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Research Article

The study of the brittle fracture resistance in fusion areas between RPV steel 15H2NMFA grade 1 and austenitic padding*

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Abstract

Brittle fracture resistance of RPV 15H2NMFA grade 1 steel is investigated. Sets of small-sized testing samples and a set of standard-sizes samples were used in the study. It was demonstrated that application of sets of small-sized specimens in mechanical tests for determining the brittle fracture resistance of RPV 15H2NMFA grade 1 steel makes possible the following:

- increasing the volume of tests in each batch by 8 times without significant changes in the design of irradiation facility thus ensuring maintaining the initial irradiation parameters during testing;
- substantially expanding the database of test results for statistical processing.

The need for large-scale modeling of process conditions arising in weld joint zones inaccessible for direct testing, such as: (1) the welding zone between the base metal and the corrosion-resistant coating metal, (2) the welding area between the weld metal and the corrosion-resistant coating metal, and (3) the fusion area between the base metal, the weld metal, and the anticorrosive cladding metal, is demonstrated in the paper.

Process modeling of the metal in fusion areas up to 0.5 mm wide (each is 100 µm in size) with an experimental electroslag refined (ESR) ingot of up to 300 mm long with similar microstructure and variable chemical composition allows the following: (1) examining not less than 1000 small-sized impact testing samples with continuous distribution of concentrations of chemical elements in accordance with a certain law; and (2) testing these samples and identifying brittle fracture dangerous zones across fusion areas between the base metal and the anti-corrosive padding metal in the initial state or after subsequent irradiation at a given fluence rate and temperature.

Keywords

Assessment of brittle fracture resistance, critical brittle point T_K, ductile-to-brittle-transition temperature T_P, conservative vessel life estimations, padding and welded joints

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Introduction

The following interplaying problems in the determination of the critical brittle point T_K for reactor vessel materials emerge in the process of radiation studies during the phase of forecasting brittle fracture resistance for objective calculation of lifespan of the base metal used in VVER reactors:

- ensuring accelerated irradiation of sets of samples for implementing impact mechanical testing;
- large scopes of impact testing of sets of samples at different temperatures and fluences;
- chemical and structural non-uniformities of reactor vessel materials developing in the process of manufacturing and operation of VVER vessels.

Design of vessels of reactor facilities of VVER type does not allow completely escaping irradiation of welded joints in reactor vessel barrels. Issues associated with different effects of metallurgical and process factors on different initial conditions of the metal and initial critical brittle point T_{K0} remain to be insufficiently investigated.

Implementation of sufficient scope of process modeling of the area not accessible for direct registration of brittle fracture resistance of the base metal and the metal of weld boundary between the base metal and the of anticorrosive cladding metal for reactor vessels of standard VVER-TOI design is the important task for planning radiation studies because these areas are structurally not removed from the limits of the reactor core.

On the other hand, there exist problems associated with implementation in large volumes of testing sets of standard-size impact testing samples at different temperatures and fluences. Application of sets of small-size samples for mechanical testing brittle fracture resistance (BFR) of 15H2NMFA grade 1 steel (hereinafter referred to as the KStK1) allows increasing the number of tests of samples in the set by eight times and more without the need of introduction of practically any changes of design of irradiation facilities and, correspondingly, maintaining original irradiation parameters and significantly increasing the volume of the database of testing results for statistical simulation.

Determination of BFR of reactor vessel steel using standard-size samples

Testing for determining the critical brittle point T_K for the sets of standard-size impact testing samples made from experimental batches of metal from commercial KStK1 purity stocks with conservative (CC) and basic (BC) chemical composition (PNAE G-7-002-86, PNAE G-7-008-89) was performed for calculating factual operating life of VVER-1200 reactor vessel materials. The technology for smelting 15H2NMFA-A steel ingots using primary burden stocks ensuring concentration of copper of up to 0.1 %, fluorine up to 0.01 % and nickel up to 1.5 % with low concentrations of other impurities was developed in the course of investigation. Two ingots with concentration of copper of 0.06 %, that of fluorine of 0.005 % and nickel of 1.23 % and with concentration of copper of 0.025 %, that of fluorine of 0.0025 % and nickel of 1.16 %, respectively, were produced (Table 1).

In accordance with TU 0893-013-00212179-2003 (TU 0893-013-00212179-2003) the first factual forged sample for steel of 15H2NMFA, 15H2NMFA-A and 15H2NMFA grade 1 types corresponds to the upper level of CC for KStK1, while the second forged sample corresponds to the lower level of the BC TU.

