Metallophysics and Advanced Technologies
Металофіз. новітні технол.
Metallofiz. Noveishie Tekhnol.
2023, vol. 45, No. 8, pp. 1015–1027
https://doi.org/10.15407/mfint.45.08.1015
Reprints available directly from the publisher

PACS numbers: 46.50.+a, 62.20.fk, 62.20.fq, 62.20.mj, 62.20.mm, 62.20.mt, 81.40.Np

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 KCV_{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 KCV_{th} considering the strength of the RPV metal. In the range of yield strength 400–690 MPa, this relationship is consistent with the KCV_{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

Citation: S. Kotrechko, V. Revka, and K. Soroka, A Physically Based Criterion for Determining the Critical Brittleness Temperature from Charpy Impact Tests for PRV Steels and Welds, *Metallofiz. Noveishie Tekhnol.*, **45**, No. 8: 1015–1027 (2023).
DOI: 10.15407/mfint.45.08.1015

Спираючись на уявлення щодо фізичної природи крихкости та пластичности металу запропоновано критерій визначення критичної температури крихкости за випробувань на ударну в'язкість. Показано, що в першому наближенні критерій сталости величини локальної пластичної деформації в околі концентратора напружень може використовуватися для кориґування порогового рівня ударної в'язкости KCV_{th} в залежності від величини границі плинности $\sigma_{0,2}$ 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'язкости 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 міцности 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 крихкости, пороговий рівень ударної в'язкости, радіяційне окрихчення, тест за Шарпі, реакторні криці.

(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_{KF} (T_{KI}) 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 characterize 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]

$$P_{ms} = \frac{R_{MC}}{\sigma_{0.2} E_m \left(e_f/0.002\right)^n}, \tag{1}$$

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,

$$e_f = 0.002\left(\frac{R_{MC}}{\sigma_{0.2} E_m}\right)^{1/n}. \tag{2}$$

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 = const. The idea of experimental determination of T_K under the condition e_f = 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:

$$A_f = V_Y \int_0^{e_f} \sigma_i(x,y,z) de_i(x,y,z), \tag{3}$$

where V_Y is the volume of the area of local yielding, $\sigma_i(x,y,z)$ and $e_i(x,y,z)$ 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 $\sigma_i(x,y,z)$:

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

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.

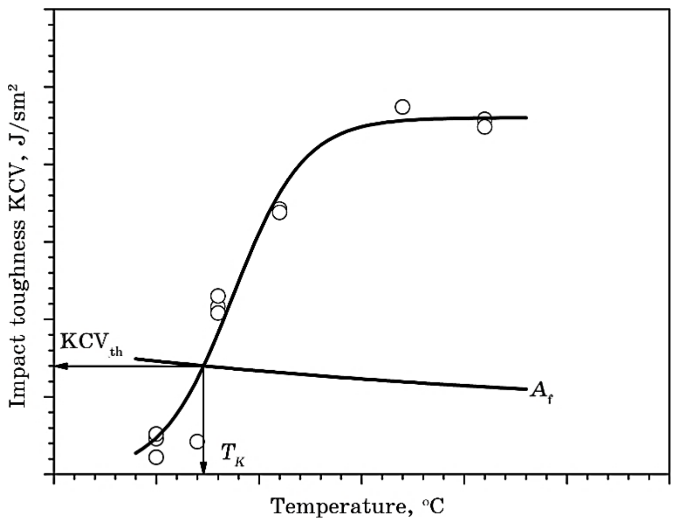

Fig. 1. Temperature dependences of impact toughness KCV and an energy of plastic deformation A_f at a fixed value of critical deformation e_f; KCV_{th} is threshold value of impact toughness; T_K is critical temperature of brittleness.

Substituting (4) into (3) we get:

$$A_f = V_Y \int_0^{e_f} \sigma_{0.2}^D(x,y,z) \left[\frac{e_i(x,y,z)}{0.002}\right]^{n(x,y,z)} de_i(x,y,z) . \tag{5}$$

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 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 σ_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:

$$A_{ef} = V_{ef}\sigma_{0.2}^D \left(\frac{1}{0.002}\right)^n \int_0^{e_f} \bar{e}_i^{\,n} d\bar{e}_i , \tag{6}$$

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 $e_i \approx 200$ s^{-1} [12]); $\bar{e}_i$ is the average value of the intensity of plastic deformations within the effective volume V_{ef}.

