Structural Materials for Fusion Power Reactors – the RF R&D Activities

V.M. Chernov 1), N.I. Budylkin 1), Yu.N. Devyatko 1), A.G. Ioltoukhovskiy 1), M.V. Leonteva-Smirnova 1), E.G. Mironova 1), M.M. Potapenko 1), A.K. Shikov 1), G.N.Yermolaev 1), A.N. Kalashnikov 2), B.V. Kuteev 3), A.I. Blokhin 4), N.I. Loginov 4), V.A. Belyakov 5), I.R. Kirillov 5), T.M. Bulanova 6), V.N. Golovanov 6), V.K. Shamardin 6), Yu.S. Strebkov 7), A.N. Tyumentsev 8), B.K. Kardashev 9), O.V. Mishin 10), B.A. Vasiliev 10)

1) Bochvar Institute, 123060, P.O.Box 369, Moscow, Russia, 2) ROSATOM, Moscow, Russia, 3) Kurchatov Institute, Moscow, Russia, 4) Leypunsky Institute, Obninsk, Russia, 5) Efremov Institute, St-Petersburg, Russia, 6) RIAR, Dimitrovgrad, Russia, 7) Dollezhal Institute, Moscow, Russia, 8) IPSM SB RAS, Tomsk, Russia, 9) Ioffe Institute RAS, St-Petersburg, Russia, 10) OKBM, Nizhniy Novgorod, Russia

e-mail contact of main author: chernovV@bochvar.ru

Abstract. Recent progress in the RF low activation structural materials R&D road map toward DEMO via the FBRs tests (BOR-60, BN-600, BN-800) and TBMs in ITER is overviewed. The properties of the RAFMS RUSFER-EK-181 (Fe-12Cr-2W-Ta-V-B-C) and V-4Ti-4Cr alloys are presented. The next important steps include further studies of the influence of high dose and high temperature irradiation on the properties of base structural materials and joints. Activation, transmutation and radiation damage of the materials in BN-600 and DEMO-RF (Kurchatov institute project) neutron spectra are calculated. The results of the application of the internal friction (ultrasonic) non-destructive method to research the DBTT are in the good correlation with results of the destructive impact method. The important influence of the boron on the heat resistance of materials and the concentration level He under irradiation are calculated. The new special regimes of the heat treatments of the alloys are suggested to widen the temperature windows of applications. The results of the BOR-60 examinations of RUSFER-EK-181 (irradiation temperature 320-340 ^{0}C and doses up to 15 dpa) are presented. The BN-600 projects for the high doses and high temperature irradiation tests of manufactured alloys are presented.

1. Introduction

The two RF concepts of the first wall/blanket in DEMO and beyond (TOCAMAK like) design on the basis of the low activation materials (LAMAs) the RAFMS (solid breeder blanket) and V-4Ti-4Cr alloy (Li-self cooled breeder blanket) are under development (Kurchatov Inst., Efremov Inst., Dollezhal Inst., Bochvar Inst., Leypunsky Inst.) [1-4]. The concepts for the TBM DEMO in ITER are the same as for the RF DEMO ones. The final DEMO concepts choice will be made, with high probability, on the base of the results of the DEMO-test blanket programs for ITER (2015-2020). The RF structure materials R&D program is the part of the RF programs (materials parts) of controlled fusion power (1990-2007, 2008-2022 – under preparation) and the FBRs material programs [2-9]. The main goals are: (1) to obtain industrial structure materials, technology and articles based on their high competitive quality and engineering properties with respect to corresponding materials of USA, EC and Japan; (2) to provide the FBRs BN-600, BN-800 (under construction, 2015) [4, 10] and BN-1800 (project) with such materials; (3) to ensure competitive participation of the RF in realization of national and international projects of TBMs DEMO in ITER (goods ~ 300-500 kg/module) before 2015; (4) to ensure competitive participation of the RF in realization of national and international projects of fusion power reactors (goods ~ 1000 ton/reactor). Development of structure materials will require several iterations of material high dose irradiation (BN-600, BN-800, IFMIF) & alloy modification to manufacture the final materials.

