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Cr–Ni alloys for fusion reactors

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Abstract

Results of comparative study on the physical and mechanical properties, radiation and corrosion resistance of XHM-1 chromium-enriched alloy (44% Cr, Ni-base, 1–2% Mo, Registered name "Bochvalloy") and stainless steels (00Cr16Ni15Mo3Nb, 06Cr18Ni10Ti) in the water coolant at temperature up to 350°C have been presented. The XHM-1 alloy is absolutely stable against corrosion cracking, which differs from the behavior of the stainless steels listed. Under tensile stress reaching the yield strength of the material, no corrosion-induced damage of the alloy has occurred in water with various chloride and oxygen contents at a temperature in the range of 50–350°C. In most of the cases, both change of the mechanical strength and relative elongation is not observed after irradiation of the alloy with a dose up to 32 dpa at a temperature of 350°C, which is another distinctive feature of the alloy, as compared to the steels. Concerning totality of the properties, the XHM-1 alloy is very promising material for water cooled fusion reactor components. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

In recent years much experience has been got in operating structural materials in water cooled nuclear power facilities at temperatures up to 350°C. Along with Zr-alloys, austenitic stainless steels have also found wide use as those structural materials [1,2].

However, the austenitic steels have a substantial disadvantage, that is they are liable to stress corrosion cracking (SCC) in water coolants [1]. For this reason, SSC RF-VNIINM searched for the material resistive to SCC. It was shown [3,4], that the XHM-1 alloy (44% Cr, Ni-base, 1–2% Mo, Registered name "Bochvalloy") meets the requirement.

This paper represents results on comparative tests of XHM-1 alloy and various austenitic steels.

2. Results of experiments

Tensile properties of the tubes made of XHM-1 alloy and 00Cr16Ni15Mo3Nb and 06Cr18Ni10Ti steels are given in Table 1. One can see the ultimate tensile strength σ_u and yield strength $\sigma_{0.2}$ of the alloy being higher than those of steel. Total elongation δ_{tot} of the alloy at 20°C is similar to the value for steel, whereas at the temperature of 350°C the elongation is somewhat higher than the value for steel.

The impact toughness of Charpy specimens of XHM-1 alloy exposed to temperature of 300°C and 350°C for 30 000 h does not substantially vary (Table 2). The alloy is structurally stable in the range of temperature of 300–350°C.

No structural changes were detected in XHM-1 alloy samples tested at 360°C with the exposition time up to 80 000 h. Fig. 1 summarizes the results of the ultrasonic acoustic measurements of elastic modulus in the temperature range up to 600°C for the samples after 20% and 40% pre-deformations (rollings). The temperature changings (linearity and hysteresis under

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Table 1
Tensile properties of XHM-1 alloy and 00Cr16Ni15Mo3Nb and 06Cr18Ni10Ti austenitic steels

Material	20°C			350°C		
	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)
XHM-1 tubing	840–1240	580–890	35–44	650–900	340–810	20–39
Mean value	960	660	40	790	490	32
00Cr16Ni15Mo3Nb tubing	530–690	–	37–59	410–540	220–310	17–37
Mean Value	590	–	42	460	250	24
06Cr18Ni10Ti tubing	540–800	–	42–64	410–530	190–360	36–53
Mean value	640	–	55	460	260	41

Note: The tabulated tensile properties are mean results of testing several ingots of each material.

heating–cooling processes) are very good indexes of temperature stability of alloy microstructure. It follows from Fig. 1 the changings of the Young modulus are linear and no temperature hysteresis is observed.

Study on the effect of neutron irradiation (fluence up to 32 dpa) on the tensile properties of XHM-1 alloy [4] has shown that the ultimate tensile strength, yield strength and, especially, total elongation δ_{tot} and uniform elongation δ_u at irradiation temperatures up to 350°C and subsequent testing temperatures up to 500°C vary to a little extent (Fig. 2). Hence, low temperature radiation embrittlement does not occur in the alloy.

This indicates a much higher irradiation resistance of the alloy as compared to austenitic stainless steels of 316, 304 and other types [4,5].

This radiation resistance of XHM-1 can be explained considering the data on structural transformation.

