EVALUATION OF TEMPERATURE SHIFT DEPENDING UPON THE SPECIMEN THICKNESS BY THE FORCE AND DEFORMATION CRITERIA OF FRACTURE MECHANICS

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Relationships between impact toughness *KCV* and crack resistance characteristics of a material, derived by the E.O. Paton Electric Welding Institute, are applicable for a case where the plane-strain state forms within the defect zone. If this condition is violated, evaluation of crack resistance of structural members is not always optimal. To solve this problem, it is suggested that temperature shift in basic curves of fracture toughness characteristics should be evaluated depending upon the thickness of an object under investigation. It is shown that, in addition to thickness of a specimen, the temperature shift should also be evaluated by allowing for strength properties of a material and its welded joints.

Keywords: *impact toughness, Charpy specimen, crack resistance characteristics, plane strain, thickness effect, temperature shift, strain hardening of material*

Relationships between impact toughness *KCV* and crack resistance characteristics of a material (δ_{Ic}, K_{Ic}), derived by the E.O. Paton Electric Welding Institute, are applicable for a case where the plane-strain state forms within the defect zone [1, 2]. If this condition is violated, such evaluation of crack resistance of structural members is not always optimal.

In practice, when using fracture mechanics approaches, there are cases where it is necessary to specify conditions of transition from the plane strain (PS) to plane-stress state (PSS) in the presence of developed plastic strains, when strain characteristic δ_{Ic} or J_{Ic}-integral can be applied.

For critical crack opening displacement δ_{Ic} and J_{Ic}, unlike critical stress intensity coefficient K_{Ic}, conditions of transition from PS to PSS are little studied as yet. For example, it is suggested in technical literature that the measured level of values of fracture toughness at plane strain, depending upon thickness t of a specimen, should be limited by the following expression:

$$t > m\delta_{Ic} \approx mJ_{Ic}/H\sigma_y, \qquad (1)$$

where H and m are the coefficients, the values of which vary from 1 to 2 and from 25 to 100, respectively.

It follows from (1) that at different values of coefficients H and m the limiting requirements to specimen thickness can change 8 times. Such substantial deviations indicate that the authors are uncertain in adequacy of the choice of the suggested requirement to the specimen thickness for determination of the PS to PSS transition conditions in the case of through cracks. Probable errors in this case may lead both to catastrophic consequences with a conservative estimation of crack resistance, and to a groundless rise in cost of a structure because of the non-optimal choice of materials.

A step toward elimination of uncertainties in condition (1) was made in standard ASTM E 1921–97 [3] in the form of an attempt to relate the PS to PSS transition conditions to a tough-brittle transition temperature for specimens of different thicknesses.

For ferritic steels with a yield stress of 275 to 825 MPa, the following approximation of temperature dependence of K_{jc} was made from the results of testing specimens with a thickness of up to 100 mm:

$$K_{jc(\mathrm{mean})} = 30 + 70 \exp [0.019(T - T_0)] \ [\mathrm{MPa}\sqrt{\mathrm{m}}], \qquad (2)$$

where $K_{jc(\mathrm{mean})}$ is the mean value of K_{jc} determined on 25 mm thick specimens; and T_0 is the temperature corresponding to $K_{jc} = 100$ MPa$\sqrt{\mathrm{m}}$, which was determined in testing 25 mm thick specimens, °C.

As follows from the recommendations of standard ASTM E 1921–97, temperature $T^{(t)}_{100}$ for specimens with a thickness of about 100 mm, when the $K_{jc} = K_{Ic} = 100$ MPa$\sqrt{\mathrm{m}}$ condition is met, corresponds to temperature $T_{28\,\mathrm{J}}$, at which the fracture energy of Charpy specimens is equal to 28 J, i.e. in fact, it is the case of using the relationship between impact toughness of the Charpy specimens and criterion K_{Ic} given in study [1].

For specimens of a smaller thickness, the PS to PSS transition occurs at lower temperatures. To find the $K^{(t)}_{jc} = 100$ MPa$\sqrt{\mathrm{m}}$ value, this circumstance is taken into account by using corresponding temperature shift $T^{(t)}$:

$$T^{(t)} = T_{28\,\mathrm{J}} + C, \qquad (3)$$

where C is the recommended temperature shift depending upon the size of standard specimens with a

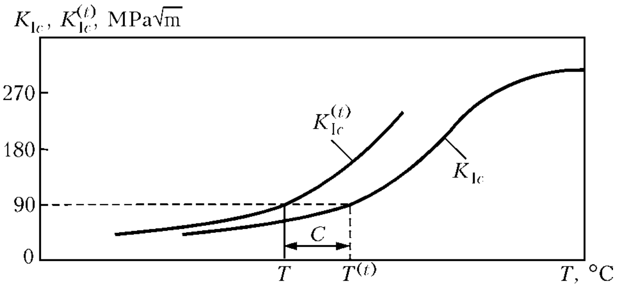

Figure 1. Graphic interpretation of temperature shift from formula (3), where the C value was obtained with decrease in specimen thickness

thickness of 10, 12.5, 25, 50, 75 and 100 mm for three-point bending or eccentric tension tests; and the values of C are assumed to be equal to −32, −28, −18, −8, −1 and +2 °C, respectively.

This approach makes it possible to evaluate resistance of a material to propagation of a through crack, allowing for characteristic violations of the PS condition with decrease in thickness of a structural member.

