal of those welded joints always contains higher amounts of the δ-ferrite compared to the base metal.

As is shown by the investigations, 16Cr12MoWSiVNbB steels as BOR-60 irradiated at $T = 340$–360°C (the maximum fluence of 2.7×10^{26} neutron/m^2, $E > 0.1$ Mev) were least prone to irradiation strengthening and a ductility reduction, Fig. 3, and had either the homogeneous martensitic structure or the structure containing not more than 20% δ-ferrite (compositions 3–6). At the same time steels containing 50–80% δ-ferrite (compositions 1–2) have a residual ductility close to zero. The impact toughness of 16Cr12MoWSiVNbB as BOR-60 and BN-600 irradiated at 340–390°C to 20–60 dpa is (40–100 g/sm^2) within (−50°C) to 250°C.

The lower level of temperature dependence of the impact to toughness does not change after irradiation and is equal to (~40 g/sm^2). The ductile-brittle-transition-temperature (DBTT) is ~80°C, Fig. 4. With the

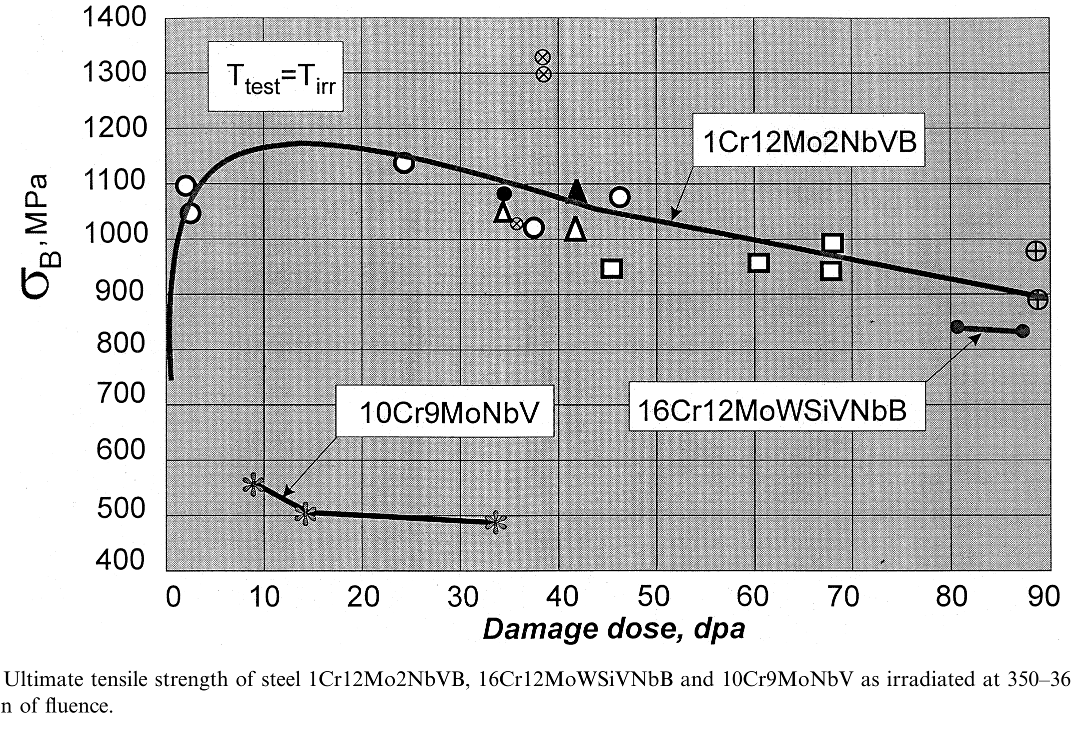

Fig. 1. Ultimate tensile strength of steel 1Cr12Mo2NbVB, 16Cr12MoWSiVNbB and 10Cr9MoNbV as irradiated at 350–365°C as a function of fluence.

