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

Viktor V. Orlov, Nikolay P. Anosov, Vladimir N. Skorobogatykh, Lyubov Yu. Gordyuk, Zhanna V. Yurgina, Konstantin N. Koshcheev, Svetlana V. Barsanova, Valentin K. Shamardin

1 JSC RPA «CNIITMASH», 4 Sharikopodshipnikovskaya st., Moscow, 115088 Russian Federation
2 JSC Institute of Reactor Materials, P.O. Box # 29, Zarechny, Sverdlovsk reg., 624250 Russian Federation
3 JSC «SSC RIAR», 9 Zapadnoye Shosse, Dimitrovgrad, Ulyanovsk reg., 433510 Russian Federation

Corresponding author: Nikolay P. Anosov (NPAnosov@cniitmash.com)

Academic editor: Georgy Tikhomirov

Received 4 June 2019 • Accepted 5 August 2019 • Published 25 September 2019


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 electro-slag 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 $T_c$, ductile-to-brittle-transition temperature $T_p$, conservative vessel life estimations, padding and welded joints

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2018, n. 4, pp. 64–75.
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 fracture 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 1.1.2.29.0920-2013, 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 stocks with conservative and basic chemical composition.

<table>
<thead>
<tr>
<th>Concentration of elements, mass. %</th>
<th>$T_{k0}^\circ C$</th>
<th>$F$, 10^{12} m^{-2}</th>
<th>$T_k$, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu 0.060</td>
<td>P 0.005</td>
<td>Ni 1.23</td>
<td>-25</td>
</tr>
<tr>
<td>0.060</td>
<td>0.005</td>
<td>1.23</td>
<td>-25</td>
</tr>
<tr>
<td>0.060</td>
<td>0.005</td>
<td>1.23</td>
<td>-25</td>
</tr>
<tr>
<td>0.060</td>
<td>0.005</td>
<td>1.23</td>
<td>-25</td>
</tr>
<tr>
<td>0.060</td>
<td>0.005</td>
<td>1.23</td>
<td>-25</td>
</tr>
<tr>
<td>0.060</td>
<td>0.005</td>
<td>1.23</td>
<td>-25</td>
</tr>
</tbody>
</table>

Real forged sample corresponding to the upper level of $T_k$ (conservative)

| 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 | 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 KStK1 chemical composition subjected to “thermal hardening” treatment.

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{ep}^0$/°C</th>
<th>$A_T$</th>
<th>$n$</th>
<th>$\delta T_p$/°C</th>
<th>$F_{ep}^{10^{15}}$ M$^{-2}$</th>
<th>Limit. $T_p$/°C</th>
<th>Lifespan, years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard-size samples AO</td>
<td>-28 (from -8</td>
<td>1.10</td>
<td>4/5</td>
<td>20</td>
<td>85</td>
<td>30</td>
<td>121</td>
</tr>
<tr>
<td>CC</td>
<td>109 (from -7</td>
<td>1.10</td>
<td>7/10</td>
<td>20</td>
<td>85</td>
<td>30</td>
<td>121</td>
</tr>
<tr>
<td>Standard-size samples AO</td>
<td>-140 (from 7</td>
<td>1.10</td>
<td>17</td>
<td>45</td>
<td>30</td>
<td>618</td>
<td></td>
</tr>
<tr>
<td>BC</td>
<td>-87 to -121</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Dose-time relationships of $T_p$ and $T_{ep}$ for the results of testing standard-size and small-size samples made of KStK1 with base chemical composition subjected to “thermal hardening” treatment.

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:

$$KV = \frac{P}{V}$$

where $P$ is the energy absorbed during fracture, $V$ is the specimen volume, and $T_p$ is the transition temperature. 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 $\delta_{S2}$ 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 $KV = 78.6$ 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 $T_{po} = 50$ °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 $202 \times 10^{12}$ m$^{-2}$.

Factual lifespan of KStK1 with base chemical composition amounting for VVER-1200 to 371 years at $T_{po} = 59$ °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 $261 \times 10^{12}$ 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.

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{pe}$, $T_{ph}$ °C</th>
<th>$A_t$</th>
<th>$N$</th>
<th>$S_{T_e}$, $T_p$ °C</th>
<th>$F_{pe}$, $10^{13}$ m$^{-1}$</th>
<th>$\text{Limit}_T$, $T_p$ °C</th>
<th>$\text{Life}$, years</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Thermal hardening” treatment</td>
<td>CLMD BC -52 (from -50 to -54)</td>
<td>1.14</td>
<td>4/5</td>
<td>2</td>
<td>202</td>
<td>30</td>
<td>287</td>
</tr>
<tr>
<td></td>
<td>CLMD BC -59 (from -57 to -61)</td>
<td>1.03</td>
<td>4/5</td>
<td>2</td>
<td>261</td>
<td>30</td>
<td>371</td>
</tr>
<tr>
<td></td>
<td>CLMD, “isothermal annealing” thermal treatment</td>
<td>-98 (from 86 to 56)</td>
<td>1/5</td>
<td>14</td>
<td>336</td>
<td>30</td>
<td>478</td>
</tr>
<tr>
<td>“Tempering” thermal treatment</td>
<td>CLMD BC -108 (from 56 to 110)</td>
<td>52.67</td>
<td>1/5</td>
<td>9</td>
<td>88</td>
<td>30</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>CLMD CC -99 to -117</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 $T_{pe} = -98 \, ^\circ\text{C}$ 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 $85 \times 10^2$ m$^{-2}$.

Factual lifespan of KStK1 with CLMD base chemical composition amounting to 125 years at $T_{pe} = -108 \, ^\circ\text{C}$ 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 $88 \times 10^2$ 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).

“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 $T_{pe} = -29 \, ^\circ\text{C}$ 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 $85 \times 10^2$ 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 as 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 mm (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 $HB$.

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 $TP$ 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.

The study was implemented under financial support from the Ministry for Science and Higher Education of the Russian Federation within the framework of the Granting Agreement No. 14.579.21.0116 (unique identifier of the agreement RFMEFI57915X0116).
References