EXPERIMENTAL EVALUATION OF δ_{1c}-CURVE TEMPERATURE SHIFT AND BRITTLE-TOUGH TRANSITION OF STRUCTURAL STEELS AND WELDED JOINTS BY THE RESULTS OF STANDARD TESTS

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Investigation results are given on fracture toughness based on the deformation criterion for the most common domestic low-alloy structural steels of different thicknesses. An approach to evaluation of the brittle-tough transition temperature depending on the thickness of the investigated rolled metal is suggested. Shift of the basic deformation δ_{1c}-curve depending on the thickness of the rolled metal and its standard strength characteristics was experimentally verified.

Keywords: *structural steels, welded joints, impact toughness, Charpy specimen, crack resistance characteristics, plane deformation, metal thickness, temperature shift, brittle-tough transition*

Conventional criteria of transition from the plane stressed state to plane strain are insufficiently studied and require an experimental confirmation. The approach suggested in study [1] to possible evaluation of temperature shift for deformation criterion δ_{1c} depending on the specimen thickness is not an exception either, and requires an experimental verification as well.

Study [1] suggested that the lower temperature bound, where it is possible to make some changes when using the deformation criterion of fracture mechanics, should be limited by temperature $T_{28\ \mathrm{J}}$, at which the Charpy impact specimen fracture energy is 28 J at the lower bound of scatter. This limitation is of a certain interest, as it allows comparing temperature shifts both by the load and deformation criteria of fracture mechanics relative to a single point corresponding to $T_{28\ \mathrm{J}}$ for standard Charpy impact specimens.

Below we give results of experimental studies of metal of the welded joints on the most common low-alloy structural steels. The temperature shift of the deformation δ_{1c}-curve was determined according to study [1].

Fracture toughness of weld metal. Consider investigation results on the characteristic of crack resistance δ_c (δ_{1c}) of the weld metal made with electrodes of the ANO-TM grade (base metal 09G2S, thickness t = 40 mm).

The weld was made in several passes into the X-groove, after which the resulting welded joint was cut normal to the weld axis into pieces to make the following test specimens:

- three-point test specimens according to GOST 25.506–85 (type 4) to determine deformation characteristic δ_c (δ_{1c});
- impact bend test specimens (Charpy specimens) according to GOST 9454–78 (type 9);
- tensile test specimens according to GOST 6996–66 (type 2).

Specimens for evaluation of characteristic δ_c and for impact bend tests, having thickness of 35 mm, were made with a notch oriented along the weld axis, normal to the plate plane. Crack opening displacement δ_c was determined in compliance with MP-170–85.

According to [1, 2], crack resistance characteristic δ_{1c} under the plane strain conditions was determined from the results of standard mechanical tests:

$$\delta_{1c} = 0.5Aa_v/\sigma_{0.2}, \tag{1}$$

where a_v is the impact toughness of the Charpy specimens (KCV) at the corresponding test temperatures, J/cm^2; A is the correlation coefficient (in the given case, A = 0.1 for low-alloy and low-carbon steels); and $\sigma_{0.2}$ is the yield stress of the material, MPa.

The specimens were cooled with liquid nitrogen in a petrol bath. Temperature of the specimens during the tests was monitored by using a thermocouple.

Mechanical properties of the weld metal made with electrodes ANO-TM at T_{test} = +20 (–60) °C were as follows: σ_t = 569 (598) MPa, $\sigma_{0.2}$ = 428 (455) MPa, δ = = 30.7 (30) %, and ψ = 67.7 (67) %.

The test results for the weld metal are presented in Table 1 and in Figures 1–3.

Fracture of the specimens was of a brittle and quasi-brittle character over the entire temperature range used to investigate toughness characteristic δ_c. Brittle fracture of the specimens until reaching the general yield was observed at a temperature down to –20 °C. At a temperature of –15 °C, fracture of a specimen took place at the point of reaching the general yield of the material beneath the notch. At the same time, no marked stable crack growth was fixed, as can be well seen in Figure 2.

Evaluation of characteristic δ_c at room temperature and analysis of the specimen fracture surfaces showed

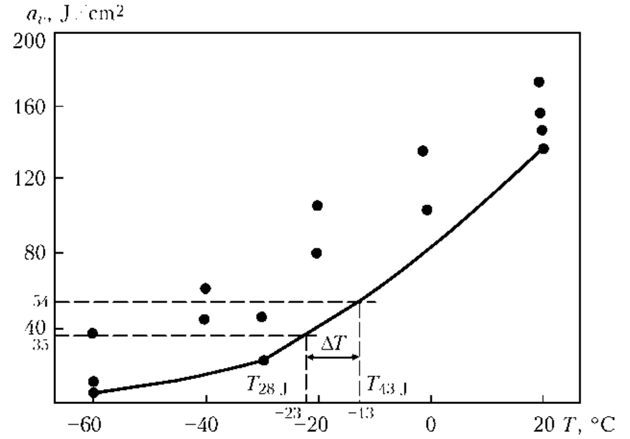

Figure 1. Temperature dependence of impact toughness (minimal values) of weld metal made by using electrodes ANO-TM (ΔT — value of temperature shift from formula (6))

an insignificant stable crack growth to a depth of about 0.4–0.6 mm, which was followed by an unstable crack growth by the quasi-brittle mechanism (see Figure 2). No drop of a load during the stable crack growth was fixed in the loading diagrams.

