A Physically Based Criterion for Determining the Critical Brittleness Temperature from Charpy Impact Tests for PRV Steels and Welds

S. Kotrechko*, V. Revka**, and K. Soroka*

*G. V. Kurdyumov Institute for Metal Physics, N.A.S. of Ukraine, 36 Academician Vernadsky Blvd., UA-03142 Kyiv, Ukraine
**Institute for Nuclear Research, N.A.S. of Ukraine 47, Nauky Ave., UA-03028 Kyiv, Ukraine

Based on ideas about physical nature of brittle and ductile fractures of RPV steels, the criterion for determining the critical temperature of brittleness from the Charpy impact test data is proposed. As shown in the first approximation, the criterion of constancy of local plastic deformation at head of stress raiser can be used to specify the level of impact toughness $K_{CV_{th}}$ depending on the yield stress $\sigma_{0.2}$. As theoretically proved, the threshold level of impact toughness is not an unambiguous function of $\sigma_{0.2}$. An additional influence is exerted by factors, which characterize the ability of RPV metal to resist brittle fracture under stress concentration conditions, in particular, the brittle strength $R_{MC}$. An approximate analytical relationship is derived, which allows predicting the level of $K_{CV_{th}}$ considering the strength of the RPV metal. In the range of yield strength 400–690 MPa, this relationship is consistent with the $K_{CV_{th}}$ values, which are given in the PNAE G-7-002-86 standard.

**Key words:** critical brittleness temperature, impact toughness threshold, radiation embrittlement, Charpy impact test, pressure vessel steels.

Corresponding author: Serhii Oleksiyovych Kotrechko
E-mail: kotr@imp.kiev.ua

DOI: 10.15407/mfint.45.08.1015

1015

PACS numbers: 46.50.+a, 62.20.fk, 62.20.fq, 62.20.mj, 62.20.mm, 62.20.mt, 81.40.Np
Спираючись на уявлення щодо фізичної природи крихкості та пластичної природи металу запропоновано критерій визначення критичної температури крихкості за випробування на ударну в’язкість. Показано, що в першому наближенні критерій сталості величини локальної пластичної деформації в околі концентратора напружень може використовуватися для коригування порогового рівня ударної в’язкості $KCV_{th}$ в залежності від величини плинності $\sigma_{0.2}$ металу. Одержано наближену аналітичну залежність рівня $KCV_{th}$ від величини $\sigma_{0.2}$ корпусного металу для реакторів ВВЕР-1000. Теоретично обґрунтовано, що пороговий рівень $KCV_{th}$ ударної в’язкості не є однозначною функцією величини $\sigma_{0.2}$. На рівень $KCV_{th}$ додатковий вплив має здатність металу чинити опір крихкому руйнуванню в умовах концентрації напружень. Одержано наближену залежність, яка уможливлює прогнозувати рівень $KCV_{th}$ з урахуванням міцності металу $\sigma_{0.2}$. В інтервалі значень $\sigma_{0.2} = 400–690$ МПа ця залежність узгоджується з пороговими значеннями, яких наведено в стандарті ПНАЕ Г-7-002-86.

Ключові слова: критична температура крихкості, пороговий рівень ударної в’язкості, радіаційне окрихчення, тест за Шарпі, реакторні кризи.

(Received 10 August, 2023; in final version, 22 August, 2023)

1. INTRODUCTION

Charpy impact tests are an effective ‘tool’ for assessment of the ability of structural materials to resist brittle fracture, since for these tests the simultaneous action of three embrittlement factors is realized, namely: dynamic load, local triaxial tension (overstress effect), low temperatures. One of the most common characteristics of fracture toughness, determined by Charpy impact test data, is the critical temperature of brittleness, $T_K$. In nuclear energy, a shift of the $T_K$ temperature is used as a measure of radiation embrittlement of the reactor pressure vessel (RPV) metal, i.e., the difference between the values of critical brittleness temperature for the irradiated ($T_{Kf}$) and non-irradiated ($T_{Ki}$) materials.