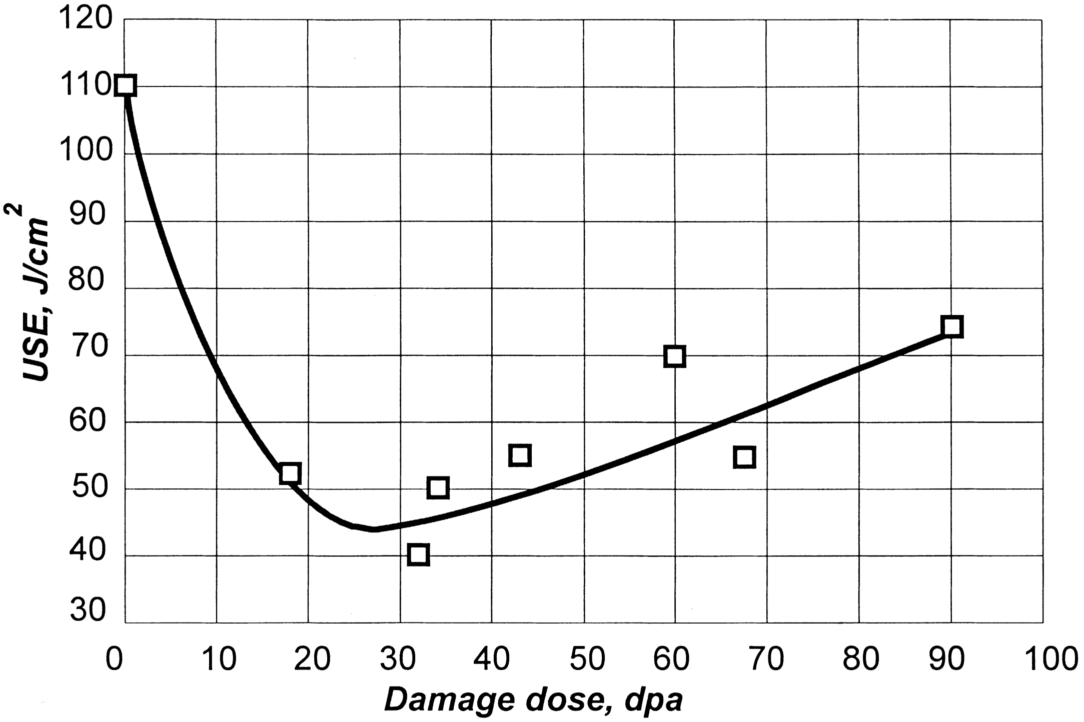

Fig. 2. Effect of damage dose on USE of the 1Cr12Mo2NbVB steel used as wrapper material in subassemblies and irradiated at 350–365°C.

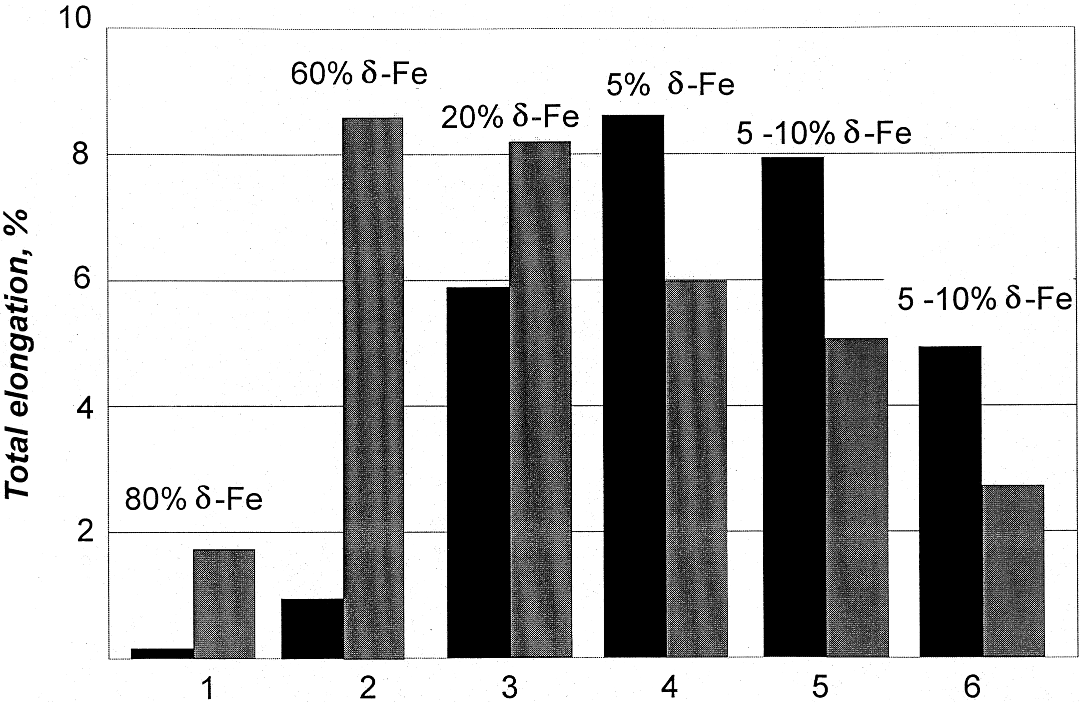

Fig. 3. Total elongation of 12% Cr steel containing different amounts of δ-ferrite and compositions (pairs 1–6) after irradiated in BOR-60 at 345–365°C to the fluence of 2.7 × 10^{26} neutron/m^2. Test temperatures are 20°C (left columns in pairs) and 365°C (right columns in pairs).