Transmission electron microscopy [4] indicates the structure of XHM-1 after neutron irradiation with a fluence of 2×10^{22} neutr/cm^2 ($E > 0.1$ MeV) at 300°C being substantially different from the structure of 00Cr16Ni15Mo3Nb steel (type 316) after irradiation with a fluence of 5×10^{21} neutr/cm^2 ($E > 0.1$ MeV) at similar temperature. The dislocation loop diameter in the XHM-1 is two or three times longer while the dislocation loop density ρ is an order of magnitude lower as compared to 00Cr16Ni15Mo3Nb steel (ρ for the steel is $\sim 3 \times 10^{16}$ cm^{-3} and for the alloy it is some 3×10^{15} cm^{-3}) despite the fact that XHM-1 was exposed to a higher fluence (a factor of 4) as compared to steel [4].

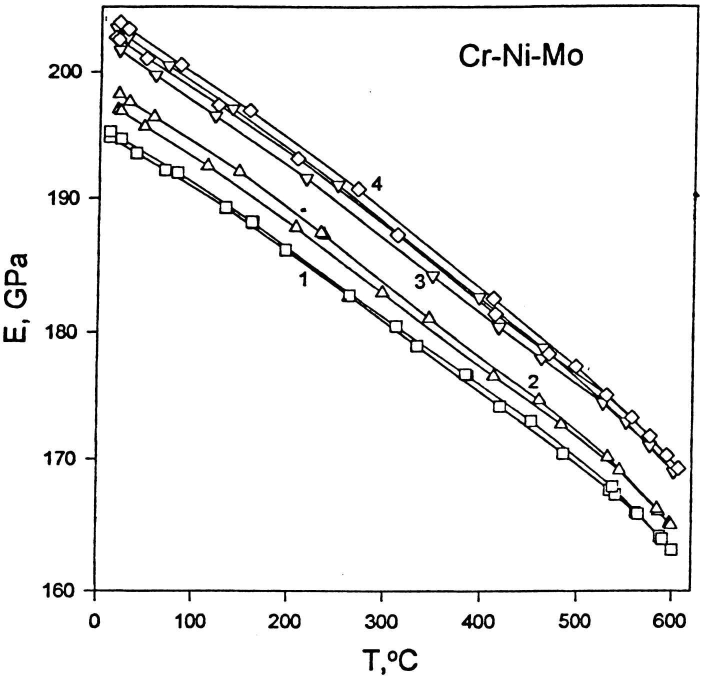

Fig. 1. Temperature dependence of Young modulus at heating–cooling of the XHM-1 alloy. 40% (1) and 20% (2) pre-deformations of samples perpendicular to the rolling direction; 40% (3) and 20% (4) pre-deformations of samples parallel to the rolling direction.

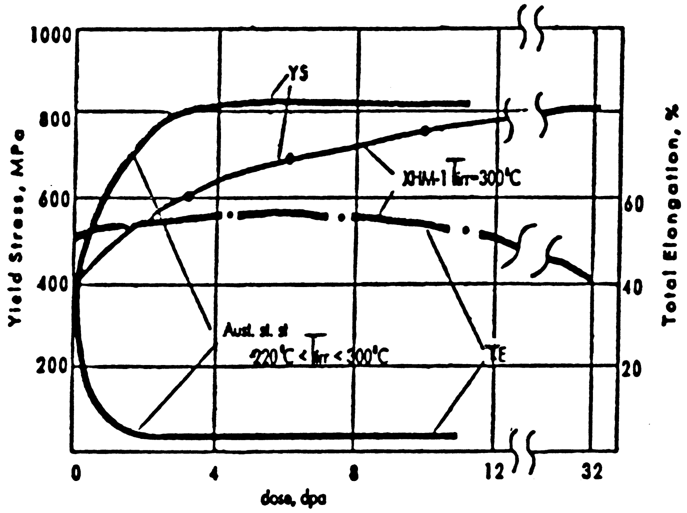

Fig. 2. Effect of irradiation on tensile properties of different austenitic stainless steels and XHM-1 alloy.

A lower dislocation density in the XHM-1 and larger size of loops cannot result in formation of a barrier high enough to prevent the motion of dislocations under loading, which takes place in steel. Therefore, the radiation-induced hardening of the alloy does not almost reveal. Although, much more transmutation helium should arise due to higher Ni content in the XHM-1 alloy, the produced helium does not affect the alloy properties.

