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Heat resistant reduced activation 12% Cr steel of 16Cr12W2VTaB type-advanced structural material for fusion and fast breeder power reactors

A.G. Ioltukhovskiy [a,*], M.V. Leonteva-Smirnova [a], M.I. Solonin [a], V.M. Chernov [a], V.N. Golovanov [b], V.K. Shamardin [b], T.M. Bulanova [b], A.V. Povstyanko [b], A.E. Fedoseev [b]

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

[b] RIAR, 433510, Dimitrovgrad-10, Ulyanovsk Region, Russia

Abstract

Heat resistant 12% Cr steels of the 16Cr12W2VTaB type (12Cr-2W-V-Ta-B-0.16C) provide a reduced activation material that can be used as a structural material for fusion and fast breeder reactors. The composition under study meets scientific and engineering requirements and has an optimal base element composition to provide a δ-ferrite content of no more than 20%. It also has a minimum quantity of low melting impurity elements and non-metallic inclusions. Short-term tensile properties for the steel tested to 700 °C are provided after the standard heat treatment (normalization, temper). Rupture strength and creep properties for the steel depending on the initial heat treatment conditions are also given. The microstructural stability of the 16Cr12W2VTaB type steel at temperatures up to 650 °C is predicted to be good, and the properties of the steel after irradiation in BOR-60 are demonstrated.

1. Introduction

The purpose of this work is to develop heat resistant ferritic–martensitic 12% Cr steels characterized by reduced long-term activation. Being a dual purpose material it may be used both for the components of the first wall and blanket of a DEMO reactor and the ITER reactor test module as well as for the components of fast breeder power reactor cores such as fuel cladding or fuel assembly wrappers [1–3].

2. Background

Calculations [3] have been performed for the model compositions of reduced activation 12% Cr steels of the 16Cr12W2VTaB type (Table 1) to determine the level of radio-activation in the neutron field of the DEMO fusion reactor. These materials do not contain the most activation susceptible elements such as Ni, Mo and Nb as well as a limited amount of Ag, Co and Cu impurities. Under irradiation, gaseous products (He and H) are also formed in the steel; the build-up of these gaseous impurities may reach hundreds of appm. Irradiation does not alter the concentrations of oxygen, nitrogen, sulphur or phosphorus. The influence of these elements on the ductile properties of steels will thus be governed by their initial concentrations. This is of practical significance in the selection of the charge materials during metallurgical manufacture of reduced activation steels.

The main prototype for these steels is a class of ferritic–martensitic 12% Cr steels being widely used in the Russian Federation nuclear power program. These are primarily activation susceptible steels with various combinations of alloying elements such as Mo, V, W, Nb, B, etc. [1–3]. The attractiveness of these materials is

* Corresponding author. Tel.: +7-095 190 2375; fax: +7-095 196 4168/6591.

E-mail address: iral@bochvar.ru (A.G. Ioltukhovskiy).

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their high yield strength, adequate ductility and heat resistance up to 600–650 °C (which is somewhat lower compared to austenitic Cr–Ni steels), and adequate irradiation resistance at 300–650 °C (absence of swelling up to 100 dpa, irradiation creep up to 550 °C and high temperature irradiation embrittlement (HTIE)) [1–3,5–8].

The major limitation inherent in these steels is their propensity for low temperature irradiation induced embrittlement (LTIE). This shows up as both a shift in the ductile-to-brittle transition temperature under irradiation to higher temperatures and as significantly lower values of per cent elongation. This effect is prominent in the narrow temperature range (270–400 °C). Currently we have carried out experiments and tests to study LTIE. It has been demonstrated that there are actually ways to reduced this effect, such as vacuum melting of the metal with higher purity charge materials, as well as use of the steels in the optimal metallurgical condition.

Another limitation of the 12% Cr steels is a drastic (3–4 times) increase in creep rate under irradiation at 600 °C and higher [3]. For this reason, special attention has been focused on the improvement of the heat resistance characteristics at high temperatures while developing new reduced activation steels.