2. DEMO structure materials

The 12%-Cr RAFMS RUSFER-EK-181 (Fe-12Cr-2W-V-Ta-B-C) and V-(4-8)Ti-(4-5)Cr alloys are the reference class of LAMAs for the DEMO concepts and for the TBMs in ITER. Two material systems are widely different in terms of physical and mechanical properties, fabrication methods, and current levels of commercialization. However, they are linked in terms of the allowable major alloying constituents and the degree to which impurities must be controlled in order to develop desirable functional and low activation properties. To identify the neutron and temperature regimes within which the loss of strain-hardening capacity could significantly impact the design of DEMO components, the high dose irradiation experiments in the FBRs (BOR-60, BN-600, BN-800) and fusion neutron source IFMIF are necessary. There is a critical temperature of the irradiation below which the LAMAs (BCC alloys) undergo a relatively sharp transition in fracture behaviour from a ductile-to-brittle failure mode and the DBTT increases under irradiation and some technologies. To research the DBTT shift of LAMAs the internal friction non-destructive method (ultrasonic) was successfully used in the correlation with results of the destructive impact method [11].

Small specimen test technology (SSTT) is used to define the initial and neutron-dose-temperature regimes within which major changes in microstructure and mechanical properties may occur. The small specimen testing provides a useful means of indexing radiation-induced changes in fracture toughness, comparing the relative behaviour of different materials, and assessing the influence of refinements to composition and microstructure. The difference of neutron spectra (different primary recoil spectra) is also very important problem of the R&D of the radiation influence on the materials properties. The levels of the cascade physics, nuclear transmutation (H, He, others), the radiation damage (dpa, H/dpa, He/dpa), nuclear data base for transmutation and damage are very important parts of the R&D of the LAMAs [12-13]. It is very important to use the physical models, computer simulation and calculations and reactor tests to improve the properties of materials. Improvements mainly aim at increasing the material lifetime and expanding its temperature windows range of application under irradiation. All transmutation and radiation damage calculations are based on the complex of the RF nuclear data library ACDAM and recommended by the IAEA code FISPACT-3.0(5). Following the transmutation calculation for DEMO-RF and BN-600 neutron spectra in alloys initial concentrations of N, O, S and P practically do not change, accumulation of gaseous H and He is the most essential for DEMO, accumulation of He weakly depends on the initial concentration of B, initial concentration of B in the alloys remains practically unchanged and B keeps the function of surface active element increasing long-term strength (the heat resistance) of alloys under irradiation. The modelling efforts will greatly depend on computational approaches based of physical models of a microstructure and radiation defects, neutron spectra and computers power [14-17].

The low level irradiation (BOR-60, 6-15 dpa, flux $3x10^{15}$ n/cm^2/s, irradiation temperature 300 – 350 ^{0}C) and post irradiation investigations for the RUSFER-EK-181 have been carried out. The neutron properties of the V-4Ti-4Cr alloy were investigated earlier very carefully (USA, Japan, RF) for low/medium radiation damage [18-19]. It is very important to investigate the functional properties of the LAMAs up to the highest level of the radiation damage (80-160 dpa). The most appropriate irradiation facility is the RF BN-600 [10] (neutron flux $6.5x10^{15}$ n/cm^2/s, irradiation temperature 380-750 ^{0}C) and, in future, BN-800 and fusion neutron source IFMIF.