To plot the theoretical curve shown in Figure 3, we use the minimal values of specific impact toughness of the Charpy specimens from the studied welded joint for determination of the temperature shift of basic curve δ_{1c}. Then we find a temperature corresponding to a value of 35 J/cm^2 in the curve (in this case, it was −23 °C) (see Figure 1). And, by using linear extrapolation, we determine yield stress $\sigma_{0.2}$ and tensile strength σ_t of the welded joint corresponding to this temperature (441 and 583 MPa, respectively).

By involving the relationship from study [3] between the calculated value of strain hardening n^c and strength characteristics $\sigma_{0.2}$ and σ_t of the material

$$n^c = -0.18 + 0.22\sigma_t/\sigma_{0.2}, \tag{2}$$

we find the calculated value of n^c at a temperature of −23 °C ($n^c = 0.11$).

If strain ε_t at the point of a loss of plastic stability of the material is known [4], the value of strain hardening n can be calculated more precisely from the following formula:

$$n = \varepsilon_t/(1 + \varepsilon_t). \tag{3}$$

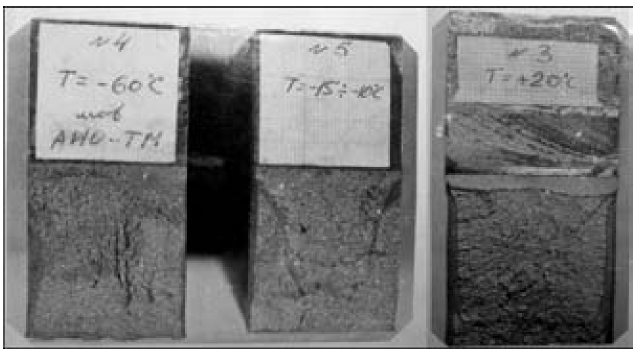

Figure 2. Fracture surface of specimens tested to three-point bending at different temperatures

Table 1. Crack resistance characteristics δ_c of the weld made with electrodes ANO-TM at three-point bending of 35 mm thick specimen

T_{test}, °C	δ_c, mm	Probable stable growth of crack, mm
−60	0.024	–
−36	0.044	–
−23	0.078	–
−15	0.139	–
+20	0.266	Up to 0.4
+20	0.323	Up to 0.6

According to studies [1, 5], the value of characteristic δ_c is expressed in terms of a function of n, β, α and δ_{1c}:

$$\delta_c = f(\beta(t))\delta_{1c}, \tag{4}$$

where $f(\beta(t))$ at $t > 10$ mm can be determined from the following expression:

$$f(\beta(t)) = \left(\frac{2}{\sqrt{3}}\right)^{\frac{n+1}{n}} \times$$

$$\times\Big[1 - \alpha + \alpha^2 + \frac{(1 - 10.24/(t + 5.24))(1 + \alpha)}{2}\times$$

$$\times\left\{\frac{(1 - 10.24/(t + 5.24))(1 + \alpha)}{2} - \alpha - 1\right\}\Big]^{\frac{1-n}{2n}} \times \tag{5}$$

$$\times\left\{1 - \frac{(1 - 10.24/(t + 5.24))(1 + \alpha) + 2\alpha}{4}\right\}/(1 - \alpha)^{1/n}.$$

To simplify, take a mean value of $\alpha = 0.3$ [1, 6] for the given welded joint with $f(\beta(t))$ at a temperature of −23 °C.

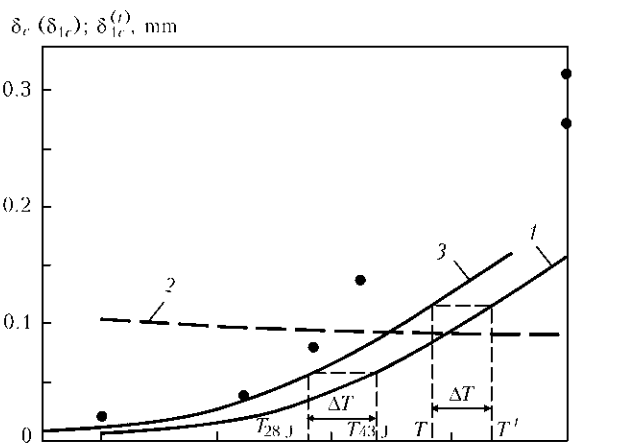

Figure 3. Temperature dependence of crack resistance characteristics of metal: *1* — theoretical curve δ_{1c} calculated from formula (1); *2* — condition from formula (9); *3* — theoretical curve $\delta_{1c}^{(t)}$ at ΔT = 10 °C calculated from formula (7); points — experimental values of δ_c