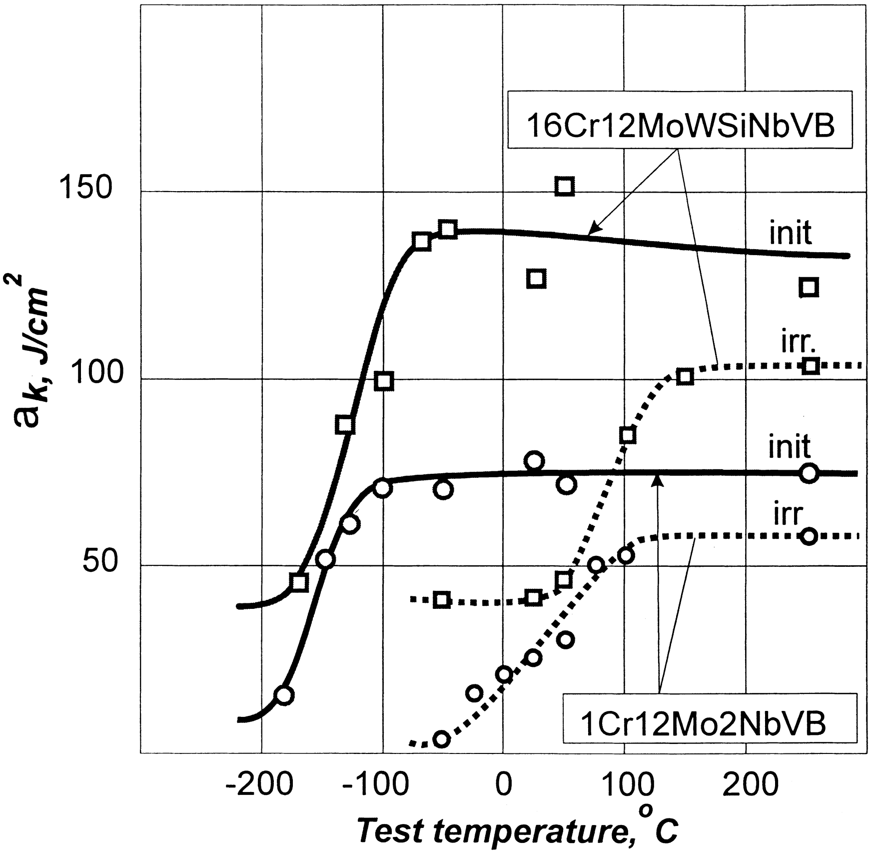

Fig. 4. Temperature dependencies of impact strength of steel 16Cr12MoWSiVNbB before and after BN-600 irradiation at 370–390°C (1Cr12Mo2NbVB to 49 dpa, 16Cr12MoWSiVNbB to 60 dpa).

irradiation temperature raised to 500°C and with an increase of the irradiation dose to 100 dpa chromium steels are observed to increase their strength; their ductility monotonously grows, no embrittlement shows up. The example is given by results obtained for 16Cr12MoWSiVNbB and 1Cr12Mo2NbVB steels BN-600 irradiated at $T = 385$–500°C, the damage dose being 60–108 dpa Fig. 5 [2,7]. The reduction of the irradiated material strength is observed on approach to $T_{\text{test}} = 700$°C. The highest margin of serviceability features the highest alloy steel 16X12MoWSiVNbB at the expense of a longer retention of the martensite base of the material and this is evidenced by the microstructure analysis.

The welded joints of the same steel tested for the impact bend after irradiation under about similar conditions had the properties that were little inferior to the base metal, Fig. 6 [6]. Although as a result of irradiation the upper threshold of the ductile–brittle transition is shifted to the side of the positive test temperatures, the shift is not large (of the order of 50–60°C). With some variations in the chemical and phase compositions of the weldment the ductile-brittle transition threshold changes insignificantly. In the region beyond the upper threshold of the ductile–brittle transition, the impact toughness was above 60 g/sm^2.

