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Determination of the Temperature Dependence of the Fracture Toughness of the Metal of a Thick-Walled Shell Taking into Account the Inhomogeneity of the Material

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Abstract—Estimates of the reference temperature T_0 obtained for the base metal and the weld-seam metal of the Cr–Ni–Mo–V type (shell 200 mm thick) on the basis of statistical modeling by the Monte Carlo method are presented. T_0 was determined according to the ASTM E1921 standard taking into account the inhomogeneity of the material. The sample size of the fracture toughness values K_{JC} for T_0 modeling was 12, 24, and 70. The Monte Carlo method was used for analysis of the correctness of metal identification (homogeneous/inhomogeneous). It is shown that sampling of 12 samples does not provide a reliable determination of whether the metal is homogeneous or inhomogeneous (incorrect results were obtained in 50% of cases for the base metal and in 37% of cases for the weld-seam metal). When the sample size increased to 24 samples, incorrect results were obtained in 5% of cases. The T_0 values with allowance for the material inhomogeneity were determined in two ways: using a screening procedure and proceeding from the actual bimodal representation of the fracture toughness distribution (parameters of the bimodal distribution were determined by the maximum likelihood method). It is shown that both methods give close results for the base and weld-seam metal, the magnitude of the shift toward positive values in the average T_0 values determined with allowance for the inhomogeneity being about 22°C. Using the obtained T_0 estimates, the lower envelopes of the temperature curves of the fracture toughness are constructed (master curves for 5% failure probability).

Keywords: reference temperature T_0, fracture toughness, master curve, statistical modeling, the Monte Carlo method

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INTRODUCTION

The metal of structures, especially large ones, is structurally heterogeneous. Heterogeneity manifests itself at the micro- and macrolevels and is a consequence of the peculiarities of the manufacturing technology of blanks and products (casting, forgings, welding, etc.) and chemical heterogeneity. Accordingly, structure-sensitive characteristics of mechanical properties, for example, such as impact and static fracture toughness, have a significant scatter.

The ASTM E1921 standard (standard test method for determination of reference temperature, T_0, for ferritic steels in the transition range) takes into account heterogeneity when determining the temperature dependence of the static fracture toughness in the form of a master curve, the position of which on the temperature axis is determined by the value of the reference temperature T_0.

The master curve for the probability of failure $P =$ 50% with a sample thickness of 25 mm is described by the equation

$$K_{Jc} = 30 + 70\exp[0.019(T - T_0)]. \quad (1)$$

The value of K_{Jc}, the elastoplastic equivalent of the stress intensity factor, is calculated using the J-integral (J_c), corresponding to the initiation of brittle fracture of the sample:

$$K_{Jc} = \sqrt{\frac{J_c E}{1 - \upsilon^2}},$$

where υ is the Poisson ratio and E is the modulus of elasticity. It follows from (1) that K_{Jc} = 100 MPa m$^{0.5}$ at $T = T_0$.

The scatter of data on K_{Jc} is described on the basis of a three-parameter Weibull distribution function:

$$P_f = 1 - \exp\left[-\left(\frac{K_{Jc} - K_{\min}}{K_0 - K_{\min}}\right)^b\right], \quad (2)$$

where P_f is the probability that the fracture toughness of the material will not be greater than K_{Jc}; K_0 is a scale parameter that depends on temperature and the sample thickness; $K_{\min} = 20$ MPa m$^{0.5}$ is the minimum value of the fracture toughness; and parameter $b = 4$ is considered independent of the type of material, the test temperature, and the sample thickness.

The formula for converting K_{Jc} values obtained on the samples of thickness B_Y to K_{Jc} for samples of thickness B_X has the form

$$\frac{K_{Jc}^X - K_{\min}}{K_{Jc}^Y - K_{\min}} = \left(\frac{B_Y}{B_X}\right)^{1/b}, \tag{3}$$

where K_{Jc}^X and K_{Jc}^Y are the values of the fracture toughness for the samples of thickness B_X and B_Y.

The scope of the ASTM E1921 standard allows one to determine the K_{Jc} (T) dependences of ferritic-pearlitic steels and their welded joints with a yield strength from 275 to 825 MPa.