The value of $T_{Kr}$ ($T_{Kr}$) corresponds to a pre-determined level of $KCV_{th}$ on a temperature dependence of absorbed energy. In the ASTM E185 standard [1], it is recommended to use the specified value of the absorbed energy of 41 J (51 J·cm$^{-2}$). Furthermore, other criterion levels of energy are also used, for example, 28 J (35 J·cm$^{-2}$) [2] or 56 J (70 J·cm$^{-2}$) [3]. In Ukraine, for a determination of the critical temperature of brittleness, PNAE G-7-002-86 [4] is used, in which the criterion level of absorbed energy is not constant, but increases with increasing the yield strength. This is quite logical, since the yield strength contributes to the magnitude of the fracture work; therefore, at the same levels of brittleness of metal, an increase in the strength causes an increase in the fracture work [5]. This means that, when the material yield strength changes, the threshold level of impact toughness must be determined in such a way as to charac-
A physically based criterion for determining the critical brittleness characterizes uniquely the level of brittleness of the metal.

The paper proposes a physically justified criterion for determining the critical temperature of brittleness, at which the value of the threshold level of impact toughness is adjusted in such a way as to provide the same level of critical deformation at fracture with a radiation-induced increase in metal strength.

2. THEORY

The cornerstone of modern fracture physics is the notion of crack nuclei, which play the same fundamental role in the fracture process as dislocations in the process of plastic deformation. These cracks are called 'crack nuclei' because they do not originally exist in the material. They are formed directly in the process of plastic deformation in the vicinity of the grain or phase boundaries. Their dimensions are given by the size of the microstructural components of the metal [6]. In Refs. [7–9], based on the fundamental properties of crack nuclei, a general approach to assessing the ability of a metal to resist brittle fracture is formulated. It was shown that the transition of metal from ductile to brittle condition is controlled by the level of dynamic stability in the ensemble of crack nuclei. If, at the time of nucleation, the crack nuclei are stable, then, the metal at the macrolevel is capable of plastic deformation, and if not, then, such a metal is in a brittle state.

In terms of macrocharacteristics, the condition for loss of stability in an ensemble of crack nuclei can be described as [10, 11]

\[
P_{ms} = \frac{R_{MC}}{\sigma_{0.2} E_m \left( e_f / 0.002 \right)^n},
\]

where \( P_{ms} \) is the parameter of mechanical stability of the metal; \( R_{MC} \) is the parameter of mechanical stability of the metal; \( \sigma_{0.2} \) is yield strength; \( n \) is strain hardening parameter; \( E_m \) is parameter of brittle action of the stress raiser; \( e_f \) is the magnitude of local plastic deformation in the vicinity of the stress raiser, where the brittle fracture is initiated.

Equation (1) allows us to establish a relationship between the force characteristics \( R_{MC}, \sigma_{0.2}, E_m \), which characterize the mechanical stability of the metal, and the magnitude of the residual deformation of fracture \( e_f \) in the vicinity of the stress raiser, namely,

\[
e_f = 0.002 \left( \frac{R_{MC}}{\sigma_{0.2} E_m} \right)^{1/n}.
\]

According to (2), the \( e_f \) value can be used as a measure of the brittleness
of a metal at the transition temperature $T_K$. In this connection, the $KCV_{th}$ value should be determined under the condition $e_f = \text{const}$. The idea of experimental determination of $T_K$ under the condition $e_f = \text{const}$ is demonstrated in Fig. 1.

According to Fig. 1, the $T_K$ value is defined as the intersection point of the Charpy curve with the temperature dependence of the energy of plastic deformation $A_f$, at which the value of local plastic deformation $e_f$ is reached. The expression for the $A_f$ energy can be written as follows:

$$A_f = V_Y \int_0^{e_f} \sigma_i(x, y, z)de_f(x, y, z),$$  \hspace{1cm} (3)

where $V_Y$ is the volume of the area of local yielding, $\sigma_i(x, y, z)$ and $e_f(x, y, z)$ are the distributions of the intensity of local stresses and plastic deformations in the vicinity of the stress raiser.

Using the Hollomon dependency for strain hardening and Mises criterion allows us to obtain an expression for $\sigma_i(x, y, z)$:

$$\sigma_i(x, y, z) = \sigma_{0.2}^D(x, y, z) \left[ \frac{e_f(x, y, z)}{0.002} \right]^{n(x, y, z)},$$  \hspace{1cm} (4)

where $\sigma_{0.2}^D(x, y, z)$ is the yield strength considering the distribution of strain rates in the vicinity of the Charpy V-notch; $n(x, y, z)$ is the parameter of strain hardening.