The resistance to the irradiation-induced low-temperature creep of the steels belonging to the class under discussion is much higher than that of austenitic Cr–Ni steels and is also dependent upon the structure and alloying. It is shown [8], that the modulus of the irradiation creep of the type steel is weakly dependent on the temperature within 290–450°C, its maximum value being $(0.4 \pm 0.06)\ 10^{-6}$ (MPAdpa)$^{-1}$.

The advantage of 12% Cr steel over other structural materials is their low propensity to irradiation effected swelling. The 1Cr12Mo2NbVB steel irradiated as a BN-600 component to 108 dpa at $T_{\text{irr}} = 430$°C; $\Delta V/V$ did not exceed 1% [7]. Similar results were obtained for 16Cr12MoWSiVNbB steel specimens irradiated under the identical conditions. The maximum swelling of the fuel rods from steel 1Cr12Mo2NbVB irradiated to 110, 130 and 142 dpa in reactor BOR-60 at 400°C was 0.4%, 1.0–1.2% and 1.9–2.0%, respectively. The swelling rate was (0.05–0.07)%/dpa.

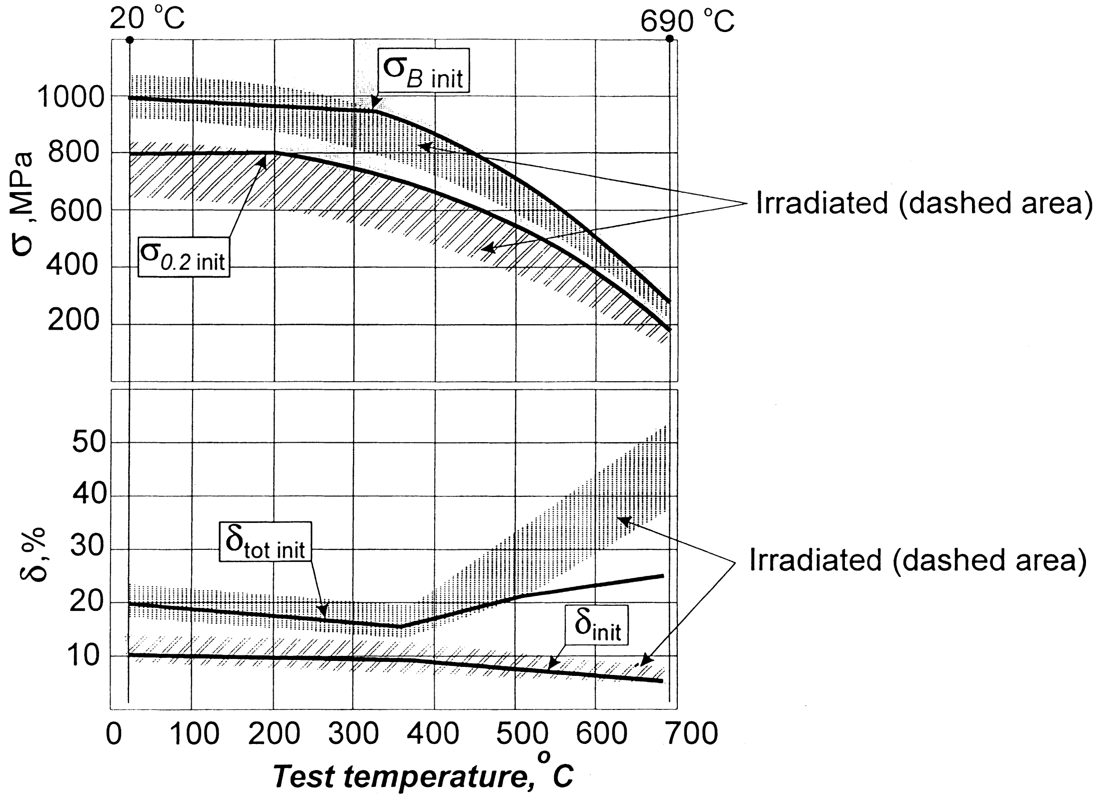

Fig. 5. Tensile properties of 16Cr12MoWSiVNbB and 1Cr12Mo2NbVB steels after irradiated in BN-600 at 385–500°C to 40–108 dpa.

The vacancy porosity was revealed in all the specimens studied both within ferrite grains and tempered martensit. In the latter the mean pore size is higher and their concentration in lower, which provides for the lower swelling of the tempered martensit compared to that of ferrite; this indicates that the single phase martensitic structure or the structure having the limited content of δ-ferrite are favourable.