RUSFER-EK-181. The behaviour and mechanisms of phase-structural transformations in the steel at different technological stages of thermal treatment (TT) of articles are under investigation. The steel meets the basic requirements on quantity ratio “martensite – δ-ferrite” and the structure stability at heating. Two basic types of martensite (lath and laminated) were found in steel structure after quenching. Self-tempering of martensite was also found. Basic structure investigations were performed with traditional thermal treatment (TTT) scheme “normalization + temper”. Steel structure after normalization (1050-1100 ^{0}C) is martensite. The quantity of δ-ferrite is no more than 20%. The structure providing high level of heat resistance with maintenance of enough plasticity is achieved under the regime “normalization at 1100 ^{0}C – temper 720 ^{0}C, 3 hours”. To reduce steel tendency to low temperature irradiation embrittlement the special cyclic thermal treatment (CTT) (the thermal cyclic around the critical point A_{c1}) of articles was developed [7]. Up to-day level of the temperature window for the RUSFER-EK-181 is 350-670(700) ^{0}C. Fabrication of RUSFER-EK-181 in industrial large quantity has little difficulty. The requirement of reduced activation is exceptionally strict about the impurity control of the steels, and some 500-1000 kg ingots were successfully produced within the harmful elements (Mo, Nb, others) well below the required levels. Other fabrication processes, such as heat treatments, shaping and joining, have been also well established. The level of physical, mechanical and technological properties of RUSFER-EK-181 steel allows to recommend it as the core structure material for application in the TBMs DEMO in ITER; DEMO and beyond; BN-600, BN-800 and BN-1800.
V-4Ti-4Cr alloys. For the RF V-(4-8)Ti-(4-5)Cr alloys there are the industrial production for metallic vanadium heats with the very high level of the purity. The experienced V-(4-5)Ti-(4-5)Cr heats (40-50 kg) and the articles from it with the same level (as in heats) of purity were manufactured and researched [9, 20-21]. There are the RF technologies to manufacture V-alloy heats with weight 100-300 kg. Vanadium alloys offer the potential for improved performance compared to steels type RUSFER-K-181, but require further alloy R&D to reach their full potential. The microstructure and composition changes before and during irradiation may engender a degradation of the mechanical properties, leading to hardening, loss of ductility, loss of fracture toughness and creep strength. It has been demonstrated that the TT allows producing phase-structure states with the multiphase and defect substructures showing high degree of dispersion (precipitation) and thermal stability, to elevate the recrystallization temperature by 100–200°, and to improve the low-temperature and high-temperature strength characteristics of alloys with their high plasticity preserved. A promising way for developing radiation-proof vanadium alloys and improving their high-temperature strength is controllable interstitial alloying followed by the special thermo-mechanical treatment to produce structural states with highly homogeneous high-dispersion (precipitation) nonmetallic phases and thermally stable multiphase and defect substructures to realize the temperature window for the alloys 350-800(850) ^{0}C.

3. BN-600 experiment (2007-2011)

To realize the high doses and high temperature irradiation of the LAMAs in BN-600 [10] the working projects have been developed for RUSFER-EK-181: (1) The project BN-600-LAMA-Fe1 (irradiation temperatures 330-700 ^{0}C, doses 40-85 dpa (560 days), number of samples of various types is 250 (SSTT), flowing and static sodium environment; (2) The project BN-600-LAMA-Fe2 (the same as the BN-600-LAMA-Fe1, but doses 80-170 dpa, irradiation time 1120 days); and for V-(4-8)Ti-(4-5)Cr alloys: The project BN-600-LAMA-V (irradiation temperatures 400-750 ^{0}C, doses 50-110 dpa (560 days), four hermetic capsules filled with samples and lithium (^{7}Li), number of samples of various types is 440 (SSTT)). Maximum error of specimen temperature measurements at 95 % confidence level is ± 12 ^{0}C and ± 25 ^{0}C for lower and upper parts of the container with specimens, respectively. Properties of the irradiated specimens under examination: elastic and plastic; short-time mechanical; swelling; irradiation creep (pressure tubes); impact ductility; the DBTT; crack-resistance; corrosion; structural and phase transformations. Some results of the above mentioned R&D are presented in Tabl. 1-2 and Figs 1-10.

TABLE I: CALCULATED FORMATION E^F AND MIGRATION E^M ENERGIES (eV), RELAXATION VOLUME V^R(O) (O – ATOMIC VOLUME) FOR VARIOUS DEFECT CONFIGURATIONS IN V AND Fe CRYSTALS.