Fig. 1. Temperature dependences of impact toughness $KCV$ and an energy of plastic deformation $A_f$ at a fixed value of critical deformation $e_f$; $KCV_{th}$ is threshold value of impact toughness; $T_K$ is critical temperature of brittleness.
Substituting (4) into (3) we get:

\[ A_f = V_f \int_0^{\varepsilon_f} \sigma_{0.2}(x, y, z) e_i(x, y, z)^n \frac{1}{0.002} d(e_i(x, y, z)). \]  

(5)

According to (5), finding the relationship between \( A_f \), the yield strength \( \sigma_{0.2} \) and local deformation \( e_i \) requires the use of numerical methods, in particular, the finite element method. In this case, such an approach is not effective, since, for engineering calculations, it is advisable to obtain the appropriate dependence in analytical form. The problem is considerably simplified if we consider the fact that the task is only to find regularity of change in \( A_f \), depending on \( \sigma_{0.2} \) at a constant value of plastic deformation.

The idea of an approximate approach is to use the effective volume \( V_{ef} \), within which stresses \( \sigma_i \) and deformations \( e_i \) are uniformly distributed, but the energy of the plastic deformation \( A_f \) is equal to that for a Charpy V-notch (CVN) specimen.

In this case, the expression (5) is significantly simplified:

\[ A_{ef} = V_{ef} \sigma_{0.2}^D \left( \frac{1}{0.002} \right)^n \int_0^{\varepsilon_f} \bar{\varepsilon}_i^n d\bar{\varepsilon}_i, \]  

(6)

where \( \sigma_{0.2}^D \) and \( n \) are the yield strength and the exponent of strain hardening at the maximum strain rate ahead of the notch (for the CVN specimen under standard test conditions \( \varepsilon_i \approx 200 \text{ s}^{-1} [12] \)); \( \bar{\varepsilon}_i \) is the average value of the intensity of plastic deformations within the effective volume \( V_{ef} \).

After integrating in the equation (6), we get:

\[ A_{ef} = V_{ef} \sigma_{0.2}^D \left( \frac{1}{0.002} \right)^n \frac{1}{1 + n} e_f^{1+n}. \]  

(7)

Considering that, for typical structural ferritic steels, \( n \approx 0.05 \) and the fact that \( n \) decreases with increasing the strain rate, we put that \( 1 + n \approx 1 \) and \( (1/0.002)^n = 1.36 \). In this case,

\[ A_{ef} = 1.36 V_{ef} \sigma_{0.2}^D e_f. \]  

(8)

When structural steels with ferritic microstructure are fractured in the temperature range of the ductile to brittle transition, the value of the critical deformation of initiation of brittle fracture in the vicinity of typical stress raisers is approximately of 2\% [13]. This allows in the first approximation to put that \( e_f = 0.02 \).

The effective volume \( V_{ef} \) in the region of local plastic deformation should also be unchanged at a fixed value of critical deformation \( e_f \). Some variations of \( V_{ef} \) may be due to different values of the strain-
hardening exponent $n$; however, taking into account the above remarks regarding this parameter, in the first approximation, the effect $n$ can be neglected.

For a typical value of the depth $h$ of the local yield region $h = 2R$ (where $R$ is the radius of a $V$-notch, $R = 0.25$ mm). At fracture in the region of ductile-to-brittle transition and cylindrical shape of the area of local yielding and the Charpy specimen thickness of 10 mm, we have $V_{ef} \approx 2 \text{ mm}^3$.

For the practical use of the proposed approach, the invariance of $V_{ef}$ to the value of the yield strength of the metal is of key importance. To verify the derived relationship (8), you can use empirical data on the dependence of the threshold level of impact toughness $KCV_{th}$ on the yield strength of RPV steels and their welds, which are given in the PNAEG-7-002-86 standard [4].

The idea of the calibration procedure is that the $V_{ef}$ value is determined based on the threshold level $KCV_{th}$ for a metal with a given yield strength $\sigma_{0.2}$.

According to (8),

$$V_{ef} = \frac{KCV_{th}}{1.36 \varepsilon_0 \sigma_{0.2}^D (T_K)},$$

where $\sigma_{0.2}^D (T_K)$ is the yield strength in the vicinity of the Charpy $V$-notch at the temperature $T_K$.