Before assessing T_0, test results are analyzed to ensure that the small-scale yield condition is met

$$K_{Jc} \le K_{Jc\,\mathrm{lim}} = \sqrt{\frac{Eb_0\sigma_{ys}}{30(1-\upsilon^2)}},$$

where E is the elastic modulus; $b_0 = W - a_0$ ($W = 2t$; t is the sample thickness; a_0 is the length of the initial fatigue crack); υ is the Poisson ratio; and σ_{ys} is the conditional yield strength.

In addition, from the fractures of the samples, the viscous crack growth is determined, which should not exceed the value

$$\Delta a_{\max} \le 0.05(W - a_0)$$

or 1 mm. If the specified conditions are not met, censoring is carried out—reducing the values of K_{Jc} to K_{Jc} lim at given temperature or the maximum set values (at $\Delta a < \Delta a_{\max}$) at which these conditions are met.

The attractiveness of using a master curve is associated with the possibility of recalculating the test results for samples of small sizes to data for larger thicknesses, as well as constructing curves for different probabilities of destruction [1–7].

When determining the reference temperature T_0, it is necessary to evaluate the heterogeneity of the metal in accordance with the ASTM E1921 standard. Reliable identification of a material as homogeneous or heterogeneous is possible with a sample size of at least 20 samples.

If the homogeneity criterion is not met, determination of temperature T_0 is allowed using several approaches: screening (SINTAP [1, 3, 4]) or on the basis of a refined assessment of the type of distribution of K_{Jc} values (bimodal and multimodal). Taking into account heterogeneity leads to a shift in T_0 toward positive values and, accordingly, to a decrease in the calculated safety margins.

In this work, for the base metal and weld metal of the Cr–Ni–Mo–V type (shell 200 mm thick), estimates of T_0 obtained on the basis of statistical modeling using the Monte Carlo method are presented without taking into account and taking into account heterogeneity on the samples of various sizes (12, 24, and 70 values of K_{Jc}). They make it possible to conservatively estimate the shifts in T_0 and the position of the lower envelope of temperature curves of viscosity. Test samples were cut from the central 1/3 of the thickness of the shell.

METHODOLOGY OF NUMERICAL EXPERIMENTS

The initial data sets for calculations are the results of tests at fixed temperatures on 70 compact samples ST-0.5T made of base metal (BM) and weld metal (WM). These results were recalculated for the thickness of the ST-1T sample, equal to 25 mm, which made it possible to use a single-temperature approach when modeling the procedure for determining T_0 (Fig. 1).

When carrying out statistical modeling, one of the varieties of the Monte Carlo method was used—bootstrap, which does not require a parametric representation of the original data in the form of distribution functions.

In accordance with this method, repeated returned samples of a given range are extracted from a set of experimental values of the fracture toughness K_{Jc}, using appropriate random number generators (the Mathcad environment was used). The procedure is repeated quite a large number of times in order to establish the dispersion characteristics of the simulated quantity.

In the case of screening at the first step, the T_0 value was determined according to the standard procedure from the following relation (in the single-temperature approach):

$$T_{0(\mathrm{step1})} = T_{\mathrm{t}} - \frac{1}{0.019}\ln\frac{K_{Jcm} - 30}{70},$$

where T_{t} is the test temperature and $K_{Jcm} = 20 + 0.91(K_0 - 20)$ is the median value of K_{Jc}. Scale parameter

$$K_0 = \left[\frac{1}{r}\sum_{i=1}^{n}(K_{Jci} - 20)^4\right]^{1/4},$$

where r is the number of uncensored values of K_{Jci} and n is the total number of samples in the series.

Then the K_{CENSi} values corresponding to the median curve are estimated:

$$K_{CENSi} = 30 + 70\exp[0.019(T_t - T_{0(\mathrm{step1})}]. \tag{4}$$

The experimental values of K_{Jci} were compared with K_{CENSi}. If $K_{Jci} > K_{CENSi}$, then $K_{Jci} = K_{CENSi}$ is