Defect configuration	V			Fe		
	E^F	E^M	V^R	E^F	E^M	V^R
<110> dumbbell	3.13	0.17	0.98	4.38	0.25	1.48
<110> dumbbell saddle point	3.30		1.07	4.63		1.48
<111> dumbbell	3.28	0.01	1.17	4.63	0.01	1.44
Crowdion	3.29		1.20	4.64		1.44
Vacancy	2.50	0.48	-0.16	1.92	0.74	-0.14
Vacancy saddle point	2.98		-0.28	2.66		-0.11
Divacancy 1st NN*	4.96		-0.21	3.76		-0.24
Divacancy 2nd NN*	4.72	0.52	-0.23	3.63	0.70	-0.36
Divacancy 4th NN*	4.95		-0.27	3.80		-0.29
Divacancy saddle point	5.25		-0.35	4.33		-0.35
Di-SIA**	5.62		2.28	7.88	0.17	2.84
*NN – nearest neighbour; ** SIA – self interstitial atom						

TABLE II: RADIATION DAMAGE DOSE K_dt, H AND He CONCENTRATIONS IN PURE VANADIUM AND IRON CRYSTALS (V/Fe) FOR DIFFERENT NEUTRON SPECTRA (IRRADIATION TIME IS 560 EFFECTIVE DAYS IN ALL CASES).

Neutron source, (n/cm^2/s, E>0)	K_dt, dpa	H, appm	He, appm	H/K_dt	He/K_dt
ITER ($3.45{\cdot}10^{14}$)	13.02/12.43	240.1/451.3	39.14/118.1	18.45/36.32	3.01/9.50
DEMO-RF ($9.00{\cdot}10^{14}$)	23.49/23.32	580.6/1084.0	97.43/286.1	24.72/46.19	4.15/12.19
GDT-NS ($1.00{\cdot}10^{14}$)	4.04/3.83	86.4/148.83	12.90/40.6	21.38/38.83	3.19/10.59
IFMIF ($6.71{\cdot}10^{14}$)	43.69/41.78	684.4/1552.0	133.8/360.8	15.66/37.14	3.06/8.64
BN-600 ($6.50{\cdot}10^{15}$)	122.1/92.20	19.59/241.5	1.09/13.65	0.16/2.62	0.01/0.15
BOR-60 ($3.00{\cdot}10^{15}$)	91.31/73.73	24.15/297.8	1.35/16.91	0.26/4.04	0.02/0.23
IVV-2? ($5.29{\cdot}10^{14}$)	6.96/5.355	2.051/24.29	0.12/1.455	0.29/4.52	0.02/0.27

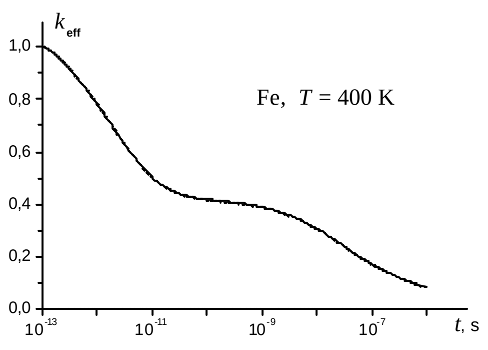

FIG. 1a. Factor k_{eff} of the defect formation by cascade (coefficient of the cascade efficiency) vs. time t (s) curve (Fe , the primary recoil energy E_{pr}=60 keV, cascade formation time t=0, crystal temperature 400 K).

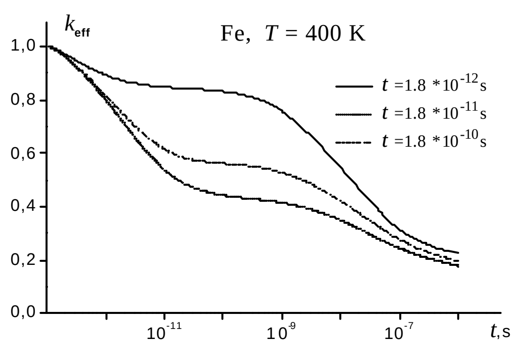

FIG. 1b. Factor k_{eff} of the defect formation by cascade (coefficient of the cascade efficiency) vs. time t (s) curves for different time (t, s) of the changing of thermal conductivity mechanism (phonon to electron) (Fe, the primary recoil energy E_{pr}=5 keV, crystal temperature 400 K).