3. EXPERIMENTAL METHODS

Experimental studies included uniaxial tensile tests of round specimens at two temperatures of 293 K and 573 K and impact tests of standard Charpy $V$-notch specimens in the temperature range from 173 K to 373 K.

VVER-1000 RPV steels and their welds were applied as research objects (Table 1).

3.1. Constructing the Temperature Dependence of Impact Toughness

The impact toughness $KCV$ is defined as the absorbed energy, $A$, divided by the cross-sectional area of the Charpy specimen, $F$, at the $V$-notch plane [12]:

$$KCV = \frac{A}{F}.$$

Typically, the temperature dependence of $KCV$ values is approximated by the following relationship [14]:
A PHYSICALLY BASED CRITERION FOR DETERMINING THE CRITICAL BRITTLENESS

\[ KCV = \left( \frac{USE}{2} \right) \left[ 1 + \tanh \left( \frac{T - T_0}{C} \right) \right], \]  

(11)

where \( USE \) is the impact toughness value on the upper shelf energy of the Charpy curve, J·cm\(^{-2}\); \( T \) is test temperature; \( T_0 \) and \( C \) are fitting parameters, °C. The values of \( USE, T_0 \) and \( C \) are found, when processing experimental data by the least squares method.

3.2. Constructing the Temperature Dependence of Yield Strength at Dynamic Loading and Determination of Critical Brittleness

To develop the dependence of the yield \( \sigma_{0.2} \) strength on the temperature and strain rate, a model of thermally activated motion of dislocations was used [15, 16], according to which

\[ \sigma_{0.2} = \sigma_{0.2} (T_r) + C_1 \exp[-\beta T] - C_1 \exp[-\beta T_r], \]  

(12)

### TABLE 1. Mechanical properties, impact toughness threshold \( KCV_{th} \) and critical brittleness temperature \( T_{KF} \), determined by criteria of PNAE-G-7-002-86 and \( \varepsilon_c = 0.02 \) for VVER-1000 base and weld metal in irradiated and non-irradiated condition.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \Phi_r ), ( \times 10^{22}/m^2 )</th>
<th>( \sigma_{0.2} ), MPa</th>
<th>( KCV_{th}^{PNAE} ), J/cm(^2)</th>
<th>( T_{KF}^{PNAE} ), °C</th>
<th>( V_{cr} ), mm(^3)</th>
<th>( \sigma_{0.2}^{P} (T_{KF}) ), MPa</th>
<th>( KCV_{th}^{PNAE} ), J/cm(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel H</td>
<td>0</td>
<td>543</td>
<td>49</td>
<td>-36</td>
<td>2.152</td>
<td>837</td>
<td>49.8</td>
</tr>
<tr>
<td></td>
<td>11.1</td>
<td>605</td>
<td>59</td>
<td>-18</td>
<td>2.482</td>
<td>874</td>
<td>52.0</td>
</tr>
<tr>
<td></td>
<td>22.2</td>
<td>620</td>
<td>59</td>
<td>-20</td>
<td>2.433</td>
<td>892</td>
<td>52.0</td>
</tr>
<tr>
<td>Steel K</td>
<td>0</td>
<td>595</td>
<td>59</td>
<td>-81</td>
<td>2.090</td>
<td>1038</td>
<td>61.0</td>
</tr>
<tr>
<td></td>
<td>18.2</td>
<td>663</td>
<td>59</td>
<td>-43</td>
<td>2.088</td>
<td>1039</td>
<td>61.0</td>
</tr>
<tr>
<td>Steel P</td>
<td>0</td>
<td>567</td>
<td>59</td>
<td>-37</td>
<td>2.317</td>
<td>936</td>
<td>54.4</td>
</tr>
<tr>
<td></td>
<td>27.6</td>
<td>593</td>
<td>59</td>
<td>-34</td>
<td>2.264</td>
<td>958</td>
<td>56.0</td>
</tr>
<tr>
<td></td>
<td>68.7</td>
<td>635</td>
<td>59</td>
<td>-23</td>
<td>2.200</td>
<td>986</td>
<td>57.6</td>
</tr>
<tr>
<td>Steel W</td>
<td>0</td>
<td>564</td>
<td>59</td>
<td>-73</td>
<td>2.197</td>
<td>987</td>
<td>58.1</td>
</tr>
<tr>
<td></td>
<td>22.2</td>
<td>615</td>
<td>59</td>
<td>-14</td>
<td>2.262</td>
<td>959</td>
<td>60.3</td>
</tr>
<tr>
<td></td>
<td>58.9</td>
<td>627</td>
<td>59</td>
<td>-10</td>
<td>2.245</td>
<td>966</td>
<td>61.2</td>
</tr>
<tr>
<td>Steel Y</td>
<td>0</td>
<td>612</td>
<td>59</td>
<td>-79</td>
<td>2.142</td>
<td>1012</td>
<td>59.3</td>
</tr>
<tr>
<td></td>
<td>13.1</td>
<td>665</td>
<td>59</td>
<td>-50</td>
<td>2.134</td>
<td>1016</td>
<td>59.6</td>
</tr>
<tr>
<td></td>
<td>27.3</td>
<td>683</td>
<td>59</td>
<td>-39</td>
<td>2.133</td>
<td>1017</td>
<td>59.8</td>
</tr>
<tr>
<td>Steel 15X2NMFA (slab 7)</td>
<td>0</td>
<td>576</td>
<td>59</td>
<td>-76</td>
<td>2.368</td>
<td>916</td>
<td>54.1</td>
</tr>
<tr>
<td>Steel 15X2NMFA (slab 5)</td>
<td>0</td>
<td>609</td>
<td>59</td>
<td>-46</td>
<td>2.575</td>
<td>843</td>
<td>51.9</td>
</tr>
</tbody>
</table>
where $\sigma_{0.2}(T_r)$ is the yield strength at room temperature $T_r = 293$ K; $C_1 = \sigma_{th}$ is the stress, which characterizes the maximum magnitude of barriers overcome by thermal activation. The coefficient $\beta$ depends on the strain rate $\dot{\varepsilon}$ and density of mobile dislocations $\rho_d$ and is evaluated by the following equation:

$$\beta = C_2 - C_3 \ln \dot{\varepsilon},$$

where $C_2 = k \left( b^2 \omega D \rho_d \right) / U_0$; $(k$ is the Boltzmann constant, $\omega$ is the Debye frequency, $b$ is the Burgers vector); $C_3 = k / U_0 = 0.000415$.

The $C_1$ and $C_2$ coefficients were defined separately for each steel by calibration using the tensile test data for the yield strength at $T = 293$ K and $T = 573$ K (Table 2). According to the results of processing experimental data in the first approximation, these coefficients do not depend on neutron fluence.

According to (12), the expression for the athermal component of the yield strength $\sigma_a$ is as follows:

$$\sigma_a = \sigma_{0.2}^{293} - C_1 \exp \left( - \left( C_2 - C_3 \ln \dot{\varepsilon}_0 \right) T_r \right),$$

where $\dot{\varepsilon}_0 = 0.0004$ s$^{-1}$ is a strain rate under quasi-static tension.

Considering (12) and (13), the expression for the yield strength $\sigma_{0.2}$

### Table 1 (Continuation)

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Phi$, $10^{20}$n/m$^2$</th>
<th>$\sigma_{0.2}$, MPa</th>
<th>$K\sigma_{0.2}^{\text{aTH}}$, J/sm$^2$</th>
<th>$n_{\text{aTH}}$, C</th>
<th>$V_{cr}$, mm$^3$</th>
<th>$\sigma_{0.2}^{\text{aTH}}(T_r)$, MPa</th>
<th>$K\sigma_{0.2}^{\text{aTH}}$, J/sm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV weld metal (VVER-1000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weld metal K</td>
<td>0</td>
<td>510</td>
<td>49</td>
<td>$-62$</td>
<td>1.946</td>
<td>926</td>
<td>54.0</td>
</tr>
<tr>
<td></td>
<td>16.9</td>
<td>593</td>
<td>59</td>
<td>$-32$</td>
<td>2.263</td>
<td>959</td>
<td>56.0</td>
</tr>
<tr>
<td>Weld metal L</td>
<td>0</td>
<td>562</td>
<td>59</td>
<td>$-21$</td>
<td>2.167</td>
<td>1001</td>
<td>59.0</td>
</tr>
<tr>
<td></td>
<td>33.5</td>
<td>648</td>
<td>59</td>
<td>33</td>
<td>2.104</td>
<td>1031</td>
<td>60.0</td>
</tr>
<tr>
<td>Weld metal P</td>
<td>0</td>
<td>603</td>
<td>59</td>
<td>25</td>
<td>2.183</td>
<td>994</td>
<td>54.8</td>
</tr>
<tr>
<td></td>
<td>22.2</td>
<td>502</td>
<td>49</td>
<td>$-37$</td>
<td>1.914</td>
<td>941</td>
<td>55.1</td>
</tr>
<tr>
<td></td>
<td>55.8</td>
<td>580</td>
<td>59</td>
<td>11</td>
<td>2.313</td>
<td>938</td>
<td>55.4</td>