Drawbacks of this method include a rigid, regulated form of the temperature dependence of K_{jc} (2), which may be different in different materials.

This study suggests using, instead of expression (2), the temperature dependencies of K_{Ic} (Figure 1) derived from the results of impact toughness tests of a material corrected for structural members of different thicknesses, like condition (3).

Relationships between impact toughness of the Charpy specimens and criterion K_{jc}, developed by the E.O. Paton Electric Welding Institute [1], can be rewritten with allowance for a thickness correction:

$$K_{Ic}^{(t)} = (AEa_V^{(t)}/(1 - \nu^2))^{0.5}, \quad (4)$$

where $K_{Ic}^{(t)}$ is the calculated characteristic of crack resistance in propagation of a through crack in a structural member with thickness t and temperature T; A is the correlation coefficient; E is the elasticity modulus; $a_V^{(t)}$ is the impact toughness of the Charpy specimens at corrected temperature $T^{(t)}$, allowing for a specimen thickness; and ν is the Poisson's ratio;

$$T^{(t)} = T + \Delta T, \quad (5)$$

where ΔT is the temperature shift at a limited thickness of structural members ($10 < t < 100$ mm), which is determined from expression (3) and assumed to be equal to C.

The approach suggested resembles the Makhutov's method of a shift of second critical brittle temperatures [4], the substantial difference being that the shift of fracture toughness characteristics, rather than fracture stresses, opens up considerably wider opportunities for calculation of crack resistance of structures. A more detailed analysis of the results of the shift of the second critical brittle temperatures depending upon the specimen thickness is also of high interest.

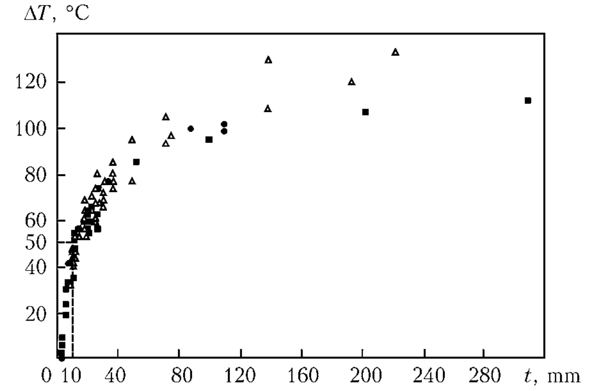

Figure 2. Dependence of critical brittle temperature shift upon the specimen thickness related to a specimen with thickness t = 10 mm, derived from formula (6) at t_{cr} > 10 mm

Figure 2 shows the generalised results of experimental data on the shift of the second critical temperatures depending upon the thickness of specimens of low-carbon and low-alloy steels in tensile tests [5]. Specimens with a section width exceeding their thickness 4–5 or more times were tested. An important point here is that the second critical brittle temperatures increase with increase in a specimen thickness, this being indicative of a risk of brittle fracture of thick-walled large-size structures. In this case, a relative shift of the critical brittle temperatures, ΔT_{cr}, for a 10 mm thick specimen can be described by the following relationship:

$$\Delta T_{cr} = 50(t_{cr} - 10)/t_{cr}, \quad (6)$$

where t_{cr} is the current thickness of a specimen, mm.

As seen from Figure 2, the temperature shift stabilises with increase in the specimen thickness and reaches approximately 50–55 °C (for a 10 mm thick specimen), which is a bit higher than the values recommended by standard ASTM E 1921–97.

To compare relationships (3) and (6), rewrite them in the following form:

$$C = T^{(t)} - T_{28\,J}; \quad (7)$$

$$C_{cr} = 50(t_{cr} - 10)/t_{cr} - 50, \quad (8)$$

where C_{cr} is the critical shift of the second critical temperatures depending upon the specimen thickness.

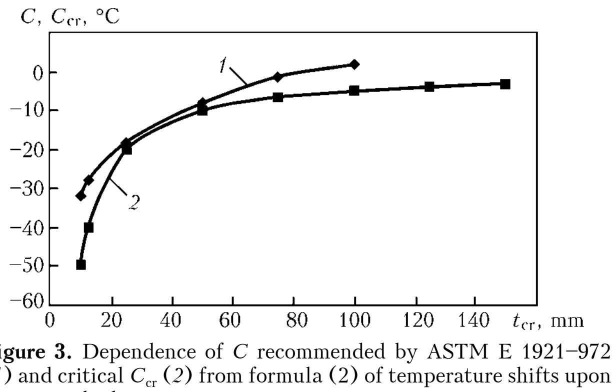

Figure 3. Dependence of C recommended by ASTM E 1921–972 (*1*) and critical C_{cr} (*2*) from formula (2) of temperature shifts upon specimen thickness t_{cr}

As seen from Figure 3, the shifts of the second critical brittle temperatures and toughness characteristics according to ASTM E 1921–97, corresponding to $K_{jc} \approx 100$ MPa$\sqrt{m}$, almost coincide over a wide range of specimen thicknesses. Moreover, the observed difference between the temperature shifts for specimens with a thickness of 10–15 mm is more likely to be associated with different sections of the specimens. Similar values of the temperature shifts are also noted in standard ASTM E 1921–97, where temperature shift C equal to −50 °C is recommended for static bending tests of a Charpy specimen with a fatigue crack.