3. Recent property measurements and product forms

This paper presents the properties of the two commercial 16Cr12W2VTaB steel heats (Table 1). A characteristic feature of the materials is the purity in terms of activation response, impurities and low melting elements, which are major limits for low activation steels. Accordingly:

- the impurity content (wppm) of these steels complies with the current limits of no more than: Cu – 0.01; As – 0.005; Pb – 0.0005; Sn – 0.001;
- their microstructure complies with current standards;
- non-metallic inclusions do not exceed the usual level for Cr steels made by similar melting methods.

The following metal products have been fabricated: hot-rolled sheet 6 mm thick and 12 mm diameter rod (thermally treated). The microstructures of these 16Cr12W2VTaB steel products have been partially investigated. Both products have a ferritic–martensitic structure (δ-ferrite content is lower than 20%) with some formation of $M_{23}C_6$ and M(C, N) [4].

The following unirradiated mechanical properties have been determined. The short-term mechanical properties (σ_u – ultimate stress, $\sigma_{0,2}$ – yield point, δ – total elongation, ψ – reduction in area) were determined based on tests over the range 20–700 °C as shown in Fig. 1. The absorbed energy measured in impact test on u-notched specimens in the range −196 to +300 °C is shown in Fig. 2. Tests for the creep and long-term strength of the 16Cr12W2VTaB type steels were carried

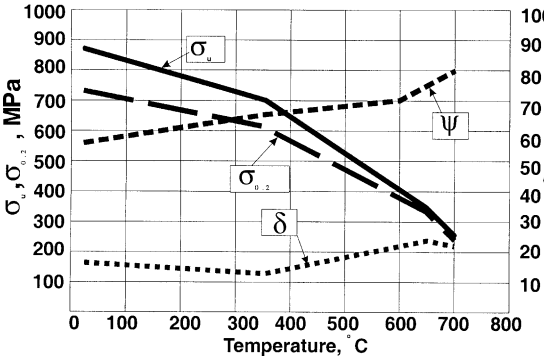

Fig. 1. Temperature dependencies of mechanical properties of steel 16Cr12W2VTaB (heat 1). σ_u – ultimate stress, $\sigma_{0.2}$ – yield point, δ – total elongation, ψ – reduction in area.

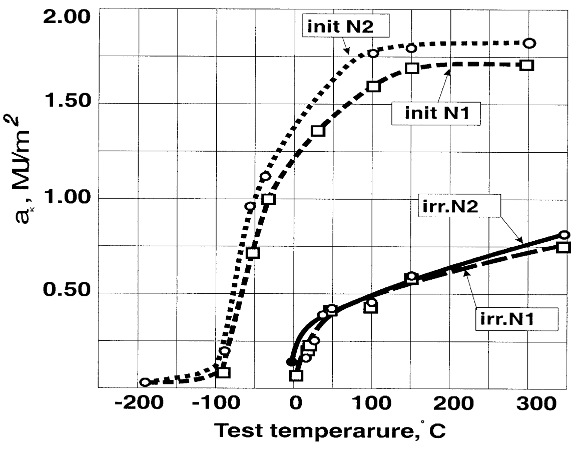

Fig. 2. Temperature dependence of absorbed energy ($\mathbf{a_k}$) of steel 16Cr12W2VTaB (heats 1 and 2) before (init Nl, init N2) and after (irr Nl, irr N2) BOR-60 irradiation.

Table 1
Chemical composition (% mass) of the 16Crl2W2VTaB type steel heats

Heat	C	Si	Mn	Cr	Ni	Mo	W	V	Nb	Ta	B	N	Ti	Zr	Cu	Co
1	0.14	0.37	0.94	11.2	<0.01	⩽0.01	1.1	0.29	<0.01	0.17	0.004	0.044	0.02	0.06	⩽0.01	⩽0.01
2	0.13	0.37	0.73	11.4	<0.01	⩽0.01	1.17	0.28	<0.01	0.18	0.005	0.024	0.04	0.07	⩽0.01	⩽0.01

Table 2
Long-term strength and creep tests for the 16Cr12W2VTaB type steel at $T = 650$ °C