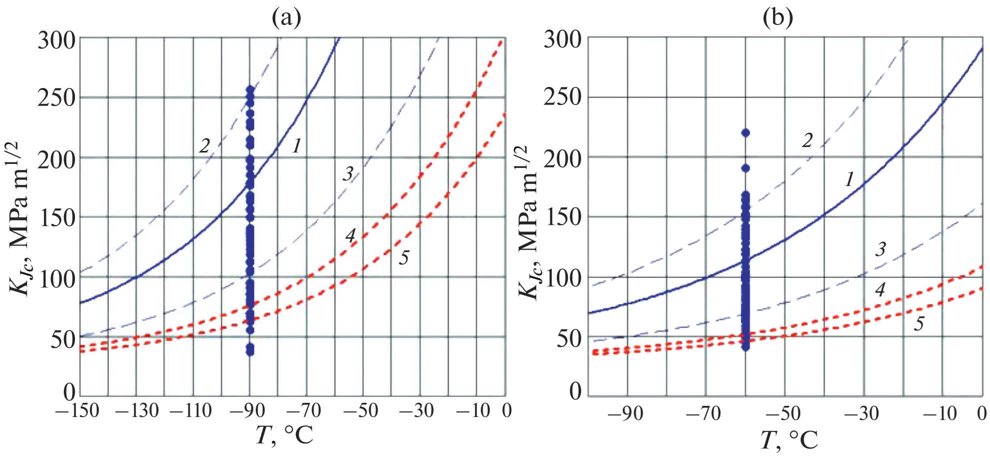

Fig. 1. Temperature dependence of the fracture toughness (master curve) (a) for the base metal ($T_0 = -130$°C) and (b) for the weld-seam metal ($T_0 = -69$°C): (*1*) median curves corresponding to 50% probability; (*2* and *3*) curves corresponding to 5 and 95% probability; (*4* and *5*) curves for $P = 5\%$ obtained taking into account screening for a sample size of 70 and 24 samples, respectively.

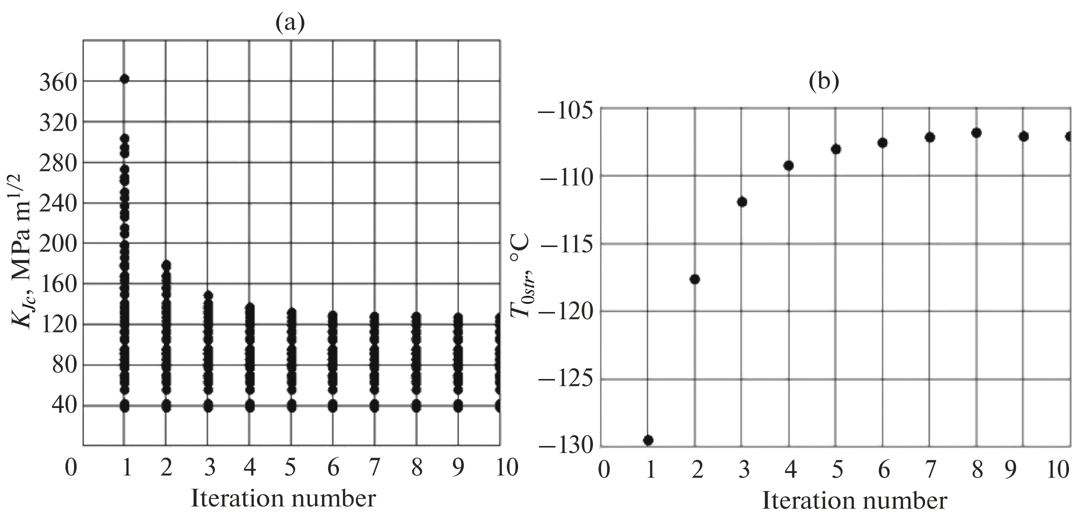

Fig. 2. Changes in the values of K_{Jc} (a) and $T_{0(\mathrm{step}\ i)}$ (b) depending on the number of iterations during screening (base metal).

accepted. On the basis of the K_{Jci} array adjusted in this way, the reference temperature was determined at the second step—$T_{0(\mathrm{step\,2})}$.

If $T_{0(\mathrm{step2})} - T_{0(\mathrm{step1})} \geq 0.5$°C, new values of K_{CENSi} were found by replacing $T_{0(\mathrm{step1})}$ with $T_{0(\mathrm{step2})}$ in (4), and the value of the reference temperature at the third step was calculated, etc. The fulfillment of the condition $T_{0(\mathrm{step}\ i)} - T_{0(\mathrm{step}\ i\ -\ 1)} < 0.5$°C is ensured after several iterations (usually no more than ten).