Therefore, it can be expected that introducing the $K_{Ic}^{(t)}$ characteristic will make it possible to use the force criterion more rationally, as it relates it to temperature $T_{28\ J}$ with allowance for dependence upon the thickness of a structural member.

Temperature shift ΔT can be used in other cases as well, for example, in the case of a change in the PS to PSS transition conditions as a result of dynamic ageing of a material within the zones of concentration of thermoplastic strains, in formation of quenching structures, case hardening of metal during operation, etc. As far as the surface cracks are concerned, for this case the PS conservation conditions are little studied.

It can be concluded on the basis of numerical and experimental studies [6] that stresses and strains near the crack apex in a real three-dimensional body depend upon the stress-strain state in two regions: region located in the immediate proximity to the crack apex, where the local restraining effect shows up, and region that is more distant from the crack apex, where strains correspond to the PSS conditions and depend upon the general stress-strain state of a section weakened by a crack.

In the first of the above regions, the degree of restraint of plastic strains can be characterised by coefficient $\beta = \sigma_{max}/\sigma_{0.2}$ (where σ_{max} is the maximal stress ahead of the crack apex, and $\sigma_{0.2}$ is the yield strength with a uniaxial stress), which amounts to 2.57 in the plane-strain state.

In the second region, the degree of restraint of a strain can be expressed by the following formula:

$$L = \sigma_{s.m}/\sigma_{0.2}, \qquad (9)$$

where $\sigma_{s.m}$ are the mean stresses in a specimen section weakened by a defect, which correspond to the beginning of yield (general yield stress).

Naturally, at $L = \beta$ there is no reason to expect violation of the plane-strain condition at any level of fracture toughness of a material, as the degrees of restraint of plastic strains under conditions of local and general yield are identical. On the contrary, at $L < \beta$ it may be expected that a gradual transition from PS to a state characteristic of the entire weakened section ($\beta \to L$) will occur in development of the plastic zone and, particularly, at the beginning of a general yield. For these cases it is necessary to determine conditions providing invariance of characteristic δ_{Ic} both in experimental measurements and in calculations. Such investigations were carried out by V.S. Girenko. The point is as follows. Crack opening displacement δ_c, like other crack resistance criteria, is not a constant in quasi-brittle states of a material. Therefore, in practice it is necessary to be guided by characteristic δ_{Ic}.

For shallow and short surface defects, this leads to an error that is allowed for in the safety factor for crack resistance and strength. However, considering a low accuracy of evaluation of sizes of the defects in non-destructive testing, as well as the probability of their close location to each other, this approach is completely adequate, and separation of conditions of the PS to PSS transition is hardly justifiable at non-admission of a through defect.

In this case, as applied to the technical diagnostics problems, crack resistance characteristic δ_{Ic} should be determined for the most severe case (PS conditions), which can be relatively easily achieved over the entire range of transition temperatures from the results of standard mechanical tests [1, 2]:

$$\delta_{Ic} = 0.5Aa_V/\sigma_{0.2}, \qquad (10)$$

where a_V is the impact toughness of the Charpy specimens at a corresponding test temperature; normally, it is assumed that $A = 0.1$ for low-alloy and low-carbon steels.

As to the use of strain criterion δ_{Ic} for evaluation of through cracks, in analogy with the force criterion (4) the strain curve can also be written down in the following form:

$$\delta_{Ic}^{(t)} = 0.5Aa_V^{(t)}/\sigma_{0.2}, \qquad (11)$$

where $\delta_{Ic}^{(t)}$ is the corrected characteristic of fracture toughness with a through crack propagating in a structural member with thickness t at temperature $T^{(t)}$.

Advantages of the crack opening displacement test method, compared to the force criterion, are beyond question. First of all, this is associated with less severe requirements to the specimen thickness, and with a possibility of evaluating crack resistance characteristic δ_c in the quasi-brittle and tough regions.

To check temperature shift ΔT by the strain criterion, worthy of notice are studies [7–9], where the effect of the weld metal thickness on a critical value of δ_c is evaluated using the «restricting plate thickness coefficient β». The authors proceeded from an assumption that the thickness intensity effect on strain along the crack front can be expressed by a model shown in Figures 4 and 5, namely by the ratio of mean stress $\bar{\sigma}_{33}$ to mean strain $\bar{\varepsilon}_{33}$ in a direction of thickness in

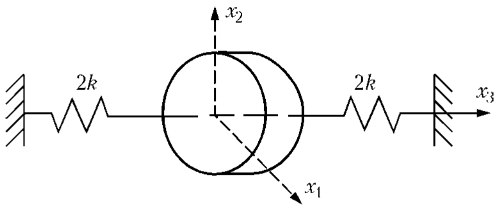

Figure 4. Model of restriction of specimen thickness according to [9]

proportion to a value of k, which is determined as a constant:

$$k = \bar{\sigma}_{33}/\bar{\varepsilon}_{33} = -\frac{2\int_0^{t/2}\sigma_{33}dx_3/t}{2\int_0^{t/2}\varepsilon_{33}dx_3/t}. \quad (12)$$

Setting k by expression

$$k = (1/\beta - 1)\bar{E}, \quad (13)$$

where $\bar{E}$ is the tangent of the angle of inclination of the strain–stress diagram under uniaxial loading in the plastic region, and solving equation (13) by the finite element method [9] yields the following relationship between β and t:

$$\beta = \begin{cases} 10.24/(t + 5.24), & t > 10; \\ 1 - t^2/(20t + 104.9), & t \le 10. \end{cases} \quad (14)$$