Heat	Thermal treatment	Stress (MPa)	Damage time (h)	Established creep rate (%/h)	Comments
1	Normalization 1050 °C, 1	100	2384	5.0×10^{-4}	$\delta = 24.4\%$, $\Psi = 87\%$
	h + Tempering 720 °C, 3 h	120	980	3.3×10^{-3}	$\delta = 21.1\%$, $\Psi = 83\%$
1	Normalization 1100 °C, 1	80	>7800	9.1×10^{-5}	Tests still in progress
	h + Tempering 720 °C, 3 h	100	>7300	2.1×10^{-4}	Tests still in progress
		120	2935	3.3×10^{-4}	$\delta = 22.6\%$, $\Psi = 87\%$
2	Normalization 1050 °C, 1	80	>6300	1.07×10^{-4}	Tests still in progress
	h + Tempering 720 °C, 3 h	100	>7400	2.6×10^{-4}	Tests still in progress
		120	>1582	1.1×10^{-3}	Tests still in progress

Table 3
Mechanical properties at 20 °C of 16Cr12W2VTaB[a] type steels (heats 1 and 2) irradiated in the BOR-60 reactor

Heat	Irradiation conditions		σ_u (MPa)	$\sigma_{0.2}$ (MPa)	Uniform elongation (%)	Total elongation δ (%)
	T_{irr} (°C)	Damage dose (dpa)				
1, initial		0	764	653	5.3	19.2
1, irradiated	325	6.0	1136	1124	0.5	2.3
	330	8.2	1173	1153	0.5	5.3
2, initial		0	829	728	4.6	19.8
2, irradiated	335	8.0	1165	1144	0.5	1.8
	345	5.8	1163	1155	0.5	1.8

[a] Thermal treatment: normalization 1050 °C, 1 h + tempering 720 °C, 3 h.

out at 650 °C in air using standard methods and $\varnothing$ 5 × 25 mm diameter cylindrical specimens that were fabricated from the two heats of steel (heats 1 and 2) under different heat treatments. The results are presented in Table 2. It also turned out that an increase in normalization temperature from 1050 to 1100 °C distinctly improved the heat resistance characteristics of the 16Cr12W2VTaB type steel.

Specimens were irradiated in the BOR-60 reactor at 325–345 °C. Tensile tests were performed on cylindrical specimens 28 mm long and 3 mm in diameter given the following thermal treatments normalization 1050 °C, 1 h + tempering 720 °C, 3 h. The first test results are shown in Table 3. At 20 °C following irradiation to a dose of 5.8–8.2 dpa, the steels are observed to increase in hardness and decrease in ductility, which is common for other 12% Cr steels as well [1–3,5]. Impact tests were performed on u-notched specimens (5 × 10 × 55 mm) fabricated from 16Cr12W2VTaB steels (heats 1 and 2) irradiated in the BOR-60 reactor at 325–345 °C to a dose of 5.8–8.2 dpa (Fig. 2). Low temperature neutron irradiation of the 16Cr12W2VTaB steel causes large LTIE effects [3,5], also common for the other 12% Cr steels. The DBTT shift is 80–90 °C at an absorbed energy value of 0.40–0.60 MJ/m^2 for the 16Cr12W2VTaB steel (Fig. 2).

4. Conclusion

A heat resistant low activation 12% Cr steel with the Ti and Zr microalloying has been developed. Its commercial manufacture ensures improved purity of the steel in terms of the impurities (S, P, O, etc.) and low melting elements (Cu, Pb, Sn, etc.).

The metallurgical structure as well as the short-term and long-term mechanical properties of the steel were examined. Initial results for the behaviour 16Cr12W2VTaB steel after irradiation in the BOR-60 reactor at 325–345 °C to a dose of 5.8–8.2 dpa were obtained.

The investigations show that these compositions and heat treatments lead to increases in creep resistance. This effect shows up particularly well in a heat normalized at a higher temperature (1100 °C). This apparently is explained by a finer dispersion of particles such as M(C, N) and by slowing down the coarsening of these particles in the process of thermal aging under stress in a heat with high nitrogen content (heat 1).

The measures taken to increase the metal purity in terms of non-metallic and low melting impurities (S, P, O, Cu, Sn, Pb, etc.) and the optimization of composition and structure of the 16Cr12W2VTaB steel produced lower ductile–brittle-transition-temperature shifts of

80–90 °C in u-notched specimens irradiated at 325–345 °C to doses of 5.8–8.2 dpa.

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