Standard-size samples taken from commercial stock were subjected to irradiation in research reactors at temperatures of 290 ± 15 °C and at high levels of fast neutron fluxes. The data on the investigation of resistance of samples made of commercial KStK1 metal against brittle fracturing with determination of T_K are presented in Table 1.

Determination of factual life span of VVER-1200 reactor vessel materials was performed during the phase of forecasting the BFR according to the results of certification testing of sets of KStK1 samples under irradiation (Table 2) (Vishkarev et al. 1980, 1980a, RD EO 1.1.2.99.0920-2013, Dub et al. 2011a).

For conservative margin of 17–20 °C (38 °C regulated value) the life of KStK1 amounts according to the results of testing to 618 years for the lower level of conservatism corresponding to T_{K0} = -104 °C and to 121 years for the upper level equal to T_{K0} = -28 °C.

Boundaries of the data scatter band for the results of testing sets of standard-size impact testing samples corresponding to the upper dose-time relationships (DTR) for T_K determine the life of KStK1 at the point of intersection with the upper level of permissible T_K (Fig. 1).

Experimental sets of small-size impact testing samples are fabricated from the laboratory metal produced by con-

Table 1. Results of testing T_K for sets of standard-size impact testing samples made of experimental metal from commercial KStK1[st]ocks with conservative and basic chemical composition.

Concentration of elements, mass. % Cu	P	Ni	T_{K0}, °C	F, 10^{22} м$^{-2}$	T_K, °C
Real forged sample corresponding to the upper level of T_K (conservative)					
0.060	0.005	1.23	-25	90	-10
0.060	0.005	1.23	-25	90	30
0.060	0.005	1.23	-25	140	40
0.060	0.005	1.23	-25	130	10
0.060	0.005	1.23	-25	140	30
0.060	0.005	1.23	-25	150	40
Real forged sample corresponding to the lower level of T_K (base)					
0.025	0.0025	1.16	-110	90	-80
0.025	0.0025	1.16	-110	90	-70
0.025	0.0025	1.16	-110	72	-90
0.025	0.0025	1.16	-110	72	-60
0.025	0.0025	1.16	-100	71	-70

Table 2. Values of coefficients of radiation embrittlement and operational life of metal of sets of standard-size impact testing samples with conservative and base KStK1chemical composition subjected to “thermal hardening” treatment.

Material	T_{K0}, °C	A_F	*n*	δT_K, °C	F_{CR}, 10^{22} м$^{-2}$	Lim. T_K, °C	Lifespan, years
Standard-size samples AO CC	-28 (from -8 to -48)	1.10	4/5	20	85	30	121
Standard-size samples AO BC	-104 (from -87 to -121)	0.91	4/5	17	435	30	618

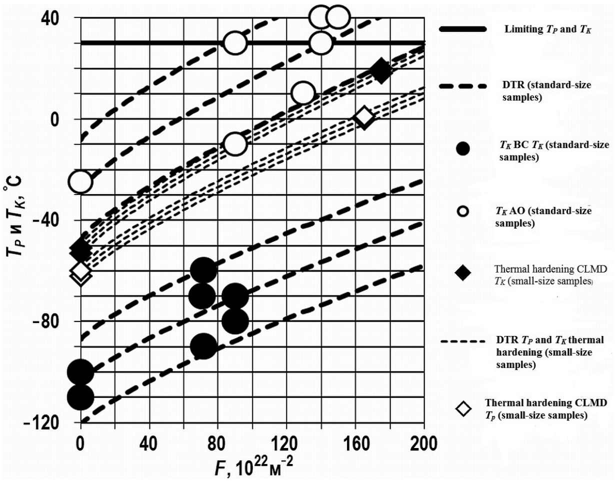

Figure 1. Dose-time relationships of T_K and T_P for the results of testing standard-size and small-size samples made of KStK1 with base chemical composition subjected to “thermal hardening” treatment.

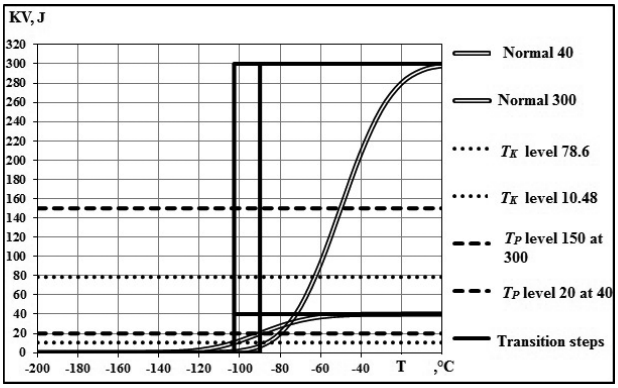

Figure 2. Comparison of T_K and T_P during testing standard-size (KV = 300 J/cm^2) and small-size (KV = 40 J/cм^2) samples for mechanical testing KStK1 brittle fracture resistance.

tinuous local melting down (CLMD) by welding in argon the stock from experimental commercial KStK1 stock metal with base chemical composition of commercial stock using non-consumable tungsten electrodes.