By considering a small specimen elongated in a direction of axis x_2 ahead of the crack front (Figure 6) with no allowance for elastic strains, the stress–strain relationship on axis x_1 can be written down as follows:

$$\varepsilon_{22} = \frac{\varepsilon_i^{\mathrm{p}}}{\sigma_i}\left(\sigma_{22} - \frac{\sigma_{33} + \sigma_{11}}{2}\right); \quad (15)$$

$$\varepsilon_{33} = \frac{\varepsilon_i^{\mathrm{p}}}{\sigma_i}\left(\sigma_{33} - \frac{\sigma_{22} + \sigma_{11}}{2}\right), \quad (15a)$$

where σ_i and $\varepsilon_i^{\mathrm{p}}$ are the intensities of stresses and plastic strains, respectively.

Express the σ_{11} to σ_{22} ratio in terms of α:

$$\alpha = \sigma_{11}/\sigma_{22}, \quad 0 < \alpha < 1. \quad (16)$$

Then the relationship between crack opening displacement δ_c and strain ε_{22} can be written down in the following form:

$$\delta_c = C_1\varepsilon_{22}, \quad (17)$$

where C_1 is the constant value.

When using the fracture mechanics approaches, it seems reasonable to limit the real strains and stresses at the crack apex to the values that correspond to the loss of plastic stability of a material. And since the latter at the moment of the neck formation is usually not in excess of 20 % of the strain, in our case it is possible to use the exponential law of strain hardening of the material:

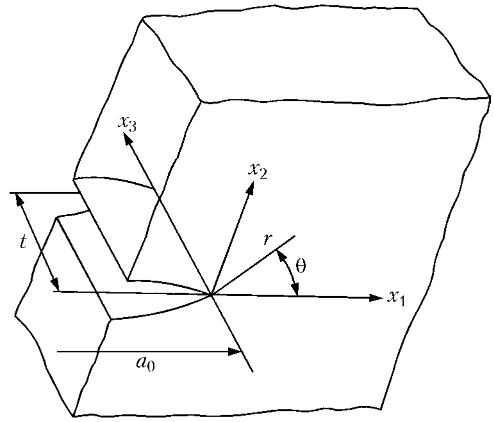

Figure 5. Location of coordinate axis ahead of the crack front: a_0 — crack length

$$\sigma_i = \sigma_{0.2}(\varepsilon_i^{\mathrm{p}}/\varepsilon_0)^n, \quad (18)$$

where ε_0 is the strain corresponding to material yield stress $\sigma_{0.2}$, and n is the material strain hardening.

Assuming that brittle fracture occurs when the normal stress of an imaginary stressed specimen (Figure 6) amounts to critical fracture stress σ_{cr}, and based on [7–9], the following expression can be written down:

$$\delta_c = C_1\frac{\varepsilon_0}{(\sigma_{0.2})^{1/n}} \times \left[1 - \alpha + \alpha^2 + \frac{(1-\beta)(1+\alpha)}{2}\left\{\frac{(1-\beta)(1+\alpha)}{2} - \alpha - 1\right\}\right]^{(1-n)/2n} \times \left\{1 - \frac{(1-\beta)(1+\alpha) + 2\alpha}{4}\right\}(\sigma_{\mathrm{cr}})^{1/n}. \quad (19)$$

Critical crack opening displacement $\delta_{\mathrm{I}c}$ at plane strain in this case has the following form:

$$\delta_{\mathrm{I}c} = C_1\frac{\varepsilon_0}{(\sigma_{0.2})^{1/n}}\left(\frac{\sqrt{3}}{2}\right)^{(1/n)+1}(1-\alpha)^{1/n}(\sigma_{\mathrm{cr}})^{1/n}. \quad (20)$$