The material is considered homogeneous when

$$T_{0scr} - T_{0(\mathrm{step1})} \leq 1.44\sqrt{\frac{\beta^2}{r}}, \tag{5}$$

where T_{0scr} is taken as the maximum temperature value of $T_{0(\mathrm{step}\ i)}$, r is the number of uncensored values K_{Jci} in the sample under consideration, and β is a coefficient depending on the level of K_{Jc} values (is in the range of 18–20). The parameters r and β are calculated for the first step.

If criterion (5) is met, then $T_0 = T_{0(\mathrm{step1})}$, and if it is not met, then T_{0scr} is taken as the reference temperature T_0 (for the series of scope $n > 10$).

As an example, Fig. 2 shows the change in the values of K_{Jc} and $T_{0(\mathrm{step}\ i)}$ during screening, illustrating the rate of convergence of the process depending on the number of iterations for the base metal (series size is $n = 70$ values of K_{Jc}).

During screening, the procedure for determining T_0 and T_{0scr} was repeated approximately 100 times.

Table 1. Calculated values of the reference temperature T_0 with and without taking into account the inhomogeneity of the material

Material	n (number of samples in the series)	$\overline{T}_0$, °C	σ_{T_0}, °C	$\overline{T}_{0scr}$, °C	$\sigma_{T_{0scr}}$, °C	$\Delta\overline{T}_0$, °C	$\overline{T}_{0scr}^{(0.95)}$, °C
BM	70	–130	–	–107	–	23	–107
	24	–129	6.9	–107	8.6	22	–92
	12	–128	8.2	–116	16.5	–	–
WM	70	–69	–	–43	–	26	–43
	24	–68	7.6	–46	9.4	22	–30
	12	–67	8.9	–51	12.9	–	–

RESULTS AND DISCUSSION

The results of calculating the reference temperature values without taking into account (T_0) and taking into account (T_{0scr}) nonuniformity, as well as the corresponding standard deviations obtained during modeling, are given in Table 1. The values of reference temperature shifts due to heterogeneity are also indicated here $\left(\overline{\Delta T}_0 = \overline{T}_{0scr} - \overline{T}_0\right)$, as well as $T_{0scr}^{(0.95)}$, corresponding to a conservative estimate of T_{0scr} (with 95% reliability), taking into account heterogeneity of the metal and scattering of results. It can be seen that the average values of $\overline{T}_0$ and $\overline{T}_{0scr}$ weakly depend on the series size. At n = 24 for the base metal, the average value of the reference temperature is $\overline{T}_0$ = –129°C; after screening, the average value is $\overline{T}_{0scr}$ = –107°C; for weld metal, $\overline{T}_0$ = –68°C and $\overline{T}_{0scr}$ = –46°C, respectively. In both cases, the shift in average values is 22°C.

As the series size decreases, the spread (standard deviation) of T_0 and T_{0scr} increases. At the same series sizes, the dispersion of the reference temperature values T_{0scr} is slightly higher than that of T_0.

When applying the screening procedure to the entire array of base metal and weld metal, the homogeneity criterion (5) is not met (the metal is heterogeneous). With a decrease in the number of samples in the series, the probability of fulfilling the criterion (5), i.e., in this case, the incorrect assessment of homogeneity, increases.

At n = 12, in 50% of cases of determining T_0 for the base metal and in 37% of cases for the weld metal, the material was identified as homogeneous. When testing 24 samples of each material, the homogeneity criterion was met for 5% of the weld metal series and 4% of the base metal series. This result is consistent with the recommendations of ASTM E1921—for a reliable assessment of homogeneity, the series size must contain at least 20 values of K_{Jc}.

The correctness of using screening to assess homogeneity was also verified for a hypothetical homogeneous material whose distribution of fracture toughness characteristics corresponds to the three-parameter Weibull distribution (2) at $b = 4$ and $K_0 = 90$ MPa m$^{0.5}$. The series of 6, 12, and 24 K_{Jc} values were considered, for which the values of T_0 and T_{0scr} were determined.

When repeating the screening procedure multiple times (more than 100 times) for series of n = 6, it was found in 5% of cases that the material was heterogeneous, which is an incorrect result. For series of 12 and 24 K_{Jc} values, the probability of nonfulfillment of the material homogeneity condition (5) was less than 1%. As for inhomogeneous metal, the reliability of correct identification of the material increases with increasing the series size.