Given that with the specific fracture energy of the Charpy specimens equal to 35 J/cm^2 the temperature is only −23 °C, a change in yield stress of the studied welded joint is insignificant and, therefore, can be ignored. In this case, based on study [1], the link between temperature shift ΔT and basic deformation curve δ_{1c} can be expressed by the following dependence:

$$a_v^{T_{28\,\mathrm{J}} + \Delta T} \approx a_v^{T_{28\,\mathrm{J}}} f(\beta(t)) = 54\ \mathrm{J/cm^2}. \qquad (6)$$

The corresponding value of impact toughness is shown in Figure 1. It can be seen from the Figure that the value of impact toughness of the Charpy specimen equal to 54 J/cm^2 corresponds to a temperature of −13 °C. Therefore, temperature shift ΔT is 10 °C.

By using the approach suggested in study [1], it is possible to find theoretical deformation curve $\delta_{1c}^{(t)}$ shown in Figure 3 by shifting basic dependence (1) to a value of ΔT:

$$\delta_{1c}^{(t)} = 0.5 A a_v^{(t)} / \sigma_{0.2}^{(t)}, \qquad (7)$$

where $\delta_{1c}^{(t)}$ is the corrected characteristic of fracture toughness δ_{1c} on a condition of a through crack propagating in a structural element with thickness t and temperature T; $a_v^{(t)}$ is the impact toughness of the Charpy specimen corresponding to corrected temperature T^t allowing for thickness $T^t = T + \Delta T$; and $\sigma_{0.2}^{(t)}$ is the yield stress at corrected temperature T^t.

As seen from Figure 3, calculated curve $\delta_{1c}^{(t)}$ describes well enough the experimental values of δ_c.

It should be noted that the test temperature of impact specimens equal to +20 °C does not yet provides the upper values of specific fracture energy $a_v^{\max}$ in the tough state along the lower bound of scatter. This makes evaluation of characteristic δ_i (critical crack opening displacement at the moment of initiation of fracture in the tough state) from the results of the impact tests somewhat difficult. At the same time, an insignificant stable tough growth of a crack to a depth of about 0.4–0.6 mm, as well as achieving the general yield state of the material beneath a notch were fixed in determination of characteristic δ_c at room temperature and analysis of specimen fracture surfaces. Therefore, the value of δ_i in the general yield state beneath the notch can be evaluated allowing for this fact and for the following dependence from study [2]:

$$\delta_c = \delta_i + \Delta l \frac{\sigma_\mathrm{t}}{\sigma_{0.2}} \frac{n}{(1-n)^2}, \qquad (8)$$

where Δl is the value of the stable crack growth.

It follows from expressions (1) and (8), as well as from the data of Table 1 that $\delta_i \approx 0.2$ mm.

Then, allowing for dependence (1), the value of the specific fracture energy in the tough state can be easily found from the lower bound of the scatter ($a_v^{\max} = 170$ J/cm^2).

At the same time, when using the non-linear fracture mechanics approaches for qualification of welded joints on a number of critical structures (deepwater off-shore stationary platforms, main pipelines, etc.), first of all it is necessary to eliminate the probability of brittle fracture of structural elements having a defect in a region of nominal elastic strains.

Thus, according to the requirements [7] worked out in collaboration with CRISM «Prometey» for metal of the welded joints on the most critical and heavy-loaded structural elements, the value of critical crack opening displacement should meet the following condition:

$$\delta_c \geq 1.35 t \frac{\sigma_{0.2}}{E}, \qquad (9)$$

where E is the elasticity modulus of the material, MPa; and $\sigma_{0.2}$ is the proof stress of this material, MPa.

This level at $\sigma_{0.2}$ = 360–450 MPa is close to the requirements of the Canadian standard [6], as well as standards DNV and API for steels used in underwater and ground-surface pipelines [8].

By assuming that $\delta_c = \delta_{1c}^{(t)}$, condition (9) can be presented in the following form:

$$\delta_{1c}^{(t)} \geq 1.35 t \frac{\sigma_{0.2}}{E}. \qquad (10)$$

As seen from Figure 3, the point of intersection of curves *2* and *3* almost coincides with the brittle-tough transition temperature, where the stable crack growth begins.

Allowing for dependence (7) and proceeding from expression (10), the requirement to impact toughness depending on the thickness of a structural element and yield stress of the material in this case can be written down as follows:

$$a_v^{(t)} \geq 0.27 t \frac{\sigma_{0.2} \sigma_{0.2}^{(t)}}{EA}, \qquad (11)$$

where yield stresses $\sigma_{0.2}$ and $\sigma_{0.2}^{(t)}$, and elasticity modulus E are expressed in megapascals, and thickness t is expressed in millimeters in order to preserve dimensions and match formulae (7) and (10).