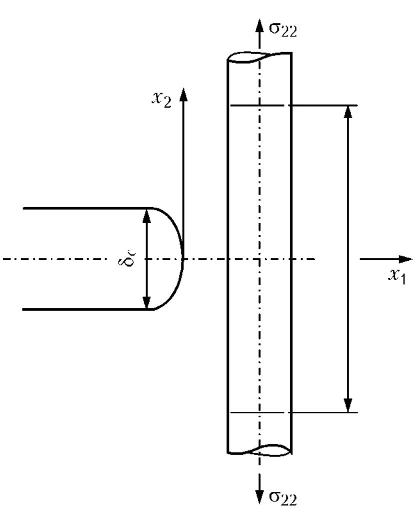

Figure 6. Schematic of conditionally tensioned specimen ahead of the crack apex

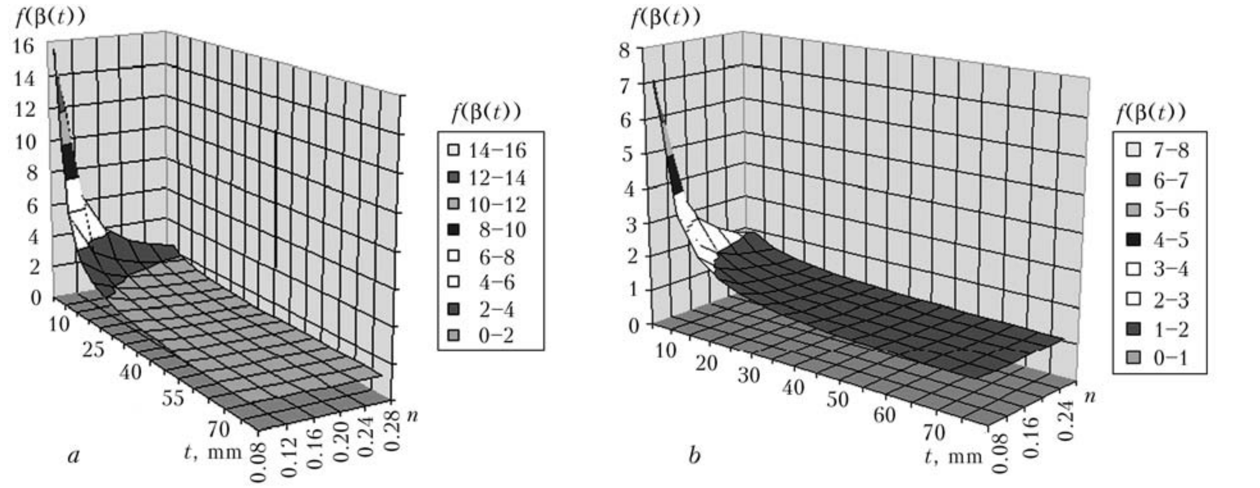

Figure 7. Variations in values of function $f(\beta(t))$ depending upon strain hardening n and thickness t of a specimen at $\alpha = 0.3$ (*a*) and 0.2 (*b*)

By dividing expression (19) by (20), δ_c can be represented in the form of a function of n, β, α and δ_{Ic}:

$$\delta_c = f(\beta)\delta_{Ic}, \tag{21}$$

where

$$f(\beta) = \left(\frac{2}{\sqrt{3}}\right)^{n + 1/n} \times \left[1 - \alpha + \alpha^2 + \frac{(1-\beta)(1+\alpha)}{2}\left\{\frac{(1-\beta)(1+\alpha)}{2} - \alpha - 1\right\}\right]^{(1-n)/2n} \times \left\{1 - \frac{(1-\beta)(1+\alpha) + 2\alpha}{4}\right\} \Big/ (1-\alpha)^{1/n}. \tag{22}$$

Proceeding from [10], the value of α in a deformed non-linear zone varies from 0 to 0.6. To simplify further calculations, assume that the value of α in some cases in the plastic zone is equal to 0.3. Then expression (22) can be simplified to some extent:

$$f(\beta) = \left(\frac{2}{\sqrt{3}}\right)^{n + (1/n)} \times [0.79 + 0.65(1-\beta)\{0.65(1-\beta) - 1.3\}]^{(1-n)/2n} \times \{0.85 - 0.325(1-\beta)\} / (0.7)^{1/n}, \tag{23}$$

where β can be determined depending upon thickness t of a specimen according to formula (14).

At $t > 10$ mm, dependence (22) in a general form will look as follows:

$$f(\beta) = \left(\frac{2}{\sqrt{3}}\right)^{n + (1/n)} \times \left[1 - \alpha + \alpha^2 + \frac{(1 - 10.24)/(t + 5.24)(1+\alpha)}{2}\left\{\frac{(1 - 10.24)/(t + 5.24)(1+\alpha)}{2} - \alpha - 1\right\}\right]^{(1-n)/2n} \times \left\{1 - \frac{(1 - 10.24)/(t + 5.24)(1+\alpha) + 2\alpha}{4}\right\} \Big/ (1-\alpha)^{1/n}. \tag{24}$$

Figure 7, *a* shows dependence (24) of correction function $f(\beta(t))$ for different values of strain hardening n and thickness t of a specimen at $\alpha = 0.3$.

As seen from the Figure, at a specimen thickness of more than 25 mm, the values of correction function $f(\beta(t))$ vary from 2 to 1. Basically, this is in agreement with general approaches of fracture mechanics to determination of δ_{Ic} at the moment of initiation of crack growth in the transition region. At the same time, this range of values of specimen thicknesses is much higher than that specified by requirement (1). The experiments conducted in study [11] to determine the critical crack opening displacement at room temperature at the moment of beginning of growth of this crack also allowed determining the transverse strain from a replica. As shown by the results, the minimal thickness required to correspond to the PS condition in a tough state should meet condition $t > 25\delta_{Ic}$. Further growth of function $f(\beta(t))$ observed with decrease in the specimen thickness from 25 to 10 mm and in strain hardening n from 0.28 to 0.08 is likely to be associated with decrease in the α value, which in this case is assumed to be equal to 0.3.

To illustrate, Figure 7, *b* shows dependence (28) of correction function $f(\beta(t))$ depending upon strain hardening n and thickness t of a specimen at $\alpha = 0.2$.

It can be seen from Figure 7 that the value of function $f(\beta(t))$ in the given range falls almost 2 times with decrease in α from 0.3 to 0.2. This is indicative of the fact that a change in the stressed state of the plastic zone ahead of the crack front occurs in this range of the specimen thickness values. It should be again noted that the choice of the α value in this case reflects only the probable qualitative jump of function $f(\beta(t))$, which makes it possible to approximately determine the brittle-tough transition region.