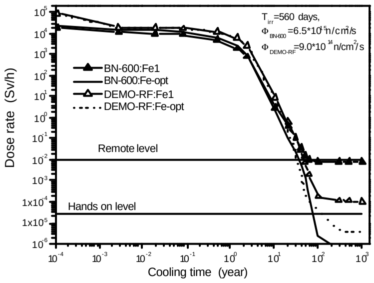

FIG. 2a. RUSFER-EK-181. Activity decay in "recommended" (Fe-opt) and manufactured (Fe1) compositions "irradiated" in BN-600 and DEMO-RF (irradiation time is 560 effective days in both cases).

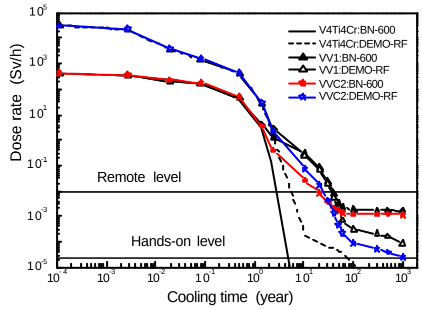

FIG. 2b. V-4Ti-4Cr. Activity decay for "pure" (V-4Ti-4Cr), recommended (VV1) and manufactured (VVC2) compositions "irradiated" in BN-600 and DEMO-RF (irradiation time is 560 effective days in both cases).

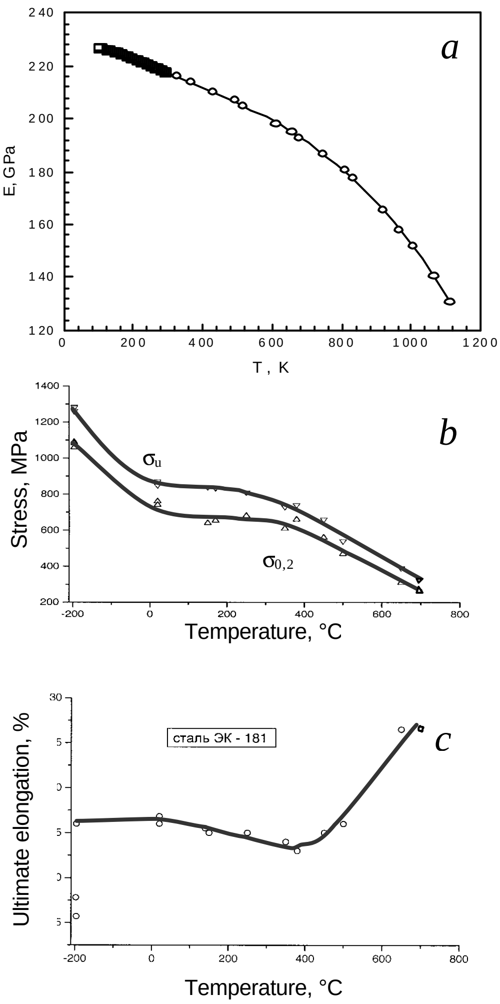

FIG. 3. RUSFER-EK-181. Mechanical properties of the specimens (TTT) vs. temperature curves: (a) elastic module (E, GPa), (b) yield point ($s_{0.2}$, MPa) and ultimate stress (s_u, MPa), (c) ultimate elongation (%).