Based on testing with the help of different techniques, the XHM-1 alloy is found to be much superior to austenitic steels concerning its corrosion resistance in water or steam containing additives of chloride ions as well as in other aggressive media.

The XHM-1 alloy and a number of austenitic steels were tested for intercrystalline corrosion cracking in an aqueous solution of chlorides by the "ampoule" technique. Tubes of 6–8 mm diameter and 0.3 mm of wall thickness have been used. Before testing the internal stress in tubes were induced by the tube mandrelling of 10–15% of diameter. Pulling a cone mandrel inside a tube results in diameter increase accompanying a small reduction of tube length. The similar deformation leads to a high internal stretching stress in axial direction of the tube.

Twice-distilled water with $FeCl_3$ additive is poured into 200 mm long ampoules (filled up to 50% of volume) made of tubes. Then these ampoules are welded and placed with a welded acoustic line into a furnace in a vertical position. The mean testing temperatures are maintained in the ranges of 150°C and 300–320°C. In the testing, the pressure in an ampoule reaches 70–80 Mpa (300–320°C) causing axial stretching stress.

The method of acoustic emission was applied to study mechanisms and kinetics of destruction caused by action of the medium [6]. It is based on registration of acoustic emission caused by corrosion, deformation and destruction of material with the help of a piezoelectric transducer.

Ampoules are periodically weighed to examine their integrity. Weight reduction indicates the through crack. To determine the length of the crack a technique of electrical resistance measurements along the ampoule was applied [6].

Specimens of 316, 08Cr18Ni10Ti, 00Cr16Ni15-Mo3Nb steels and XHM-1 alloy were tested (Fig. 3). The results of ampoule testing at a temperature of 300°C [3] show that, in spite of certain differences among the steels concerning the incubation time of crack initiation and lifetime before destruction, the steels are almost similar with respect to corrosion resistance. At the testing temperature of 150°C, the lifetime before destruction is about 3–4 times higher but retains very low values. Moreover, acoustic pulses caused by corrosion processes are detectable at a temperature exceeding 50°C. None of the ampoules made of XHM-1 alloy show corrosion cracking, even after 86 000 h.

To assess the effect of simultaneous action of the neutron irradiation, mechanical stress and corrosion-active coolant on the deformation ability, in-pile testing of tubular samples under conditions of rigid and soft loading (Tables 2 and 3) has been carried out.

Table 2 represents the results of testing of tubular specimens made of XHM-1 and 00Cr16Ni15Mo3Nb steel under rigid loading. For rigid loading the solids swelling under neutron irradiation were used. The experimental results indicate the ability of the material to deform at the rate of about 10^{-6} h^{-1} up to a considerable dose. One can see (Tables 2 and 3), that the fracture of the steel specimens starts at a dose of 1–2 dpa, whereas

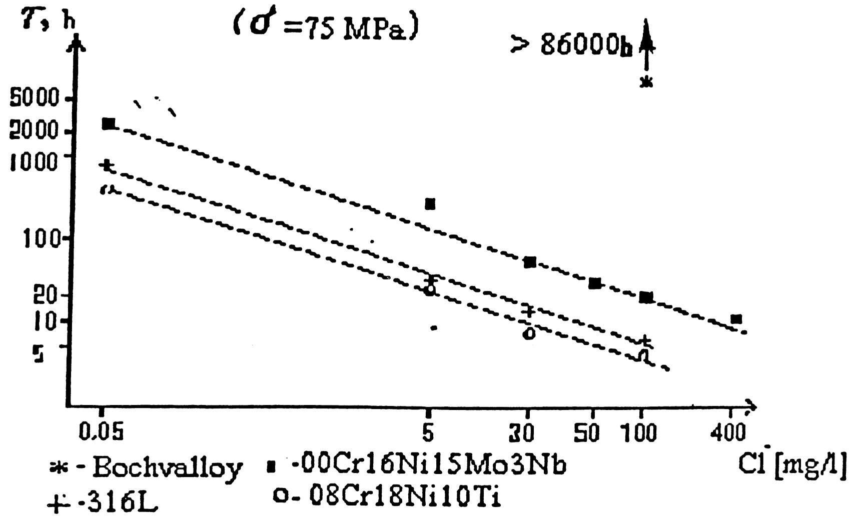

Fig. 3. Long-term corrosion resistance of austenitic steels and XHM-1 alloy at the testing temperature of 300°C in water and 75 MPa of stretching pressure.