</tr>
<tr>
<td>Weld metal W</td>
<td>0</td>
<td>437</td>
<td>49</td>
<td>$-22$</td>
<td>2.032</td>
<td>887</td>
<td>52.0</td>
</tr>
<tr>
<td></td>
<td>17.4</td>
<td>565</td>
<td>59</td>
<td>$-17$</td>
<td>2.149</td>
<td>1009</td>
<td>59.3</td>
</tr>
<tr>
<td>Weld metal Y</td>
<td>0</td>
<td>550</td>
<td>59</td>
<td>7</td>
<td>2.077</td>
<td>1044</td>
<td>61.2</td>
</tr>
<tr>
<td></td>
<td>20.1</td>
<td>609</td>
<td>59</td>
<td>20</td>
<td>2.373</td>
<td>914</td>
<td>53.9</td>
</tr>
<tr>
<td></td>
<td>56.9</td>
<td>545</td>
<td>49</td>
<td>$-43$</td>
<td>1.875</td>
<td>961</td>
<td>55.9</td>
</tr>
</tbody>
</table>

TABLE 1 (continuation).

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Phi$, $10^{20}$n/m$^2$</th>
<th>$\sigma_{0.2}$, MPa</th>
<th>$K\sigma_{0.2}^{\text{aTH}}$, J/sm$^2$</th>
<th>$n_{\text{aTH}}$, C</th>
<th>$V_{cr}$, mm$^3$</th>
<th>$\sigma_{0.2}^{\text{aTH}}(T_r)$, MPa</th>
<th>$K\sigma_{0.2}^{\text{aTH}}$, J/sm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld metal Sv-10XGNMAA</td>
<td>0</td>
<td>471</td>
<td>49</td>
<td>$-52$</td>
<td>1.886</td>
<td>955</td>
<td>55.8</td>
</tr>
<tr>
<td></td>
<td>8.9</td>
<td>608</td>
<td>59</td>
<td>$-8$</td>
<td>2.109</td>
<td>1029</td>
<td>60.6</td>
</tr>
<tr>
<td></td>
<td>20.9</td>
<td>593</td>
<td>59</td>
<td>14</td>
<td>2.203</td>
<td>985</td>
<td>58.0</td>
</tr>
</tbody>
</table>
A PHYSICALLY BASED CRITERION FOR DETERMINING THE CRITICAL BRITTLENESS

1023

at the strain rate $\dot{e}_D = 200 \text{ s}^{-1}$ in the vicinity of the Charpy V-notch is:

$$
\sigma_{0.2}^D = \sigma_a + C_1 \exp \left[ -(C_2 - C_3 \ln \dot{e}_D) T \right]. \quad (15)
$$

Formula (15) was used to develop the temperature dependence of the $\sigma_{0.2}^D$ for the RPV metal in the initial and irradiated states.

To determine the transition temperature $T_{KF}$, the $KCV_{th}$ values for four ranges of strength of ferrite steels given in the PNAE G-7-002-86 standard were used (Table 3).

4. RESULTS AND DISCUSSION

In accordance with the results obtained, the $V_{ef}$ value practically does not depend on the strength of RPV metal (Fig. 2). In the range of yield strength 437–683 MPa, the average value of $V_{ef}$ equals to 2.16 mm$^3$