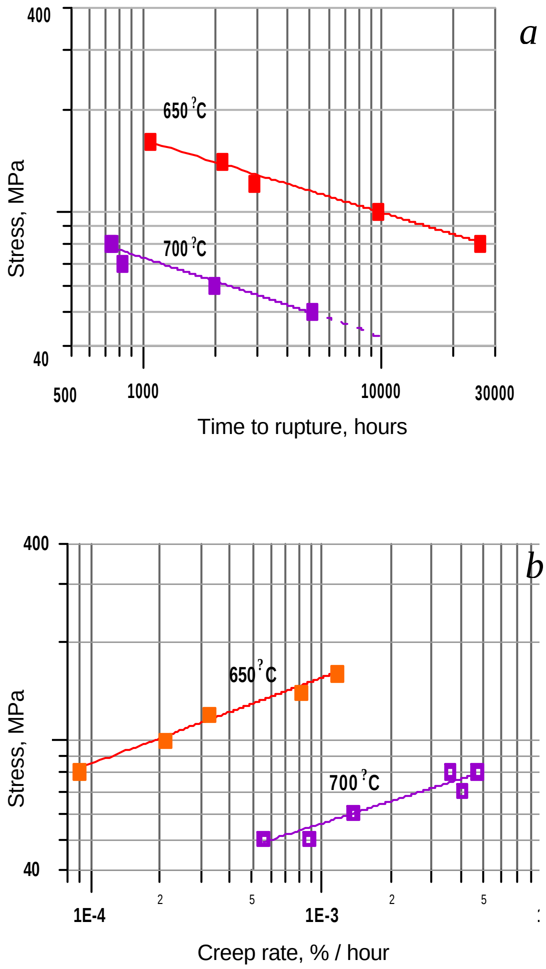

FIG. 4. RUSFER-EK-181. Time of the creep-rupture time (hours) (a) and creep rate (%/hour) (b) of the specimens (TTT) under temperature 650 ^{0}C and 700 ^{0}C in dependence from stress (MPa).

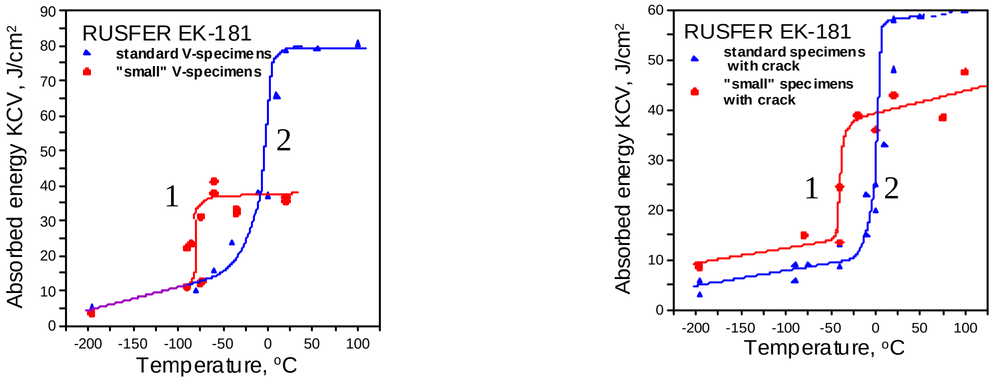

FIG.5. RUSFER-EK-181. Charpy impact energy vs. test temperature curves for small (1) and standard (2) specimens (TTT) without and with crack.

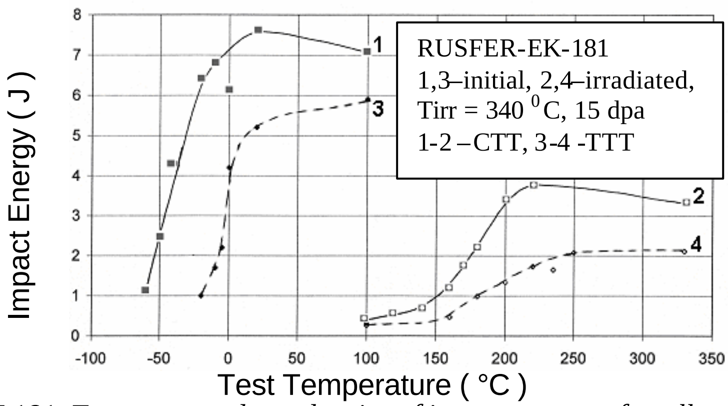

FIG. 6. RUSFER-EK-181. Temperature dependencies of impact energy of small specimens (v-Charpy-KLST) with different thermal treatments (1-2 – cyclic thermal treatment – CTT, 3-4 – traditional thermal treatment – TTT) before (1, 3) and after (2, 4) irradiation in BOR-60 reactor (radiation damage 15 dpa, irradiation temperature 340 °C).