The high irradiation resistance of 12% Cr steels, the intricate dose-temperature-mechanical property relations are dictated by the specific structure and phase transformations [2,9,10]. Of importance is the initial (non-irradiated) structure and the phase composition of steels. We have previously demonstrated [5,11] that the δ-ferrite content of ferritic–martensitic steels must not exceed 50%, and it is desirable to lower it down to 20% and lower. Aside from this, the solid solution in the initial condition must not contain any heterogeneous formations of the lamination type accompanied by the appearance of zones enriched, e.g., in Cr, or segregation zones. The initial composition of the solid solution and the phases is determined by the alloying of the steel and the methods of process working semi-products and finished items.

The detailed studies of the structure transformations were carried out using 1Cr12Mo2NbVB steel [12] high dose irradiated at 425–500°C (the maximum dose is 108 dpa). The irradiated 1Cr12Mo2NbVB steel contains for the most part carbides (Nb, V) C and $(Cr,Fe,Mo)_{23}C_6$. As the irradiation temperatures is raised the fraction of carbides increases. The maximum precipitation of $M_{23}C_6$ type carbides takes place in the range of $T_{irr} = 470°C$. In the irradiation temperature range of 450–470°C at the maximum damage dose no (Nb, V) C carbides were revealed. At higher irradiation temperatures the quantity of (Nb, V) C carbides becomes higher. The possibility is not excluded that under irradiation dispersed intermetallic phases may precipitate. Approximately similar structure and phase transformations were observed in high dose irradiated 16Cr12MoWSiVNbB steel, Table 2.

The properties of 12% Cr steels, namely, 16Cr12MoWSiVNbB and 1Cr12Mo2NbVB, discussed in the paper demonstrate that:

1. These steels that have found a wide application in commercial and experimental fast reactors at temperatures within 270–650°C and the damage doses up to 142 dpa may be considered to be candidate structural materials for the first wall and the DEMO Fusion Reactor blanket.
2. 12% Cr steels and their welded joints are prone to long temperature irradiation embrittlement (LTIE) in the

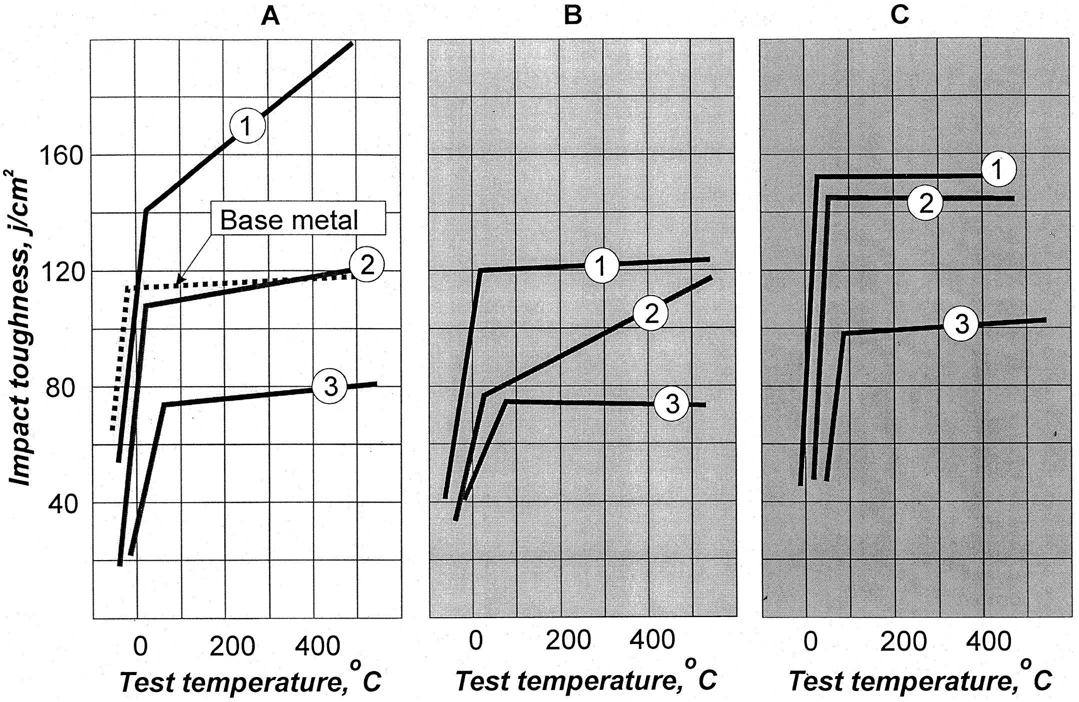

Fig. 6. Influence of ageing and in-pile irradiation at 450°C and >30 dpa on T_c shift in different alloyed weld joints. The compositions of weld joint metal are: A – 16Cr12MoWSiVNbB, B – 14Cr12MoWSiVNbB, C – 10Cr12NiMoWSiVNbB. 1 – initial condition, 2 – isothermal heating, 3 – irradiation.