At low values of temperature shift ΔT, it can be assumed in the first approximation that $\sigma_{0.2} \approx \sigma_{0.2}^{(t)}$. Then expression (11) will have the following form:

$$a_v^{(t)} \geq 0.27 t \frac{\sigma_{0.2}^2}{EA}. \qquad (11a)$$

Relationship (11a) between the values of impact toughness, thickness and standard strength properties differs substantially from the dependence given in study [8]

$$a_v\ [\mathrm{J/cm^2}] \geq 0.125 \sigma_{0.2}\ [\mathrm{MPa}]. \qquad (12)$$

Table 2. Mechanical properties of welded joint (T = 20 °C)

Material	$\sigma_{0.2}$, MPa	σ_t, MPa	n^c acc. to (2)	δ, %	ψ, %
Base metal	407–424 / 415	585–592 / 588	0.13	23.6–24.6 / 24.3	67.9–69.8 / 69.1
Weld metal	416–450 / 433	540–561 / 550	0.10	23.6–24.6 / 24.3	66.0–67.9 / 66.9

It can be seen from expression (11a) that the requirement to impact toughness should be directly proportional to the square of yield stress of the material and thickness of the structural element, in contrast to the linear dependence from formula (12).

To illustrate, Figure 4 shows a three-dimensional plot of the required value of impact toughness $a_v^{(t)}$ depending on the thickness of the structural element and yield stress of the investigated welded joint made with electrodes ANO-TM in the brittle-tough transition range.

Fracture toughness of heat-affected zone of welded joint. To minimise heterogeneity of the welded joint and decrease error in evaluation of strength properties of the HAZ metal, mechanical properties of the weld metal were chosen to be close to those of the base metal. For this purpose, and to provide a straighter embrittlement zone parallel to the plate thickness, the welded joint was made with the K-groove by using electrodes UONI-13/55, the base metal being 25 mm thick steel 10KhSND.

Mechanical properties of the weld and base metals are given in Table 2.

Investigation results on evaluation of the characteristic of fracture toughness δ_c and value of impact toughness a_v within the studied temperature range are presented in Table 3 and in Figures 5 and 6.

It should be noted that the given investigation results characterise crack resistance of the welded joint in the HAZ metal only at a distance of 1 mm from the fusion line.

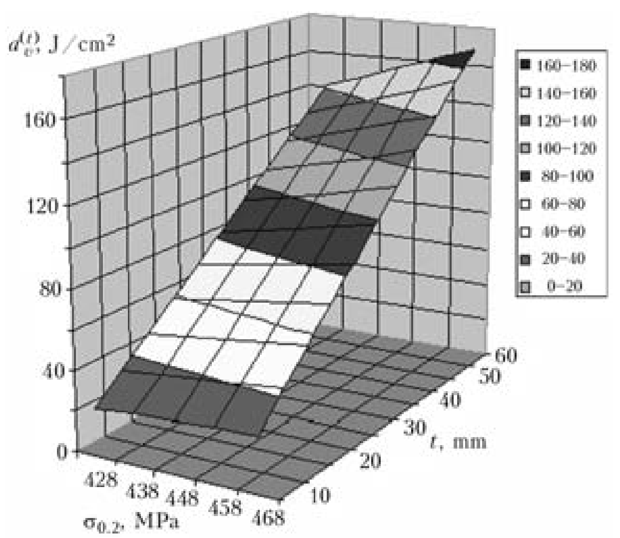

Figure 4. Values of impact toughness from formula (11a) for the welded joint made with electrodes ANO-TM in the brittle-tough transition range depending on thickness of a structural element and its strength properties

Like for the weld, the temperature corresponding to a value of 35 J/cm^2 (−25 °C in this case) is found from the minimal temperature curve of impact toughness shown in Figure 5.

We take values corresponding to the mean values of the base metal and weld equal to 424 and 569 MPa, respectively, as yield stress $\sigma_{0.2}$ and tensile strength σ_t in HAZ.

Using formulae (2) and (5), we determine values of n^c and $f(\beta)$ ($n^c = 0.115$; $f(\beta) = 2.02$). Then, according to expression (6), $a_v^{T_{28\,J} + \Delta T} \approx 70$ J/cm^2.

As seen in the curve in Figure 5, the value of impact toughness of the Charpy specimen equal to 70 J/cm^2 corresponds to a temperature of −5 °C. Therefore, temperature shift ΔT is 20 °C.

In turn, this allows deformation curve δ_{1c} shown in Figure 6 to be shifted to the same value. Curve *1* in Figure 6 was plotted by using the minimal experimental values of impact toughness of the Charpy specimens from the investigated zone of the welded joint.

Calculated theoretical deformation curve $\delta_{1c}^{(t)}$ corresponding to a temperature shift of 20 °C is shown in Figure 6. As seen from the Figure, the obtained point of intersection of curves *2* and *3* almost coincides with the brittle-tough transition temperature, where the stable crack growth begins.