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

$$A_{ef} = V_{ef}\sigma_{0.2}^D \left(\frac{1}{0.002}\right)^n \frac{1}{1+n} e_f^{1+n} . \tag{7}$$

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,

$$A_{ef} = 1.36 V_{ef}\sigma_{0.2}^D e_f . \tag{8}$$

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 $h \approx 2R$ (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 $V_{ef} \approx 2$ 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 PNAE G-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),

$$V_{ef} = \frac{KCV_{\text{th}}}{1.36 e_c \sigma_{0.2}^{D}\left(T_{KF}\right)}, \tag{9}$$

where $\sigma_{0.2}^{D}\left(T_{KF}\right)$ 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]:

$$KCV = \frac{A}{F}. \tag{10}$$

Typically, the temperature dependence of KCV values is approximated by the following relationship [14]:

$$KCV = \left(\frac{USE}{2}\right)\left[1 + \tanh\left(\frac{T - T_0}{C}\right)\right], \qquad (11)$$

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

$$\sigma_{0.2} = \sigma_{0.2}(T_r) + C_1 \exp[-\beta T] - C_1 \exp[-\beta T_r], \qquad (12)$$

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 $e_c = 0.02$ for VVER-1000 base and weld metal in irradiated and non-irradiated condition.

Material	Φ, 10^{22}n/m^2	$\sigma_{0.2}$, MPa	$KCV_{\text{th}}^{\text{PNAE}}$, J/sm^2	T_{KF}^{PNAE}, °C	V_{ef}, mm^3	$\sigma_{0.2}^{D}(T_{KF})$, MPa	$KCV_{\text{th}}^{0.02V_{ef}}$, J/sm^2
			RPV steel (VVER-1000)				
Steel H	0	543	49	−36	2.152	837	49.8
	11.1	605	59	−18	2.482	874	52.0
	22.2	620	59	−20	2.433	892	52.0
Steel K	0	595	59	−81	2.090	1038	61.0
	18.2	663	59	−43	2.088	1039	61.0
Steel P	0	567	59	−37	2.317	936	54.4
	27.6	593	59	−34	2.264	958	56.0
	68.7	635	59	−23	2.200	986	57.6
Steel W	0	564	59	−73	2.197	987	58.1
	22.2	615	59	−14	2.262	959	60.3
	58.9	627	59	−10	2.245	966	61.2
Steel Y	0	612	59	−79	2.142	1012	59.3
	13.1	665	59	−50	2.134	1016	59.6
	27.3	683	59	−39	2.133	1017	59.8
Steel 15X2NMFA (slab 7)	0	576	59	−76	2.368	916	54.1
Steel 15X2NMFA (slab 5)	0	609	59	−46	2.575	843	51.9

TABLE 1 (*continuation*).

Material	Φ, 10^{22}n/m^2	$\sigma_{0.2}$, MPa	$KCV_{\text{th}}^{\text{PNAE}}$, J/sm^2	T_{KF}^{PNAE}, °C	V_{ef}, mm^3	$\sigma_{0.2}^{D}(T_{KF})$, MPa	$KCV_{\text{th}}^{0.02V_{ef}}$, J/sm^2
RPV weld metal (VVER-1000)							
Weld metal K	0	510	49	−62	1.946	926	54.0
	16.9	593	59	−32	2.263	959	56.0
Weld metal L	0	562	59	−21	2.167	1001	59.0
	33.5	648	59	33	2.104	1031	60.0
	43.5	603	59	25	2.183	994	54.8
Weld metal P	0	502	49	−57	1.914	941	55.1
	22.2	558	59	−11	2.306	941	55.4
	55.8	580	59	11	2.313	938	55.4
Weld metal W	0	437	49	−22	2.032	887	52.0
	17.4	565	59	−17	2.149	1009	59.3
	42.7	625	59	7	2.077	1044	61.2
Weld metal Y	0	545	49	−43	1.875	961	55.9
	20.1	590	59	20	2.373	914	53.9
	56.9	609	59	37	2.379	912	53.9
Weld metal Sv-10XGNMAA	0	471	49	−52	1.886	955	55.8
	8.9	608	59	−8	2.109	1029	60.6
	20.9	593	59	14	2.203	985	58.0

where $\sigma_{0.2}(T_r)$ is the yield strength at room temperature $T_r = 293$ K; $C_1 = \sigma_{\text{th}}$ is the stress, which characterizes the maximum magnitude of barriers overcome by thermal activation. The coefficient β depends on the strain rate $\dot{e}$ and density of mobile dislocations ρ_d and is evaluated by the following equation:

$$\beta = C_2 - C_3 \ln \dot{e}\,, \tag{13}$$

where $C_2 = k\left(b^2\omega_D\rho_d\right)/U_0$; ($k$ is the Boltzmann constant, ω_D 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 σ_a is as follows:

$$\sigma_a = \sigma_{0.2}^{293} - C_1 \exp\left(-\left(C_2 - C_3 \ln \dot{e}_0\right) T_0\right), \tag{14}$$