Table 2
Phase composition of 16Cr12MoWSiVNbB type steel

Condition	Phase	Lattice type	Lattice parameter (nm)
Before irradiation	$M_{23}C_6$	FCC	1.064
	Nb (C,N)	FCC	0.444
	V (C)	FCC	0.415
	Laves phase	HCP	a – 0.470
	Fe_2 (Mo,W)		b – 0.770
	α^1-phase	BCC	0.287
After irradiation	$M_{23}C_6$	FCC	1.063
	Nb (C,N)	FCC	0.442
	V (C)	FCC	0.415
	α^1-phase	BCC	0.287
	χ-phase	BCC	0.890

range of 270–350°C. However, this phenomenon shows up at the damage doses up to 10–30 dpa after which some recovery of their strength properties and impact strength is observed. The higher purity of the metal in terms of harmful impurities and a lower content of the δ-ferrite in the initial structure reduces the tendency of the steels and their welded joints for LTIE.

3. The discussed 12% Cr steels irradiated to 100–110 dpa are not susceptible to vacancy-induced swelling. However, at 120–142 dpa the swelling is observed at a temperature of 400°C; its rate is an order of magnitude lower than that of austenitic steels as cold-worked and for 1Cr12Mo2NbVB steel it is (0.05–0.07)%/dpa.
4. 12% Cr steels are not prone to high temperature irradiation embrittlement (HTIE). When high fluence irradiated the steels show ductility at the test temperature above 650°C.

References

[1] A.G. Ioltukhovsky, V.P. Kondrat'ev, M.V. Leont'eva-Smirnova et al., J. Nucl. Mater. 233–237 (1996) 299.

[2] A.G. Ioltukhovsky, M.V. Leont'eva-Smirnova, A.V. Kozlov et al., Proceedings of the International Conference on Radiation Material Science, Kharkov, USSR, vol. 7, 1990, p. 139.

[3] K.A. Lanskaya, E.N. Gorhakova, M.V. Leont'eva-Smirnova et al., An influence of alloying on structure and properties of 12%-chromium steel 18Cr12WMoNbVB, High-grade Steels and the Ways of Improving their Behaviour, 1988, pp. 81–85.

[4] V.S. Khabarov, S.I. Porollo, A.M. Dvorjashin, IV Conference of Radiation Materials Science, Dimitrovgrad, vol. 3, 1996, p. 122.

[5] A.G. Ioltukhovsky, M.V. Leont'eva-Smirnova, V.S. Ageev et al., The Third Conference on Reactor Material Science – Collection of Reports, Dimitrovgrad, RF, 1994, p. 56.

[6] Yu.I. Kazennov, E.A. Krylov, A.V. Minrev, R.Kh. Gnibadullin, V.V. Brovko, J. Nucl. Mater. 233–237 (1996) 299.

[7] S.A. Averin, A.V. Kozlov, E.A. Medvedeva, Physical-mechanical properties of stainless steel EP 450 as high dose irradiated in reactor BN-600 to 108 dpa, Investigation of Structural Materials of Fast Reactor Core Components, Publication of Russian Academy of Sciences, Ural Section, Ekaterinburg, 1994, pp. 160–167.

[8] V.N. Karaulov, T.Y. Shkol'nik, Proceedings of the International Conference on Radiation Material Science, Alushta, May 22–25 1990, vol. 8, Kharkov, 1991, p. 132.

[9] V.S. Khabarov, A.M. Dvoriashin, S.I. Porollo, J. Nucl. Mater. 233–237 (1996) 236.

[10] O.V. Borodin, V.V. Bryk, V.N. Voevodin, J.M. Neklydov, J. Nucl. Mater. 207 (1995) 295.

[11] V.S. Khmelevskaya, A.G. Ioltukhovsky, A.Y. Malynkin et al., Atomn Energ 63 (1987) 318.

[12] S.A. Averin, A.V. Kozlov, V.A. Tsygvintsev, E.N. Ushakova, E.A. Medvedeva, IV Conference of Radiation Material Science, Dimitrovgrad, vol. 3, 1996, p. 131.