Substituting expressions (10) and (24) to (21) yields the following relationship between δ_c and standard mechanical characteristics a_V and $\sigma_{0.2}$ depending upon thickness t of a structural material ($t > 10$ mm):

$$\delta_c = 0.5A\,\frac{a_V}{\sigma_{0.2}}\left(\frac{2}{\sqrt{3}}\right)^{(n+1)/n} \times$$
$$\times \left[1 - \alpha + \alpha^2 + \frac{(1 - 10.24)/(t + 5.24)(1 + \alpha)}{2}\left\{\frac{(1 - 10.24)/(t + 5.24)(1 + \alpha)}{2} - \right.\right. \qquad (25)$$
$$\left.\left. - \alpha - 1\right\}\right]^{(1-n)/2n} \times$$
$$\times \left\{1 - \left(\frac{1 - 10.24)/(t + 5.24)(1 + \alpha) + 2\alpha}{4}\right\}/(1 - \alpha)^{1/n}.$$

In this case, the choice of specimen thickness $t > 10$ mm is related to a standard Charpy specimen. Transition to thinner impact specimens with the V-notch does now allow using the earlier developed relationship (10).

However, if results of testing the standard Charpy specimens are known, it is possible to theoretically evaluate strain characteristic δ_c for a specimen of a smaller thickness. Using the second expression of relationship (14) at $t < 10$ mm yields

$$\delta_c = 0.5A\,\frac{a_V}{\sigma_{0.2}}\left(\frac{2}{\sqrt{3}}\right)^{(n+1)/n} \times$$
$$\times \left\{1 - \frac{(1 - t^2)/(20t + 104.9)(1 + \alpha) + 2\alpha}{4}\right\} \times$$
$$\times \left[1 - \alpha + \alpha^2 + \frac{(1 - t^2)/(20t + 104.9)(1 + \alpha)}{2}\left\{\frac{(1 - t^2)/(20t + 104.9)(1 + \alpha)}{2} - \right.\right. \qquad (26)$$
$$\left.\left. - \alpha - 1\right\}\right]^{(1-n)/2n}/(1 - \alpha)^{1/n},$$

where correction function $f(\beta(t))$ is assumed to be equal to

$$f(\beta(t)) = \left(\frac{2}{\sqrt{3}}\right)^{(n+1)/n} \times$$
$$\times\left\{1 - \frac{(1 - t^2)/(20t + 104.9)(1 + \alpha) + 2\alpha}{4}\right\} \times$$
$$\times \left[1 - \alpha + \alpha^2 + \frac{(1 - t^2)/(20t + 104.9)(1 + \alpha)}{2} \times\right. \qquad (27)$$
$$\times \left\{\frac{(1 - t^2)/(20t + 104.9)(1 + \alpha)}{2} - \right.$$
$$\left.\left. - \alpha - 1\right\}\right]^{(1-n)/2n}/(1 - \alpha)^{1/n}.$$

As seen from Figure 8, the strongest effect on the $f(\beta(t))$ value is exerted by the characteristic of strain hardening n of a material, in addition to specimen thickness t.

Therefore, dependencies (25) and (26) make it possible to demonstrate the use of strain characteristics δ_c and δ_{ic} in a region of transition temperatures depending upon thickness t of a specimen and strain hardening n.

Given that the value of δ_i in the tough state depends but very slightly upon the specimen thickness, it is necessary to use a corresponding criterion to determine the upper limit of temperature transition proceeding from the following condition:

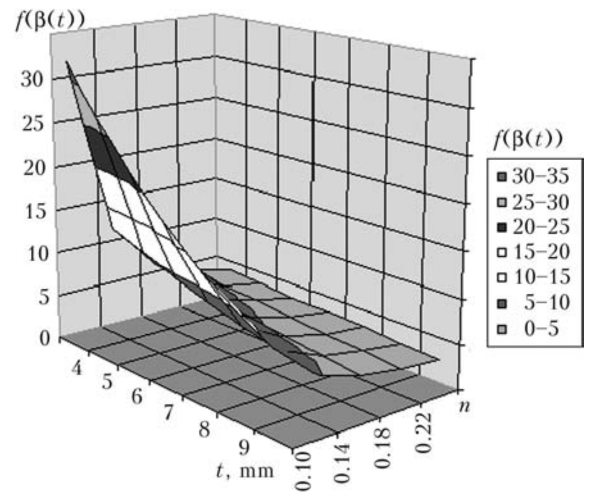

Figure 8. Variations in function $f(\beta(t))$ according to formula (27) depending upon strain hardening n and thickness t of a specimen at $\alpha = 0.3$

$$\delta_i = \delta_c, \qquad (28)$$

where δ_i is the critical crack opening displacement at the moment of initiation of a stable growth of the crack in the tough state, and δ_c is determined from formula (25) or (26) depending upon specimen thickness t.

Based on dependence (10), it can be written down that

$$\delta_i = \frac{A}{2}\,\frac{a_V^{\max}}{\sigma_{0.2}}, \qquad (29)$$

where $a_V^{\max}$ is the minimal value of the specific fracture energy of a standard Charpy specimen at the upper shelf.