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

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

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

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

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

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

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

Yield strength $\sigma_{0.2}$ at 20°C, MPa	Impact toughness	
	E, J	KCV, J/sm^2
Before 304	23	29
304–402	31	39
402–549	39	49
549–687	47	59

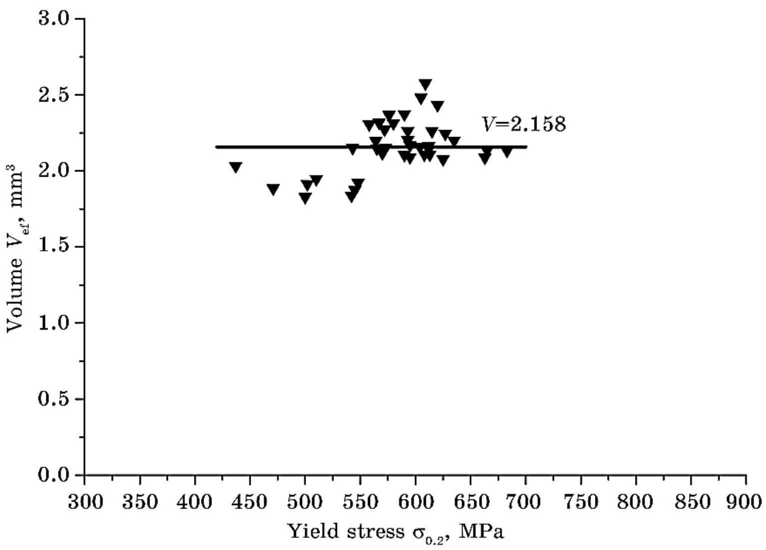

Fig. 2. The effective volume V_{ef} of the Charpy V-notch specimen for the RPV base and weld metal. Line is an average value $V_{ef} = 2.16$.

with a standard deviation of $\pm 8\%$. This is quite close to the estimate above $V_{ef} = 2.00$ mm^3.

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

$$KCV_{\text{th}} = 1.36 V_{ef} e_f \sigma^{D}_{0.2}(T_{KF}). \tag{16}$$

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

$$\begin{gathered}\left(\frac{USE}{2}\right)\left[1 + \tanh\left(\frac{T_{KF} - T_0}{C}\right)\right] = \\ = 1.36 V_{ef} e_f \left\{\sigma_a + C_1 \exp\left[-\left(C_2 - C_3 \ln \dot{e}_D\right) T_{KF}\right]\right\}.\end{gathered} \tag{17}$$

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 $KCV_{\rm th}$ for different ranges of $\sigma_{0.2}(T_r)$ (Table 3).

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

$$KCV_{th} = a + b\sigma_{0.2}\,, \tag{18}$$

where

$$a = 1.36V_{ef}e_f C_1\left\{\exp\left[-\left(C_2 - C_3\ln\dot{e}_D\right)T_{KF}\right] - \exp\left[-\left(C_2 - C_3\ln\dot{e}_D\right)T_K\right]\right\}, \tag{19}$$

$$b = 1.36V_{ef}e_f\,. \tag{20}$$

In accordance with Eqs. (18)–(20), the threshold level, $KCV_{\rm th}$ is not an unambiguous function of the yield strength $\sigma_{0.2}(T_r)$, 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 σ_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 $KCV_{\rm th}$ is characterized by the coefficient b.

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

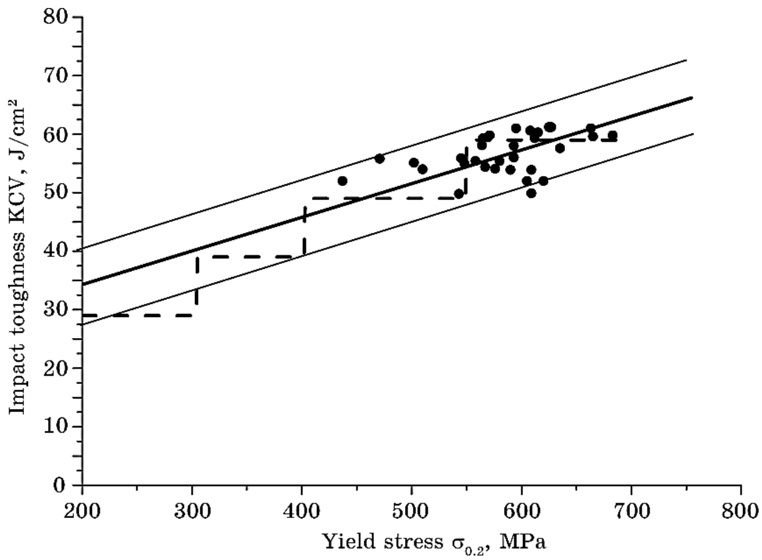

Fig. 3. Dependence of $KCV_{\rm th}$ values on the yield strength $\sigma_{0.2}(T_r)$ at room temperature under quasi-static loading conditions: solid lines—calculations by Eq. (18) at $a = 22.63 \pm 6.77$ J·cm^{-2}; dashed lines—the $KCV_{\rm th}$ values according to PNAE G-7-002-86.