<table>
<thead>
<tr>
<th>Material</th>
<th>$C_1$, MPa</th>
<th>$C_2$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV steel (VVER-1000)</td>
<td>933</td>
<td>0.00633</td>
</tr>
<tr>
<td>Steel K</td>
<td>1036</td>
<td>0.00584</td>
</tr>
<tr>
<td>Steel P</td>
<td>900</td>
<td>0.00518</td>
</tr>
<tr>
<td>Steel W</td>
<td>900</td>
<td>0.00513</td>
</tr>
<tr>
<td>Steel Y</td>
<td>983</td>
<td>0.00606</td>
</tr>
<tr>
<td>Steel 15X2NMFA (slab 7)</td>
<td>1100</td>
<td>0.00755</td>
</tr>
<tr>
<td>Steel 15X2NMFA (slab 5)</td>
<td>1100</td>
<td>0.00843</td>
</tr>
<tr>
<td>RPV weld metal (VVER-1000)</td>
<td>1049</td>
<td>0.00581</td>
</tr>
<tr>
<td>Weld metal K</td>
<td>900</td>
<td>0.00423</td>
</tr>
<tr>
<td>Weld metal L</td>
<td>900</td>
<td>0.00467</td>
</tr>
<tr>
<td>Weld metal W</td>
<td>900</td>
<td>0.00414</td>
</tr>
<tr>
<td>Weld metal Y</td>
<td>1045</td>
<td>0.00542</td>
</tr>
<tr>
<td>Weld metal Sv-10XGNMAA</td>
<td>1041</td>
<td>0.00483</td>
</tr>
</tbody>
</table>

TABLE 2. The $C_1$ and $C_2$ coefficients for the PRV steels, determined by calibration using the yield stress $\sigma_{0.2}$.

TABLE 3. Threshold levels of impact toughness depending on the yield strength of structural steels and their welds.

<table>
<thead>
<tr>
<th>Yield strength $\sigma_{0.2}$ at $20^\circ C$, MPa</th>
<th>Impact toughness $KCV$, J/sm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 304</td>
<td>23</td>
</tr>
<tr>
<td>304–402</td>
<td>31</td>
</tr>
<tr>
<td>402–549</td>
<td>39</td>
</tr>
<tr>
<td>549–687</td>
<td>47</td>
</tr>
</tbody>
</table>
with a standard deviation of ±8%. This is quite close to the estimate above $V_{eff} = 2.00$ mm$^3$.

According to (9), invariance of $V_{eff}$ to the yield strength means the linear dependence of $KCV_{th}$ on the yield strength $\sigma_{0.2}^D(T_{KF})$ at the temperature $T_{KF}$ under the condition of dynamic loading:

$$KCV_{th} = 1.36V_{eff}e_t\sigma_{0.2}^D(T_{KF}).$$  \hspace{1cm} (16)

According to (8), (11) and (15), the $T_{KF}$ value can be calculated by solving a nonlinear equation:

$$\left(\frac{USE}{2}\right)\left[1 + \tanh\left(\frac{T_{KF} - T_0}{C}\right)\right] =$$

$$= 1.36V_{eff}e_t\left[\sigma_a + C_t \exp\left[-(C_2 - C_3 \ln \dot{\epsilon}_D)T_{KF}\right]\right].$$ \hspace{1cm} (17)

The threshold level of impact toughness, $KCV_{th}$, depends on the yield strength at the temperature $T_{KF}$ under dynamic loading conditions. However, from a practical point of view, it is relevant to establish a relationship between the $KCV_{th}$ and value of the yield strength $\sigma_{0.2}(T_r)$ at room temperature under conditions of uniaxial quasi-static tension. Such an attempt was made in the PNAE G-7-002-86 standard within the framework of a purely empirical approach (Table 3). It should be noted that the threshold levels of impact toughness in PNAE G-7-002-86 are given not as a monotonic function of the material yield.
strength, but as a number of fixed values of $KCV_{th}$ for different ranges of $\sigma_{0.2}(T)$ (Table 3).

The results obtained in this study allow us to establish a relationship between $KCV_{th}$ and the yield strength at room temperature. Substituting the expression (15) for $\sigma_{0.2}^D$ in Eq. (16) considering Eq. (14), after the math conversions, we get:

$$KCV_{th} = a + b\sigma_{0.2},$$

where

$$a = 1.36V_{ef}\varepsilon_C \{ \exp[-(C_2 - C_3 \ln \varepsilon_T) T_{KF}] - \exp[-(C_2 - C_3 \ln \varepsilon_T) T_{K}] \},$$

$$b = 1.36V_{ef} \varepsilon_f.$$  

In accordance with Eqs. (18)–(20), the threshold level, $KCV_{th}$ is not an unambiguous function of the yield strength $\sigma_{0.2}(T)$, since this parameter is influenced by the $T_{KF}$ temperature, which, in turn, depends not only on the $\sigma_{0.2}$ and $n$, but also on the local cleavage stress $\sigma_F$ in the vicinity of the stress raiser. The value of the latter is determined by the brittle strength $R_{MC}$ [9, 10]. In the relationship (18), the influence of these factors on $KCV_{th}$ is characterized by the coefficient $b$.