Generalized data characterizing the dispersion of T_0 and T_{0scr} for the base metal and weld metal (at series sizes of n = 12 and n = 24) are shown in Fig. 3. At n = 24 (points *1*), the T_0 and T_{0scr} arrays for BM and WM are grouped around the average values. At n = 12 (points *2*), the arrays are divided into two parts. The points obtained on the series for which the homogeneity condition (5) was satisfied are located along the lines $T_0 = T_{0scr}$. Chaotic location of points, being approximately in the same area of the scatter as for the series with a size of n = 24, indicates that the metal is heterogeneous.

It should be noted that for an inhomogeneous metal, the correlation between the values of T_0 and T_{0scr} is weak [8], which does not allow estimating T_{0scr} from the value of T_0. At n = 24, the correlation coefficient K_{cor} for the weld metal is 0.49 and for the base metal is 0.54.

On the basis of the results of calculations for the base metal and weld metal at a series size of n = 24, empirical distribution curves T_0 and T_{0scr} were constructed (Fig. 4), and conservative values $T_{0scr}^{(0.95)}$ were determined with 95% reliability that take into account the heterogeneity of the metal and the scattering of the results. For the base metal $T_{0scr}^{(0.95)}$ is –92°C; for the welding metal, it is –30°C.

According to the established reference values of temperature $T_{0scr}^{(0.95)}$, the lower 5% envelopes of the master curve were constructed taking into account

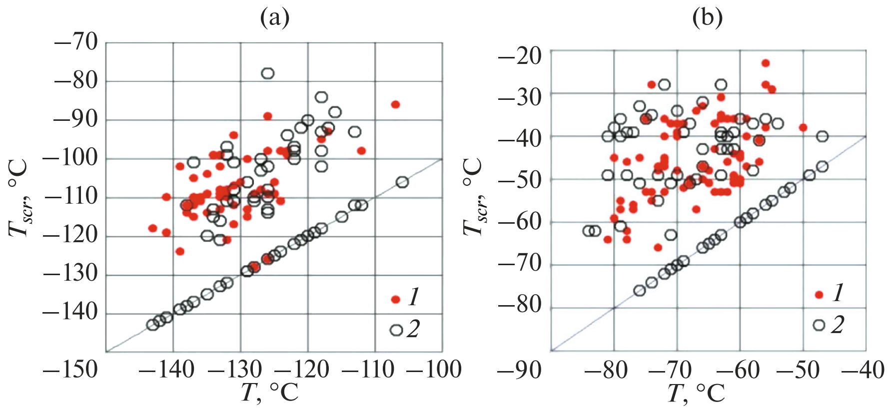

Fig. 3. Ratio between T_0 and T_{scr} obtained on the basis of statistical modeling for the base metal (a) and weld-seam metal (b): (*1*) $n = 24$; (*2*) $n = 12$.

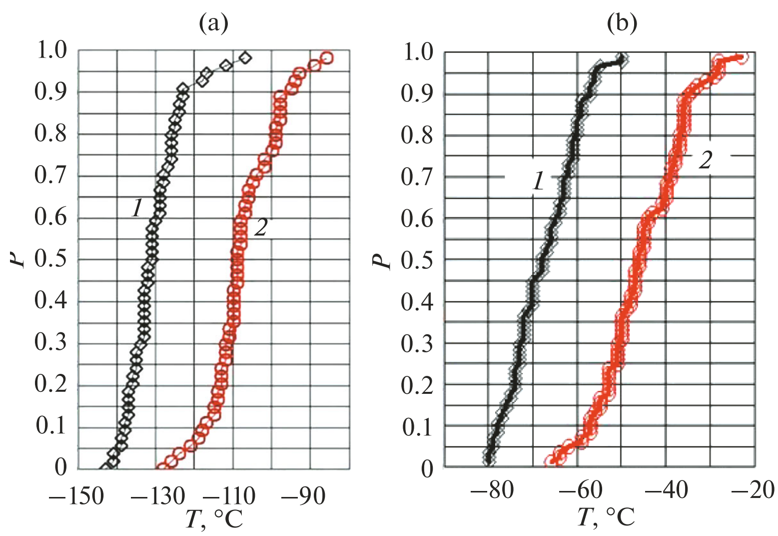

Fig. 4. Integral distribution function of T_0 (*1*) and T_{0scr} (*2*) for base metal (a) and weld-seam metal (b), $n = 24$.

heterogeneity (Fig. 1, curves *5*) for the base metal and the weld metal for series with a size of $n = 24$. For comparison, 5% envelopes for $n = 70$ (curves *4*) are also given for the base metal (reference temperature is $\overline{T}_{0scr} = -107$°C) and weld metal ($\overline{T}_{0scr} = -43$°C). A possible decrease in conservatism (T_0 shift) by increasing the series size to $n = 70$ is about 15°C for the base metal and 13°C for the weld metal.