Fracture toughness of low-alloy structural steels. Consider investigation results on fracture characteristics δ_c (δ_{1c}) in the plane of rolled structural steels 09G2S, 10KhSND and 14G2AF.

Table 3. Characteristics of crack resistance δ_c and impact toughness of welded joint in the HAZ metal on the three-point bend test specimen 25 mm thick

T_{test}, °C	δ_c, mm	δ_c^{max}, mm	$f(\beta(t))$ acc. to (5)	a_v, J/cm^2
+20	–	–	2.02	122; 120; 130
−25	0.245	–	–	–
−25	–	0.670	–	–
−30	–	–	–	27; 31; 32
−40	0.045	–	–	–
−55	0.100	–	–	–
−60	0.065	–	–	16; 22; 27

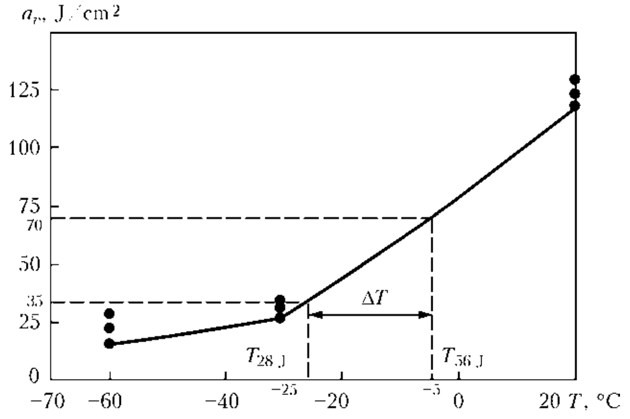

Figure 5. Temperature dependence of impact toughness of the near-weld zone: points — experimental values (the curve was plotted using the minimal experimental values)

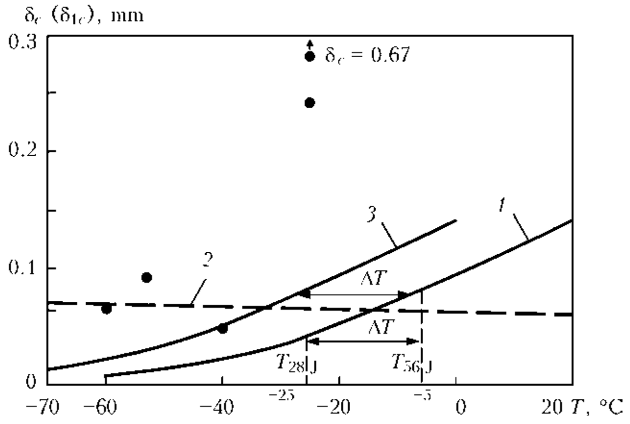

Figure 6. Temperature dependence of crack resistance characteristics: *1* — theoretical curve δ_{1c} calculated from formula (1); *2* — condition from formula (10); *3* — theoretical deformation curve $\delta_{1c}^{(t)}$ at ΔT = 20 °C calculated from formula (7); points — experimental values of δ_c

Mechanical properties and strain hardening factor n^c calculated from formula (2) for the investigated structural steels in the rolling plane are given in Table 4.

Chemical composition of the investigated steels is given in Table 5.

To determine crack resistance characteristics and impact toughness values of steel 10KhSND in rolling plane (with plate thicknesses of 40 and 25 mm), the 37 and 25 mm thick specimens were made for evaluation of characteristic δ_c according to the recommendations of GOST 25.506–85 (type 4). Similarly, for evaluation of characteristic δ_c of structural steels 09G2S, 09G2S-Sh and 14G2AF, the 19, 70 and 36 mm thick specimens, respectively, were made from them. The Charpy specimens for the above materials were cut from the central part of the rolled metal through thickness with a notch oriented in the same direction as for evaluation of characteristic δ_c.

Table 4. Mechanical properties and strain hardening factor n^c of structural steels

Steel grade	t, mm	T_{test}, °C	σ_y, MPa	σ_t, MPa	n^c	δ, %	ψ, %
10KhSND	25	+20	353.4	523–530 / 526	0.147	32.7–33.0 / 32.6	67.9
		−30	422.7	627–630 / 526	0.147	33.7–36.6 / 35.1	73.3
		−60	453.5–488.2 / 470.8	633–682 / 668	0.133	28.7–36.6 / 31.6	67.9–71.6 / 69.7
	37	+20	350.0	544–551 / 545	0.162	32.0	75.0
		−30	346.5–381.6 / 363.8	561–566 / 564	0.161	30.0–36.0 / 33.6	72.0
		−60	380.2	590	0.161	32.3–34.0 / 33.0	71.6–73.3 / 72.0
09G2S	19	+20	294.8–315.6 / 306.1	503–517 / 508	0.185	36.6–38.6 / 37.4	78.2
		−30	336.1–329.1 / 332.6	544–551 / 547	0.182	38.3	78.2
		−60	347.0–353.4 / 350.2	589	0.190	40.0	75.0
09G2S-Sh	70	+20	275.0	450	0.180	39.1	
		−60	332.0	530	0.171	40.0	
		−70	384.0	556	0.139	39.0	
14G2AF	40	+20	400.0–415.0 / 406.0	576–586 / 581	0.135	32.0–33.3 / 32.6	67.2–67.7 / 67.5
		−60	430.0	612	0.133	32.0	67.0