Application of this method for producing steel 15H2NMFA grade 1 allows significantly improving brittle fracturing characteristics of the metal.

Despite the partial solution of problems of factual critical brittle point T_K determination for reactor vessel materials by their sorting according to the critical brittle point values in initial state T_{K0} and with chemical composition of the metal the results of implemented studies are characterized with excessive conservatism of the estimations (Dub et al. 2011b, 2016).

Application of small-size samples in testing for determining BFR of reactor vessel steel

It has to be noted that temperature dependences of fracture energy KV and impact resistance KCV on the transition temperature T_P and critical brittle point T_K (Fig. 2) correspond to the standard Gaussian distribution law.

Thus, KV temperature dependences for KStK1 are graphically represented by the steps of metal transition from ductile to brittle state (Fig. 2); here KV values on the upper plateau of viscosity for standard-size impact testing samples can amount to 300 J/cm^2 for standard-size impact testing samples and to 40 J/cm^2 for small-size shock testing samples.

Brittle-to-ductile transition of the metal occurs not at a certain point, but within the interval of temperatures reflecting the scatter band of KV results dependent on the testing temperature corresponding to the statistical distribution center at the inflection point and determining the steel brittle-to-ductile transition temperature.

For standard-size impact testing samples T_P = -90 °C for KV = 150 J/cm^2, and for small-size impact testing samples T_P = -90 °C for KV = 20 J/cm^2.

KCV impact resistance steps intersect depending on the testing temperature KCV the levels determined according to $\delta_{0.2}$ and Gaussian distribution in the respective point corresponding to statistical center of distribution determining the critical brittle point for steel T_K = -102.75 °C for KCV = 78.6 J/cm^2 for standard-size impact testing samples and T_K = -102.75 °C for KCV = 10.48 J/cm^2 for small-size impact testing samples.

Sets of small-size impact testing samples made of metal from commercial KStK1 stock with base chemical composition for nickel, fluorine and copper (Ni – 1.16%, P – 0.0025%, Cu – 0.025%) ensure the lower level of T_K (Table 3, Fig. 1).

Factual lifespan of KStK1 with base chemical composition amounting for VVER-1200 to 287 years at T_{P0} = -50 °C is determined according to the critical fluence at the point of intersection of the limiting level for critical brittle point equal to 30 °C with statistically substantiated DTR for T_P equal to 202×10^{22} m^{-2}.

Factual lifespan of KStK1 with base chemical composition amounting for VVER-1200 to 371 years at T_{P0} = -59 °C is determined according to the critical fluence at the point of intersection of the limiting level for critical brittle point equal to 30 °C with statistically substantiated DTR for T_P equal to 261×10^{22} m^{-2}.

Table 3. Values of radiation embrittlement coefficients and operational life of metal in the sets of small-size impact testing samples with base KStK1 chemical composition.

Material	T_{K0}, T_{P0} °C	A_F	N	δT_K, T_P °C	F_{KP}, 10^{22} m^{-2}	Lim.T_K, T_P °C	Life, years
"Thermal hardening" treatment							
CLMD BC T_{P0} (Fig. 1)	-52 (from -50 to -54)	1.14	4/5	2	202	30	287
CLMD BC T_{K0} (Fig. 1)	-59 (from -57 to -61)	1.03	4/5	2	261	30	371
CLMD, «isothermal annealing» thermal treatment							
CLMD BC T_{P0} (Fig. 3)	-98 (from -86 to -110)	36.10	1/5	12	336	30	478
CLMD CC T_{P0} (Fig. 3)	-108 (from -99 to -117)	52.67	1/5	9	88	30	125
«Tempering» thermal treatment							
CLMD BC T_{P0} (Fig. 3)	-31 (from -29 to -33)	13.42	1/3	2	85	30	121

The produced CLMD metal stock was subjected to thermal treatment according to regimes ensuring certain structure and grain size of metal in the stock material (Markov 2011, GOST 5639-82):

- weld joint metal and base metal on the well fusion boundary possess after technological stress relieving operations tempered cast structure with grain size within 90–120 µm for "stress relieving" treatment;
- metal after thermal treatment in basic mode consisting of air hardening, thermal hardening and tempering possesses improved structure with grain size within 40–60 µm – "thermal hardening" treatment;
- metal after thermal treatment in thermal hardening mode accompanied with isothermal annealing and subsequent tempering possesses structure with additional phase recrystallization of pearlite type effectively reducing the size of congenital austenitic grain to the level of 15–25 µm – "isothermal annealing" treatment.