A characteristic feature of the initial K_{Jc} arrays (Fig. 1) is that 24% of experimental points fall beyond the lower 5% scattering limit of the master curve (curves *3*, without taking into account heterogeneity) for the weld metal; this value is 30% for the base metal; i.e., scattering of the results is higher than what follows from the Weibull distribution.

The actual empirical distribution of K_{Jc} values presented in Fig. 5 (uncensored data) differs from the three-parameter Weibull distribution (2), which underlies the concept of the master curve. The discrepancy between the experimental data and the Weibull distribution (2) was also noted in the papers [9–12].

Histograms of relative frequencies W of the fracture toughness K_{Jc} for the base metal and weld metal are shown in Fig. 6. It can be seen that the test results are grouped around two centers—with lower and higher levels of K_{Jc}—and can be represented by bimodal distribution curves.

It should be noted that the bimodality of the distribution of characteristics of mechanical properties in the temperature range of the brittle–ductile transition is a manifestation of a fairly general pattern and is observed not only for the static fracture toughness but also for other characteristics, for example, the impact strength [13, 14] and relative elongation [15].

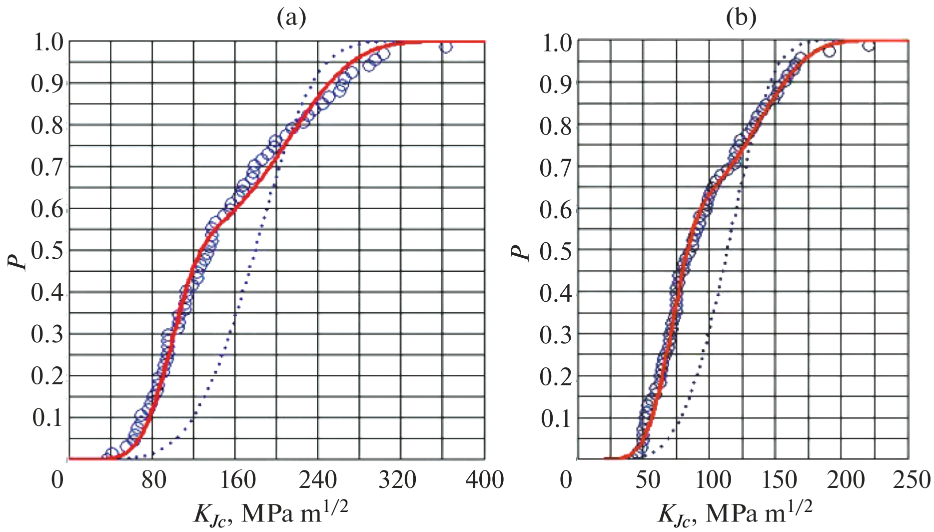

Fig. 5. Integral functions of the Weibull distribution (2) (dotted line) and the bimodal distribution (8) (solid line): (a) the base metal (K_0 = 194 MPa m$^{0.5}$); (b) the weld-seam metal (K_0 = 122 MPa m$^{0.5}$); points indicate the experimental data.

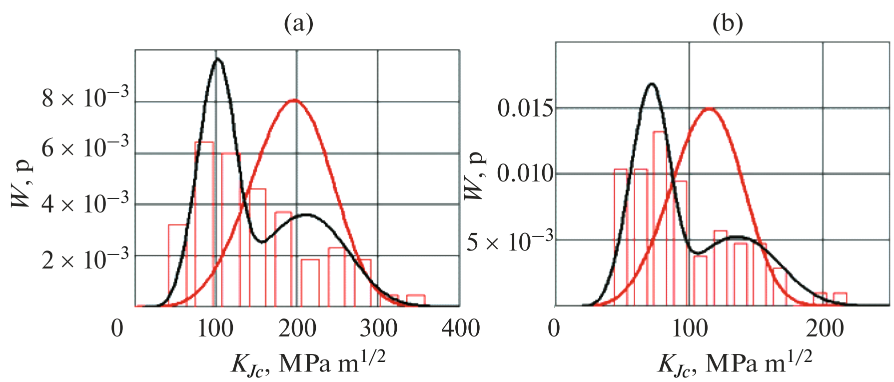

Fig. 6. Histograms of the relative frequencies W and probability density curves p of K_{Jc} values for the base metal (a) and weld-seam metal (b); (curve *1*) Weibull distribution (2); (*2*) bimodal distribution (6).