Table 5. Actual chemical composition of investigated structural steels, wt.%

Steel grade	Specimen thickness, mm	C	Mn	Si	Ni	Cu	S	P	Cr
10KhSND	25	0.079	0.73	0.944	0.61	0.40	0.027	0.022	0.74
10KhSND	37	0.073	0.55	0.844	0.59	0.42	0.023	0.014	0.73
09G2S	19	0.050	1.13	0.670	0.02	0.05	0.045	0.017	0.10
14G2AF	40	0.200	1.67	0.458	0.09	0.35	0.036	0.030	0.17

Table 6. Results of three-point bend tests of Charpy specimens (orientation of specimens — across the rolling direction)

Steel grade	t, mm	T_{test}, °C	a_v, J/cm^2	a_v^{max}, J/cm^2	ΔT, °C
10KhSND	25	+20	82; 80; 68	82	24
		0	63; 59		
		−30	30; 28; 26		
		−60	21; 18		
10KhSND	37	+20	210; 192; 181	210	17
		0	175; 150; 131		
		−20	106; 85; 78		
		−40	72; 58; 51		
		−60	52; 47; 35		
09G2S	19	+20	315; 198; 196	315	20
		−20	155; 87; 75		
		−40	92; 55; 52		
		−60	72; 14; 7		
		−70	22; 16; 15		
09G2S-Sh	70	+20	>375	>375	1
		0	>375		
		−20	>375		
		−30	>375; 300; 314		
		−40	234; 285; 282		
14G2AF	36	−60	212; 207; 229	256	6
		−80	20; 15; 9		
		+20	256; 256		
		0	205; 196; 161		
		−40	150; 97; 92		
		−70	61; 51; 15		

Table 7. Results of evaluation of crack resistance characteristics δ_c (δ_{1c})

Steel grade	t, mm	$f(\beta)$ acc. to (5)	$T_{28\,J}$, °C	$a_v^{T_{28\,J}+\Delta T}$, J/cm²	T_{test}, °C	δ_c (δ_i), mm
10KhSND	25	1.73	−22	60	−20	0.365
					−40	0.040
					−53	0.115
					−60	0.038
10KhSND	37	1.36	−60	48	−25	0.227
					−40	0.099
					−60	0.117
09G2S	19	1.90	−48	66	+20	(0.500)
					+20	(0.480)
					+20	(0.480)
					−37	0.475
					−40	0.515
					−40	0.545
					−51	0.305
					−53	0.190
					−60	0.125
					−63	0.480
					−63	0.510
					−67	0.085
09G2S-Sh	70	1.16	−77	40	−65	0.950
					−73	0.373
					−74	0.133
					−75	0.202
14G2AF	36	1.44	−62	50	+20	(0.305)
					−40	0.300
					−53	0.190

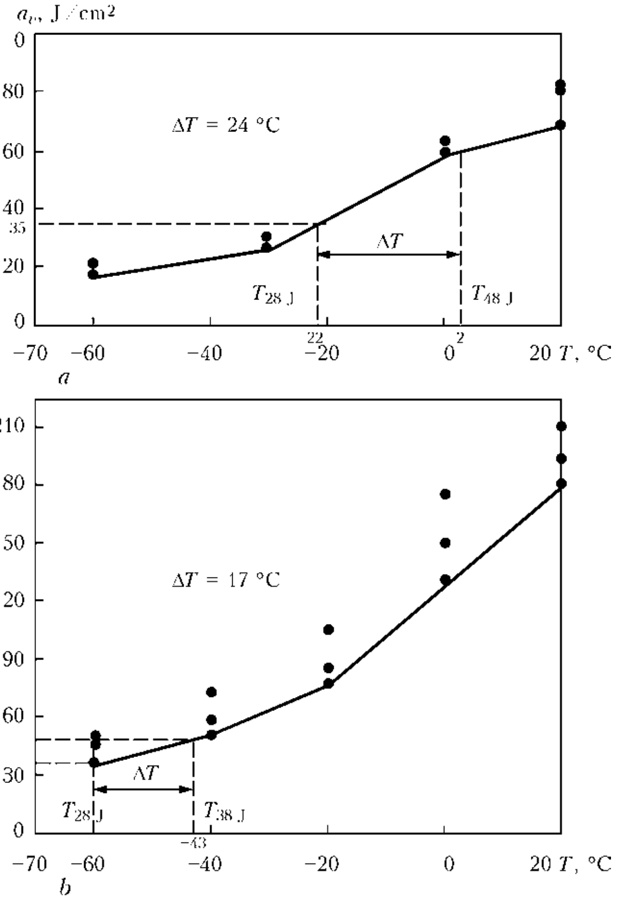

Figure 7. Temperature dependence of impact toughness of rolled steel 10KhSND 25 (a) and 37 (b) mm thick (see designations in Figure 5)