Isothermal annealing is the normal procedure of thermal treatment of KStK1 reactor vessel barrels matching the part of the vessel corresponding to reactor core during manufacturing VVER-1200 vessels and ensures high degree of structural uniformity of metal and extended lifespan of the vessel.

Factual lifespan of KStK1 with base chemical composition amounting to 478 years at T_{P0} = -98 °C is determined by the critical fluence at the point of intersection of the limiting level for critical brittle point of 30 °C with statistically substantiated DTR for T_P equal to 336×10^{22} m^{-2}.

Factual lifespan of KStK1 with conservative CLMD chemical composition amounting to 125 years at T_{P0} = -108 °C is determined by the critical fluence at the point of intersection of the limiting level for critical brittle point of 30 °C with statistically substantiated DTR for T_P equal to 88×10^{22} m^{-2}.

Increasing concentrations of fluorine and copper from the level of BC for base chemical composition equal to 0.0025% and 0.025%, respectively, to the level of CC above that permissible in pursuance with TU (GOST R ISO 148-1-2013) equal to 0.0100% and 0.090%, respectively, corresponding to the upper level for 15H2NMFA-A steel, is accompanied with significant reduction of metal resistance against brittle fracturing (see Fig. 3) (Dub et al. 2012, Anosov et al. 1982, 1985).

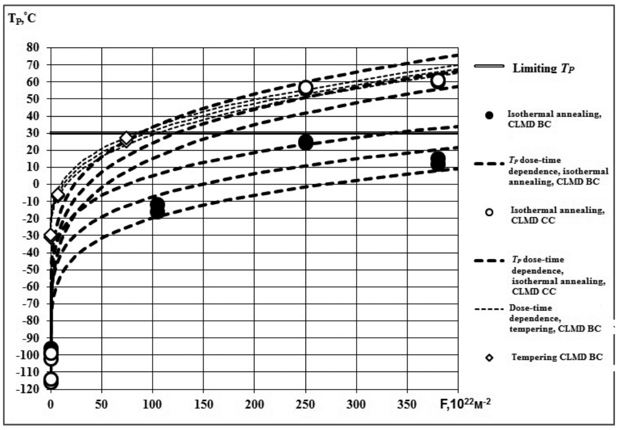

Figure 3. Dose-time relationships of T_P for the results of testing small-size impact testing samples made of experimental CLMD metal from commercial of KStK1 stock with base chemical composition subjected to standard "isothermal annealing" thermal treatment and "tempering" thermal treatment.

"Tempering" thermal treatment corresponding to the factual thermal treatment regime of treatment of base metal on the weld fusion boundary is the most dangerous from the viewpoint of structural non-uniformity with low concentrations of harmful impurities.

Factual lifespan of KStK1 with CLMD base chemical composition amounting to 121 years at T_{P0} = -29 °C is determined by the critical fluence at the point of intersection of the limiting level for critical brittle point of 30 °C with statistically substantiated DTR for T_P equal to 85×10^{22} m^{-2}.

Determination of BFR using T_P for metal on the fusion boundary of reactor vessel material and the anticorrosive cladding metal in original state

Determination of brittle fracture resistance in fusion area between the base metal and the anticorrosive cladding metal using T_P criterion involves implementation of necessary scope of process modeling of welding fusion areas inaccessible for conducting testing (Surkov et al. 1979, Anosov et al. 1990, RD EO 1.1.2.09.0789-2012) and includes the following:

- development of the methodology of process modeling for metal of the weld fusion area with width up to 0,5 мм (several grains with sizes of about 100 µm) with experimental electroslag refined ingot with length of up to 300 mm having similar structure;

- manufacturing and testing small-size impact testing samples from experimental metal stock for investigating brittle fracture resistance within weld fusion area of base metal and anticorrosive cladding metal.

Distribution of chromium and nickel along the length of the process model of the weld fusion boundary between the base metal and the anticorrosive cladding metal in the state without additional melting down is presented in Fig. 4 and that in the state with additional equalizing melting down is shown in Fig. 5.

It is advisable to apply additional equalizing melting down for homogenizing chemical composition, structure and properties along the length and over the cross-section of the process model of the weld fusion boundary between the base metal and the anticorrosive cladding metal.