In this case, allowing for expression (29) dependence (28) will have the following form:

$$\frac{A}{2}\,\frac{a_V^{\max}}{\sigma_{0.2}} = \frac{A}{2}\,\frac{a_V^{T_{cr}}}{\sigma_{0.2}^{T_{cr}}}\,f(\beta), \qquad (30)$$

where $a_V^{T_{cr}}$ is the specific fracture energy of the standard Charpy specimen at temperature T_{cr} (Figure 9), and $\sigma_{0.2}^{T_{cr}}$ is the proof stress at temperature T_{cr}.

Upon determining the value of impact toughness $a_V^{T_{cr}}$ from expression (30), find T_{cr} and T_i corresponding to $a_V^{T_{cr}}$ and $a_V^{T\,\max}$ on the temperature curve of impact

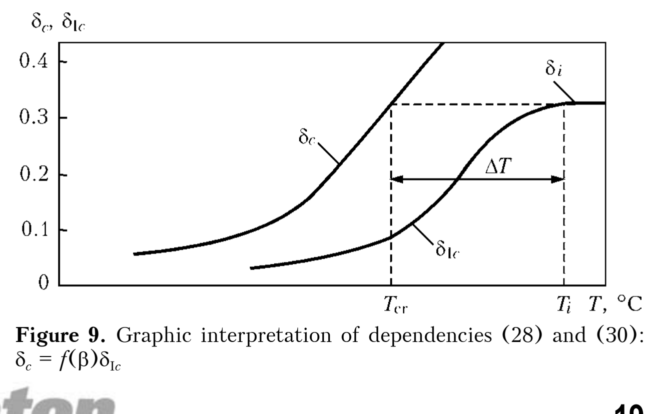

Figure 9. Graphic interpretation of dependencies (28) and (30): $\delta_c = f(\beta)\delta_{Ic}$

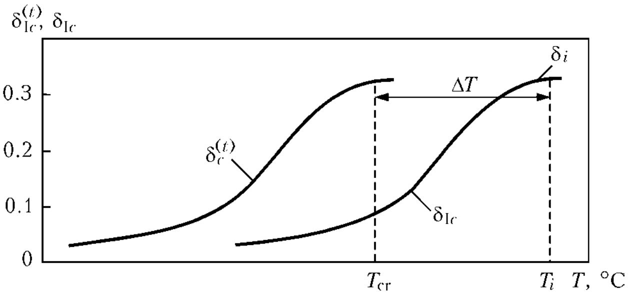

Figure 10. Graphic interpretation of equation (11)

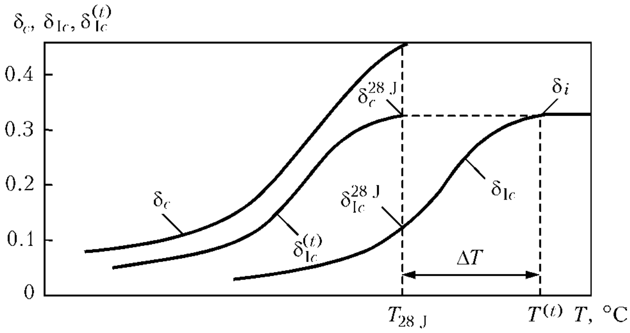

Figure 12. Graphic interpretation of dependence (35) for a case of meeting the inequality: $\delta_i < f(\beta)\delta_{Ic})^{28\ J}$

toughness. Temperature difference $T_i - T_{cr}$ yields the required value of shift ΔT, to which it is necessary to displace the basic strain curve at the upper limit (Figure 10).

It follows from expression (30) at a constant value of A that

$$\frac{a_V^{max}}{a_V^{T_{cr}}} \approx f(\beta)\,\frac{\sigma_{0.2}}{\sigma_{0.2}^{T_{cr}}}. \qquad (31)$$

At a temperature not lower than −60 °C, yield stresses $\sigma_{0.2}$ and $\sigma_{0.2}^{T_{cr}}$ negligibly change as well. In practice, for the most extensively used structural steels such deviations are normally not in excess of 20 %. Hence, it can be assumed that $\sigma_{0.2} \approx \sigma_{0.2}^{T_{cr}}$, this making dependence (31) even simpler:

$$\frac{a_V^{max}}{a_V^{T_{cr}}} \approx f(\beta). \qquad (32)$$

At a small specimen thickness and low values of strain hardening n of a material, function $f(\beta)$ will have high values (Figures 7 and 9). The latter displaces impact toughness $a_V^{T_{cr}}$ to a range of very low values, which can be much lower than a generally accepted value of 35 J/cm^2.

At the same time, the suggested limitation at the upper shelf equal to δ_i is related, first of all, to the probability of a stable growth of the crack in the transition temperature range.

As noted above, depending upon the materials thickness, requirements to force characteristic K_{Ic} can be mitigated at a temperature below $T_{28\ J}$. In this case, the lower temperature limit, where some mitigation can be made when using the strain criterion depending upon the thickness, can also be limited to a value of $T_{28\ J}$. This limitation is of a certain interest, as it allows comparing temperature shifts both by the force and strain criteria with respect to a single point corresponding to $T_{28\ J}$.