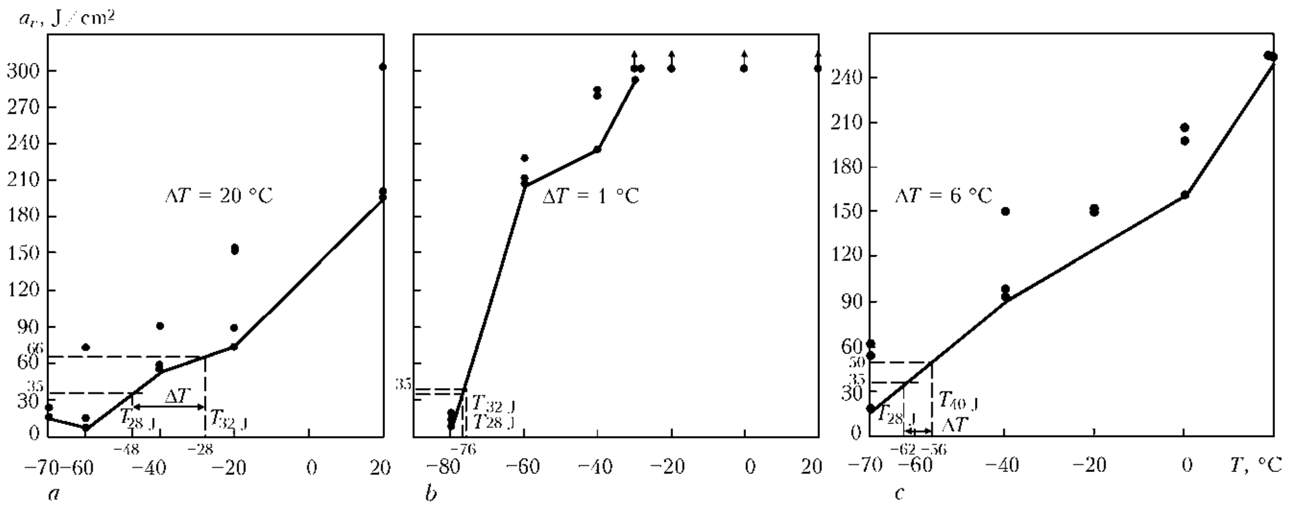

Figure 8. Temperature dependencies of impact toughness of 19 mm thick rolled steel 09G2S (a), 70 mm thick rolled steel 09G2S-Sh (b), and 36 mm thick rolled steel 14G2AF (c) (see designations in Figure 5)

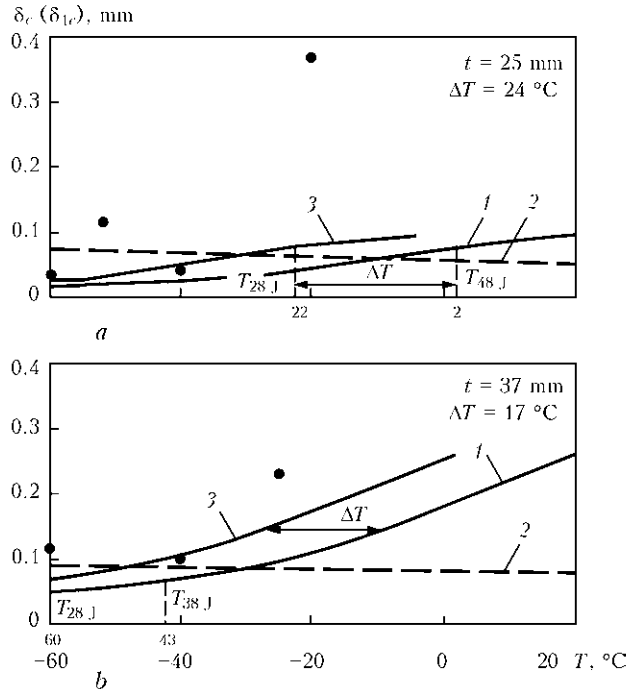

Figure 9. Temperature dependence of crack resistance characteristics of rolled steel 10KhSND: *1* — theoretical curve δ_{1c} calculated from formula (1); *2* — condition from formula (10); *3* — curve $\delta_{1c}^{(t)}$ calculated from formula (7)

The impact bend test results are presented in Table 6 and in Figures 7 and 8.

As seen from Table 6 and Figure 7, the investigated 25 mm thick rolled steel 10KhSND is characterised by too low values of fracture energy a_v^{max} and increased temperature to meet the requirement of 28 J.