The derived values of $KCV_{th}$ (Fig. 3) allow us to estimate the degree of variation of this parameter for RPV steels and welds in the initial

![Fig. 3. Dependence of $KCV_{th}$ values on the yield strength $\sigma_{0.2}(T)$ at room temperature under quasi-static loading conditions: solid lines—calculations by Eq. (18) at $a = 22.63 \pm 6.77 \text{ J} \cdot \text{cm}^{-2}$; dashed lines—the $KCV_{th}$ values according to PNAE G-7-002-86.](image-url)
and irradiated states. For this, the data in Fig. 3 were approximated using the relationship (18) provided that $b = 0.058\text{J/(cm}^2\cdot\text{MPa})$ ($e_f = 0.02, V_{ef} = 2.16\text{mm}^3$). In this case, $a = 22.63 \pm 6.77\text{J/cm}^2$, that is, the coefficient of variation of parameter $a$ is of 30%.

Thus, using Eq. (18) with specified $a$ and $b$ allows us to outline the entire array of $KCV_{th}$ values. For the range of yield strength 400–690 MPa at room temperature, this dependence is generally consistent with the empirical $KCV_{th}$ values used in PNAE G-7-002-86; however, unlike PNAE G-7-002-86, dependence of $KCV_{th}$ on the yield strength $\sigma_{0.2}(T_r)$ is a monotonic function.

Finally, it should be emphasized that a scatter of the $KCV$ values in Fig. 3 is not due to the test conditions (a variation of test temperature from a specimen to a specimen, $V$-notch parameters, impact velocity, etc.). This scatter is due to influence of additional factors, first of all, the $R_{MC}$ parameter, which characterizes the brittle fracture resistance of RPV steels and depends on their microstructure.

5. CONCLUSIONS

To assess the ability of structural steels to resist the brittle fracture using the transition temperature $T_{KF}$, the threshold value of impact toughness $KCV_{th}$ should increase with increasing the strength in such a way as to ensure a constant value of local plastic deformation in the vicinity of the $V$-notch for the Charpy specimen.

The $KCV_{th}$ value is not an unambiguous function of the yield strength $\sigma_{0.2}(T_r)$ at room temperature. An additional influence on the $KCV_{th}$ is exerted by factors that characterize the ability of RPV metal to resist brittle fracture under stress concentration conditions, in particular the brittle strength $R_{MC}$.

For practical use, the dependence of $KCV_{th}$ on $\sigma_{0.2}(T_r)$ can be represented in the 1st approximation as a linear function $KCV_{th} = a + b\sigma_{0.2}$, where the influence of additional factors on $KCV_{th}$ is taken into account by the variation of the parameter $a = 22.63 \pm 6.77\text{J/cm}^2$. In this interpretation, the proposed relationship is generally consistent with the empirical $KCV_{th}$ values used in PNAE G-7-002-86 in the range of yield strength 400–690 MPa.

The research leading to these results was funded by the National Academy of Sciences of Ukraine (Grant Number 0121U107569).

REFERENCES

2. K. Wallin, Innovative Approaches to Irradiation Damage and Fracture Analy-
A PHYSICALLY BASED CRITERION FOR DETERMINING THE CRITICAL BRITTLENESS

14. Inzhenernaya, Nauchnaya i Tekhnicheskaya Podderzhka. Metodika Opredele-


Inzhenernaya, Nauchnaya i Tekhnicheskaya Podderzhka. Metodika Opredele-
niya Radiatsionnogo Okhrupchivaniya Metalla Korpusov Reaktorov i Srokov Vyekruzi Obrazstv-Svideteley po Rezultatam Ikh Ispytaniy, [Engineering, Scientific and Technical Support. Method for Determining the Radiation Embritt-
lement of The Metal of Reactor Vessels and The Timing of Unloading Witness Samples Based on The Results of Their Tests], SOU NAEK 087:2015 (in Russian).