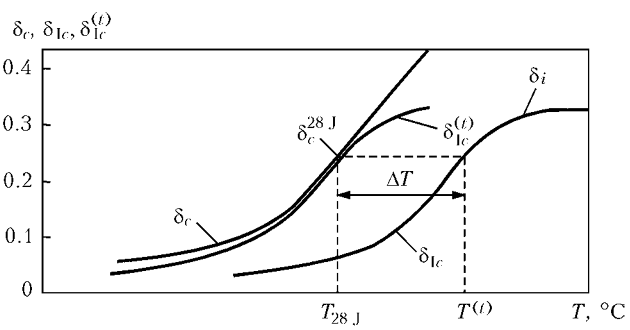

Figure 11. Graphic interpretation of dependence (33): $\delta_c = f(\beta)\delta_{Ic}$

Proceeding from dependencies (10), (11) and (21), the value of $\delta_{Ic}^{(t)}$ at the lower limit at temperature $T_{28\ J}$ will be

$$\delta_{Ic}^{(t)} = \frac{A}{2}\,\frac{a_V^{T_{28\ J}}}{\sigma_{0.2}^{T_{28\ J}}}\,f(\beta), \qquad (33)$$

where $\delta_{Ic}^{(t)}$ is limited on the top by a value of $\delta_i(\delta_{Ic}^{(t)} \le \le \delta_i)$.

Graphic interpretation of dependence (33) for a case of $\delta_i \ge \delta_{Ic}^{(t)} = \frac{A}{2}\,\frac{a_V^{T_{28\ J}}}{\sigma_{0.2}^{T_{28\ J}}}\,f(\beta)$ is shown in Figure 11.

As can be seen from the Figure, dependence (33) also comprises condition (3) as a particular case. Using expression (1), reduce dependence (33) to the following form:

$$\frac{A}{2}\,\frac{a_V^{T^{(t)}}}{\sigma_{0.2}^{T^{(t)}}} = \frac{A}{2}\,\frac{a_V^{T_{28\ J}}}{\sigma_{0.2}^{T_{28\ J}}}\,f(\beta), \qquad (34)$$

where $a_V^{T^{(t)}} \le a_V^{max}$.

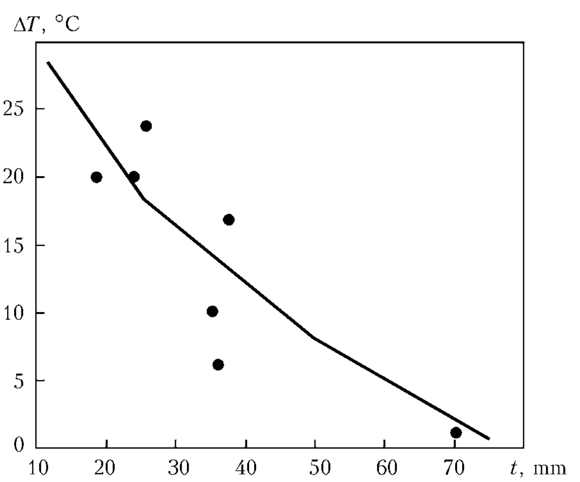

Figure 13. Dependence of temperature shift ΔT on thickness of specimens tested to three-point bending under static loading: *curve* — temperature shift specified by standard ASTM E 1921–97; *points* — experimental data obtained from formula (34)

In analogy with expressions (31) and (32), dependence (34) in the first approximation can also be reduced to the following form:

$$\frac{a_V^{T^{(t)}}}{a_V^{T_{28\,J}}} \le \frac{\sigma_{0.2}^{T^{(t)}}}{\sigma_{0.2}^{T_{28\,J}}} f(\beta), \quad (35)$$

where, when the inequality is met, the value of $a_V^{T^{(t)}}$ is assumed to be equal to $a_V^{\max}$:

$$\frac{a_V^{T^{(t)}}}{a_V^{T_{28\,J}}} \approx f(\beta) \quad (36)$$

at $a_V^{T^{(t)}} \le a_V^{\max}$.

This case is illustrated in Figure 12.

Therefore, expressions (34) and (35) allow establishing the necessary requirements to impact toughness of a standard Charpy specimen depending upon its thickness and strength characteristics of a material.

It follows from Figure 12 and formulae (33) and (34) that, to determine temperature shift ΔT depending upon the specimen thickness, it is necessary to know temperature dependencies of impact toughness of the standard Charpy specimen, strength characteristics of a material and strain hardening n.

To illustrate, Figure 13 shows the data obtained from the experimental values of ΔT using formula (34) for specimens of different thicknesses cut from steels 09G2S, St3 and 10KhSND and their welded joints tested to three-point bending, and the recommended temperature shift according to standard ASTM E 1921–97.

It can be seen from the Figure that the temperature shift specified by standard ASTM E 1921–97 is only of a recommendation character, as it limits the temperature range of finding the values corresponding to $K_{jc} = 100$ MPa$\sqrt{m}$ and describes only the mean values of the experimental data.

Suggested dependencies (34) and (35) also allow for the strain and strength characteristics of a material in determination of the temperature shift, which, along with expression (2), makes it possible to reasonably select the calculation requirements to the temperature shift and determine the temperature transition by taking into account thickness of a structural member.

Detailed experimental verification of the suggested approach to evaluation of the temperature shift and calculation characteristics of fracture toughness of a welded joint, heat-affected zone and base metal is beyond the scope of this article and will be presented in the next study.

Therefore, the coincidence of the temperature shift between the recommended requirement of standard ASTM E 1921–97 and second critical temperature depending upon the specimen thickness has been shown.

The approach has been suggested to evaluation of the temperature shift depending upon the specimen thickness and strength characteristics of a material based on the strain characteristic of fracture toughness δ_{Ic}.

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