The value of δ_c was determined under static loading of the specimens at three-point bending within a temperature range of −75 to + 20 °C. Displacement of the crack edges was measured by using two displacement sensors. The test results are presented in Table 7 and in Figures 9 and 10. Also, it should be noted that toughness characteristic δ_c at temperatures below −20 °C were determined under the maximal load.

To determine δ_i in tough fracture of steels 09G2S and 14G2AF, stable crack growth Δl was fixed during the tests conducted at room temperature, after that the value of critical crack opening displacement corresponding to the beginning of tough fracture was evaluated from the results of tests of several specimens [9, 10].

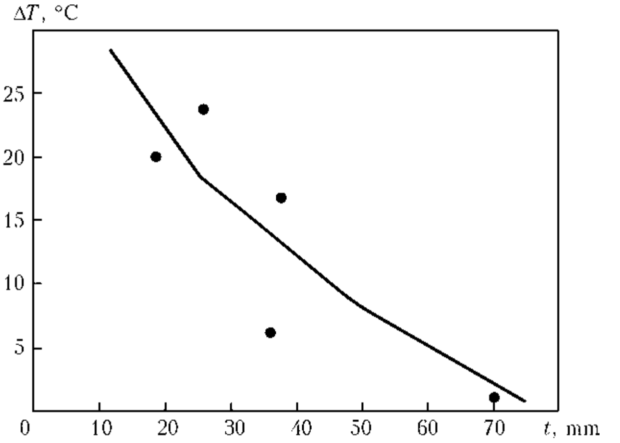

Figure 11. Dependence of temperature shift ΔT on thickness of specimens tested to three-point bending under static loading: curve — recommended temperature shift C according to standard ASTM E 1921–97; points — experimental values of ΔT

Corrected calculated fracture toughness characteristic $\delta_{1c}^{(t)}$ obtained with a temperature shift of curve *1* to the ΔT value, according to Table 7, is shown in Figures 9 and 10.

As seen from the data presented, the proposed calculated values of $\delta_{1c}^{(t)}$ describe well enough the experimental values of deformation characteristic δ_c at the lower bound of their scatter depending on the specimen thickness. This is indicative of the fact that the selected characteristics affecting the plane strain to plane stressed state transition condition depending on the specimen thickness are correct.

As far as a change in temperature shift C according to standard ASTM E 1921–97 is concerned, despite the general tendency to decrease in the ΔT value with increase in thickness of the specimens investigated, no direct relationship was observed between these two characteristics. The obtained experimental values of ΔT depending on thickness of the specimens tested to three-point bending are shown in Figure 11. As seen from the Figure, the recommended temperature shift C according to standard ASTM E 1921–97 only limits the temperature range of search for the values that correspond to K_{jc} = 100 MPa·m$^{0.5}$, as it describes only the mean values of the experimental data.

In general, it should be noted that, according to the results of experimental verification, when determining the temperature shift by using the approach

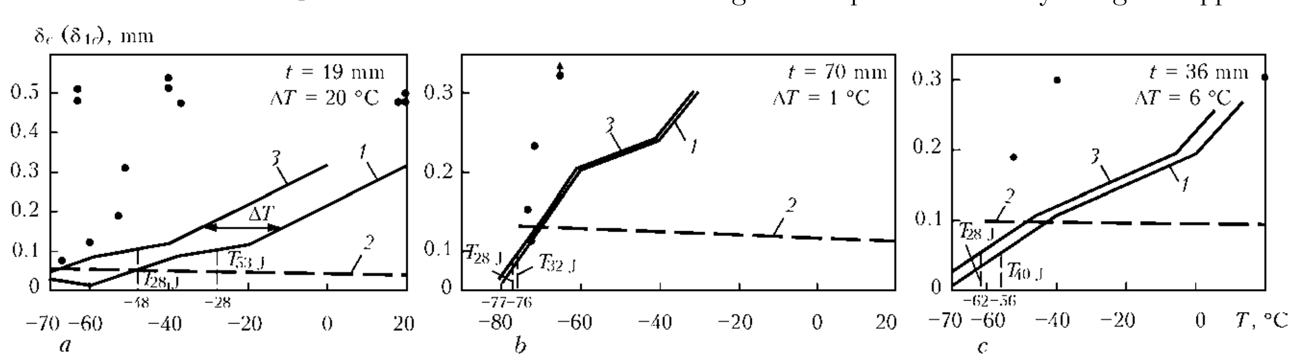

Figure 10. Temperature dependence of crack resistance characteristics of rolled metal: *a* — steel 09G2S; *b* — steel 09G2S-Sh; *c* — steel 14G2AF; *1–3* — same as in Figure 9

suggested in study [1] it is necessary to take into account both deformation and strength characteristics of the material. This makes it possible to more reasonably approach both selection of the temperature shift and determination of the temperature transition allowing for thickness of a structural element.

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