and irradiated states. For this, the data in Fig. 3 were approximated using the relationship (18) provided that $b = 0.058\,\mathrm{J}/(\mathrm{cm}^2 \cdot \mathrm{MPa})$ ($e_f = 0.02$, $V_{ef} = 2.16$ mm^3). In this case, $a = 22.63 \pm 6.77$ 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 $KCV_{\mathrm{th}} = a + b\sigma_{0.2}$, where the influence of additional factors on KCV_{th} is taken into account by the variation of the parameter $a = 22.63 \pm 6.77$ 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

1. *Standard Practice for Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels*, ASTM E185-16 (2016).
2. K. Wallin, *Innovative Approaches to Irradiation Damage and Fracture Analy-*

sis, *ASME Pressure Vessels and Piping Conference-JSME Co-sponsorship (July 23–27, 1989, Honolulu, Hawaii)*.
3. B. Tanguy, J. Besson, R. Piques, and A. Pineau, *Engng. Fract. Mech.*, **72**: 49 (2005).
4. *Normy Raschyota na Prochnost Oborudovaniya i Truboprovodov Atomnykh Ehnergeticheskih Ustanovok* [Standards for Strength Calculation of Equipment and Pipelines of Nuclear Power Plants], PNAE G-7-002-86 (in Russian).
5. S. A. Kotrechko and Yu. Ya. Meshkov, *Problemy Prochnosti*, No. 4: 352 (2001) (in Russian).
6. S. A. Kotrechko, Yu. N. Podrezov, I. N. Maksimchuk, and A. V. Kranikov, *Mekhanicheskoe Razrushenie Materialov* [Mechanical Failure of Materials]. *Inorganic Materials Science* (Eds. G. G. Gnesin and V. V. Skorohod) (Kiev: Naukova Dumka: 2007), vol. **1** (in Russian).
7. S. A. Kotrechko, Yu. Ya. Meshkov, and G. S. Mettus, *Metallofiz. Noveishie Tekhnol.*, **12**, No. 6: 3 (1990) (in Russian).
8. S. A. Kotrechko and Yu. Ya. Meshkov, *Ukr. Phys. J.*, **36**, No. 7: 1087 (1991) (in Russian).
9. S. A. Kotrechko, Yu. Ya. Meshkov, G. S. Mettus, and D. I. Nikonenko, *Problemy Prochnosti*, No. 1: 72 (2000).
10. S. A. Kotrechko and Yu. Ya. Meshkov, *Problemy Prochnosti*, No. 2: 55 (2009) (in Russian).
11. S. A. Kotrechko and Yu. Ya. Meshkov, *Predelnaya Prochnost. Kristally, Metally, Konstruktsii* [Ultimate Strength. Crystals, Metals, Structures] (Kiev: Naukova Dumka: 2008) (in Russian).
12. *Materialy Metalevi. Vyprobuvannya na Udarnyi Vygyn za Charpi. Chastyna 1. Metody Vyprobuvannya* [Metallic Materials. Charpy Impact Bending Test. Part 1. Test Method], DSTU EN 10045-1:2006 (in Ukrainian).
13. S. Kotrechko, B. Strnadel, and I. Dlouhy, *Appl. Fract. Mech.*, **47**: 171 (2007).
14. *Inzhenernaya, Nauchnaya i Tekhnicheskaya Podderzhka. Metodika Opredeleniya Radiatsionnogo Okhrupchivaniya Metalla Korpusov Reaktorov i Srokov Vygruzki Obraztsov-Svideteley po Rezultatam Ikh Ispytaniy*, [Engineering, Scientific and Technical Support. Method for Determining the Radiation Embrittlement 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).
15. F. J. Zerilli, and R. W. Armstrong, *J. Appl. Phys.*, **65**, No. 5: 1816 (1987).
16. V. D. Yaroshevich and D. G. Ryvkina, *Fiz. Met. Metalloved.*, **31**, Iss. 6: 1293 (1971) (in Russian).