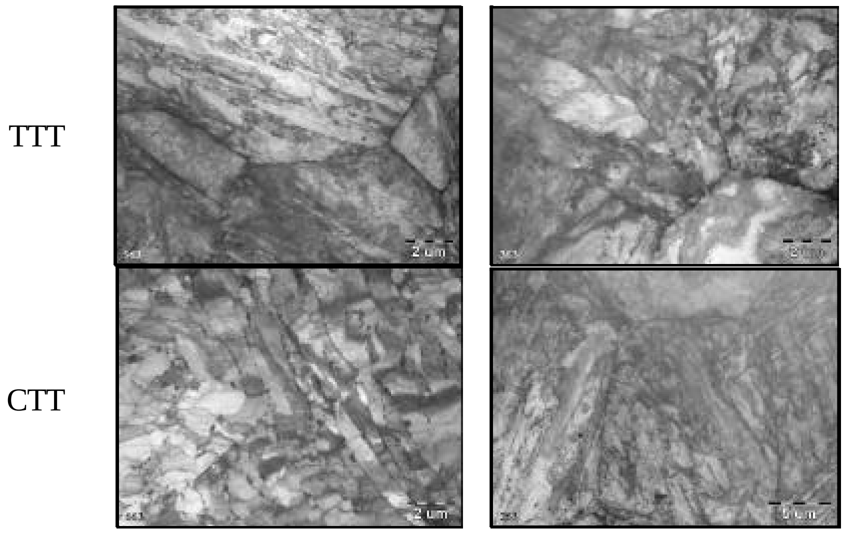

FIG. 7. RUSFER-EK-181. Microstructure of the specimens after traditional (TTT, upper row) and cyclic thermal treatment (CTT, lower row) before (left row) and after (right row) irradiation (BOR-60, 325 °C, 6 dpa).

General character of the structure-phase state do not change under irradiation. No significant differencies in distribution, size and concentration of secondary phases compared to the initial state were found independently of initial thermal treatment. Disperse particles VC and (VTa)C of size up to 3–5 nm remain after irradiation independently of initial thermal treatment.

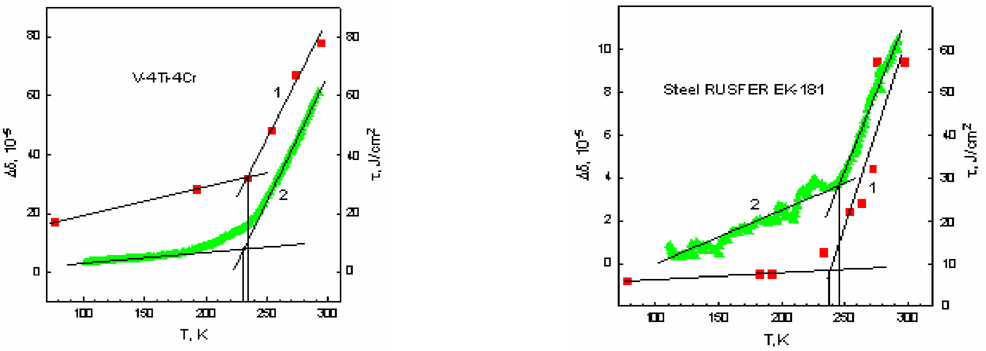

FIG. 8. Comparative behavior of impact toughness (1)and logarithmic decrement (2) with temperature for vanadium alloy V-4Ti-4Cr (left) and steel RUSFER-EK-181 (right) samples. One can see a good correlation of the both properties for both materials.