Distribution of hardness *HB* along the length and over the cross-section of the technological model of the weld boundary between the base metal and the anticorrosive cladding metal has step-like character (Fig. 6) with shift corresponding to the forging of the initial model and subsequent melting the forged piece down at significantly higher level of *HB*.

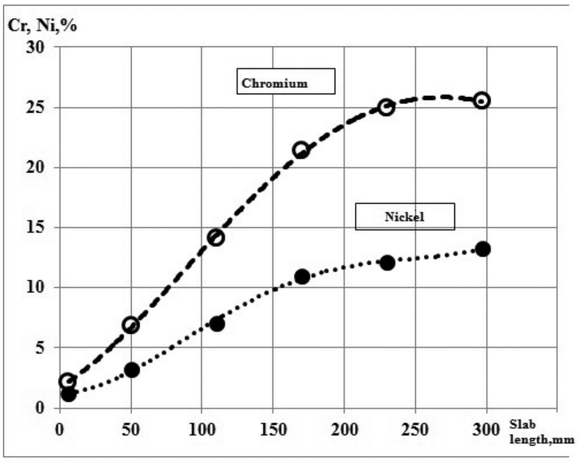

Figure 4. Distribution of chromium and nickel along the length of the process model of the weld boundary between base metal and the anticorrosive cladding metal in the state without additional melting down.

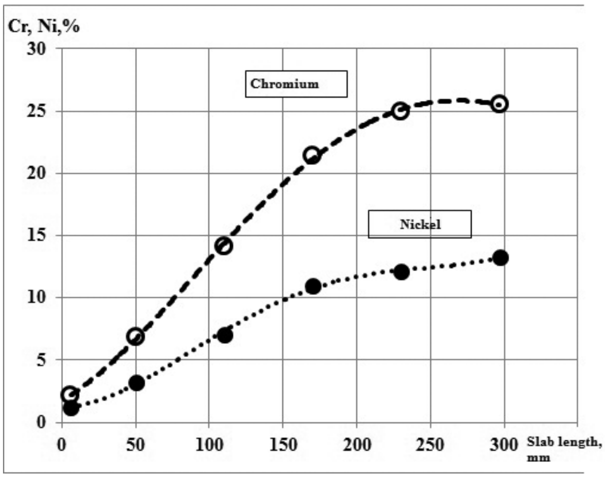

Figure 5. Distribution of chromium and nickel along the length of the process model of the weld boundary between base metal and the anticorrosive cladding metal after additional equalizing melting down.

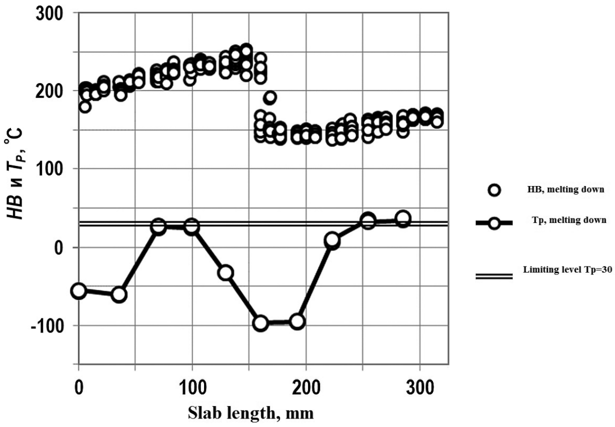

Figure 6. Distributions of hardness *HB* after additional equalizing melting down and T_P after melting down along the length of the process model of the weld fusion boundary between the base metal and the anticorrosive cladding metal before and after equalizing melting down.

Distribution of hardness HB along the length of the process model of the weld fusion boundary between the base metal and the anticorrosive cladding metal in initial state corresponds to a higher degree to the distribution of T_P allowing identification of the zone of increased brittle fracture risk according to the intersection of the limiting value of T_P = 30 °C.

Conclusion

Application of small-size samples in numbers initially preset for the sets of standard-size shock testing samples allows significantly reducing the size of the structures of irradiation facilities and, correspondingly, improving stability of irradiation parameters for each set.

Factual lifespan for 15H2NMFA grade 1 steel taking into account the chemical and structural non-uniformities of reactor vessel materials emerging in the process of manufacturing and operation of VVER-1200 reactor vessels satisfies with significant margin the design requirements providing for the operating life of up to 60 years and more.

The method of process modeling of metal of the weld fusion boundary between the base metal and the anticorrosive cladding metal with width of up to 0.5 mm using experimental electroslag refined (ESR) ingots with varying chemical composition with length of up to 300 mm and diameter of 100 mm was developed.

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