Table 2
Results of tests of tubular 00Cr16Ni15Mo3Nb and XHM-1 specimens irradiated at 300°C in water under rigid loading

Material		Irradiation dose (dpa)/effective irradiation time (h)	
		<1/1830	5/12000
XHM-1	Number of specimens in test	4	6
	Number of cracks detected	0	0
	Diameter increase, (%)	0.9–1.2	2.7–3.1
00Cr16Ni15Mo3Nb	Number of specimens in test	6	8
	Number of cracks detected	0	8
	Diameter increase, (%)	0.7–1.4	0.7–1.4

the XHM-1 specimens withstand doses more than 5 dpa without fracture; the strain of the XHM-1 specimens being several times higher than the values for the steel.

In Table 3 the results of testing of tubular specimens with respect to deformation ability under soft (helium) loading and irradiation are given. In this case, tubular specimens with welded capillaries were placed in a water loop of the reactor and initially filled with helium up to a pressure of 200 MPa, after which the pressure was being increased with a step of 3–10 MPa according to the program specified. Considering the stress dependence of the yield strength, the program prevents plastic deformation at the early stages of irradiation.

One can see (Table 3) that at a dose of 3 dpa the total strain of 00Cr16Ni15Mo3Nb steel specimens was equal to 0.5%, and all the specimens broke. Under similar testing conditions the XHM-1 specimens reveal a total deformation of 6.8% without fracture.

Table 3
Results of in-reactor tests of tubular specimens under soft loading conditions ($T_{test} = T_{irr} = 300$°C, coolant: water)

Materials	Properties	Irradiated dose, (dpa)		
		0 [a]	2	3
XHM-1	Fracture stress (MPa)	760	950	1070
	δ total (%)	17	6.5	6.8
	δ uniform (%)	14	5.5	5.2
00Cr16Ni15Mo3Nb	Fracture stress (MPa)	480	700	790
	δ total (%)	16	1.2	0.5
	δ uniform (%)	12	0.6	0.2

[a] The tests of witness specimens were conducted by loading with water heated in autoclaves.

The XHM-1 is fabricable and possesses a good weldability. The properties of its weld joints are close to the properties of the base metal. Also, XHM-1 can be welded with austenitic steels of 316 type. As nickel based alloy, XHM-1 has an advantage concerning joints with copper alloys of outer layer of the first wall.

3. Conclusion

1. After thermal aging for a time exceeding 30,000 h at temperatures up to 350°C, the XHM-1 alloy is structurally stable and its tensile properties do not change.
2. Structure of the XHM-1 alloy after neutron irradiation to a high fluence differs significantly from the structure of irradiated austenitic steel; the density of irradiation induced defects (dislocation loops) in the XHM-1 is of an order of magnitude lower, whereas loop diameter is about 2–3 times longer as compared to steel of 316 type. The XHM-1 alloy after irradiation up to a fluence of 32 dpa does not suffer low temperature irradiation embrittlement. The total elongation of the XHM-1 alloy after irradiation up to a fluence of 10 dpa in the temperature range of 100–350°C is about 4–5 times higher than the values for steel of 316 type.
3. Corrosion testing in water coolant with the chloride content of various magnitude at the temperature of 150°C and 300°C shows no corrosion cracking of XHM-1 alloy, even after 86 000 h of testing, whereas all specimens made of austenitic steels (316 type) suffer corrosion cracking after tens or hundreds of hours.
4. Testing series involving simultaneous action of the neutron irradiation, mechanical stress and aggressive medium (coolant) show that the XHM-1 does not suffer corrosion cracking and possess high deformation ability. None of XHM-1 specimens has broken whereas all specimens of austenitic steels of 316 type failed at the time and fluence of an order of magnitude lower than the highest parameters for testing of XHM-1 specimens.
5. Concerning totality of the properties, the XHM-1 alloy is a very promising material for water cooled fusion reactor components.

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