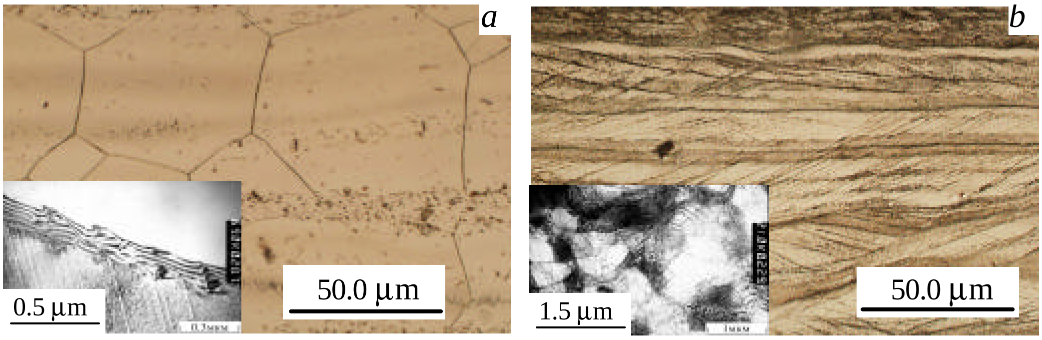

FIG. 9. Microstructures of V-4Ti-4Cr (RF) specimens: (a) traditional thermal treatment, (b) new treatment.

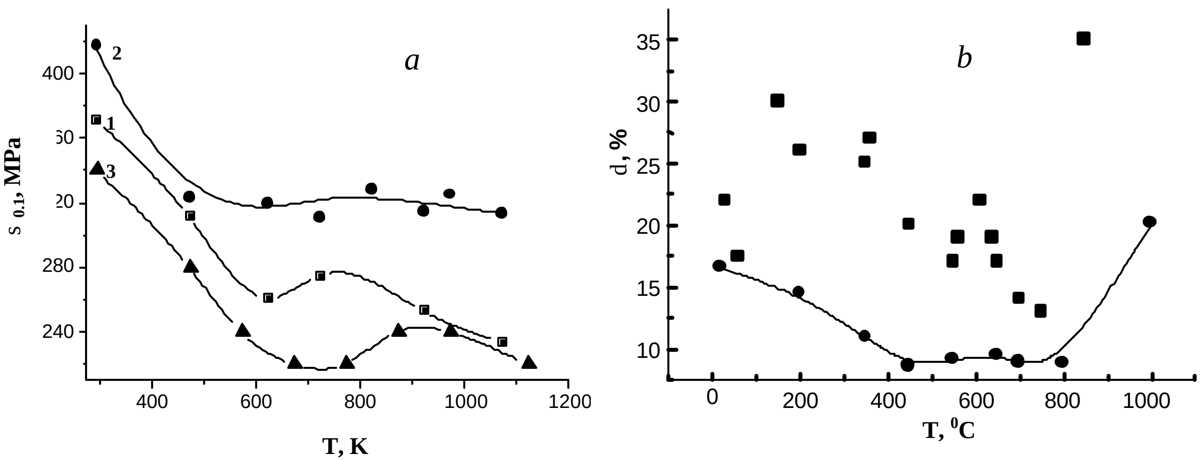

FIG. 10. V-4Ti-4Cr alloys (3 - USA, 1-2 – RF): (a) temperature dependence of the yield stress after traditional thermal treatments (1, 3) and after new thermo-mechanical treatment (2); (b) ultimate elongation of the V-4Ti-4Cr (RF) alloy after traditional (squares) and new (circles) regimes of thermal treatments.

4. Conclusion

In the RF R&D on fusion structure materials and technology covers most of the key issues of the fusion power reactors concepts (DEMO and beyond). The ferritic-martensitic 12%-Cr steel RUSFER-EK-181 (Fe-12Cr-2W-Ta-V-B-C) and the V-(4-8)Ti-(4-5)Cr alloys are the focus of the RF fusion power reactor concepts and upcoming work. The RF LAMAs, technology and industry database is practically ready to manufacture the TBMs both of

RUSFER-EK-181 and V-4Ti-4Cr (ceramic and lithium self-healing blanket, articles made of LAMAs 300-500 kg).
The high dose level of the irradiation and the post irradiated researches of the specimens of the RUSFER-EK-181 (40-180 dpa, irradiation time 560-1120 days, irradiation temperature 400-700 ^{0}C) and the V-4Ti-4Cr alloy (40-120 dpa, irradiation time 560 days, irradiation temperature 400-750 ^{0}C) in the BN-600 is the main focus on 2007-2011. The RF (Dollezhal Inst., Efremov Inst., Bochvar Inst., industry) is able to manufacture the solid and self cooling TBMs in ITER of RUSFER-EK-181 and V-4Ti-4Cr alloy.

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