The reason for this is the structural heterogeneity of the metal and the possibility of transitioning of different structures to a brittle state at different temperatures. In the temperature regions of the upper and lower shelves, bimodal distributions degenerate into unimodal ones.

At a sufficient number of tested samples ($n > 20$), the ASTM E1921 standard makes it possible to more accurately establish the type of distribution of K_{Jc} values. If the experimental data are the sum of two sets with different average values and scattering characteristics, the integral bimodal distribution of the fracture toughness K_{Jc} can be represented as

$$P = 1 - p_a \exp\left[-\left(\frac{K_{Jc} - 20}{K_A - 20}\right)^4\right] - (1 - p_a)\exp\left[-\left(\frac{K_{Jc} - 20}{K_B - 20}\right)^4\right], \quad (6)$$

where K_A and K_B are scale parameters and p_a is the parameter for the redistribution of probabilities over modes A and B (in the range from 0 to 1).

The scale parameters are found from the relations

$$K_A = 31 + 177\exp 0.019(T - T_a);$$
$$K_B = 31 + 177\exp 0.019(T - T_b), \quad (7)$$

where T_a and T_b ($T_b \leq T_a$) are reference temperatures corresponding to mode A and mode B.

To determine the parameters of the bimodal distribution, the maximum likelihood method (MLM) was used, which was integrated into the statistical modeling procedure for determining T_0 using the Monte Carlo method.

As the "most plausible" value of the parameters of the bimodal distribution, the values that maximized the probability of obtaining a series $X = X(K_{Jc1}, ..., K_{Jcn})$ in n experiments were taken.

Table 2. Parameters of the bimodal distribution

Material	n	$\overline{K}_A$, MPa m$^{0.5}$	$\overline{K}_B$, MPa m$^{0.5}$	$\overline{p}_a$	σ_{p_a}, °C	$\overline{T}_a$, °C	σ_{T_a}, °C	$\overline{T}_b$, °C	σ_{T_b}, °C	$\overline{NH}$	$\sigma_{T_{0bm}}$, °C	$\overline{T}_{0bm}$, °C	$\overline{T}^{(0.95)}_{0scr}$, °C
BM	70	104	225	0.5	–	–87	3.8	–139	3.8	7.7	–98	–	–
BM	24	106	250	0.5	0.14	–89	9.6	–141	16.2	4.8	–100	7.4	–88
WM	70	74.8	145	0.57	–	–30	3.6	–80	2.6	8.4	–40	–	–
WM	24	74.2	145	0.6	0.15	–31	8.2	–81	6.9	5.5	–40	6.8	–30

A function that determines the probability of the occurrence of a joint event, extraction of the series $X = X(K_{Jc1}, \ldots, K_{Jcn})$,

$$f(X, p_a, K_A, K_B) = f_1(K_{Jc1}) f_2(K_{Jc2}), \ldots, F_n(K_{Jcn}) = \prod_{i=1}^{n} f_i(K_{Jci})$$

is the likelihood function. The distribution density $f(X, p_a, K_A, K_B)$ is determined by differentiating formula (6).

Instead of the likelihood function, a logarithmic function of likelihood was used, which allows one to go from the product to the sum of logarithms (which simplifies the calculations). By virtue of monotonicity, the maxima of the likelihood functions and the logarithmic likelihood function coincide.

The logarithmic likelihood function [1]

$$\ln L = \sum_{i=1}^{n} [\delta_i \ln f_i + (1 - \delta_i) \ln S_i], \quad (8)$$

where δ_i is the Kronecker symbol ($\delta_i = 1$ for uncensored and $\delta_i = 0$ for censored data);

$$f_i = 4p_a \frac{(K_{Jci} - 20)^3}{(K_A - 20)^4} \exp\left[-\left(\frac{K_{Jci} - 20}{K_A - 20}\right)^4\right] + (1 - p_a) \frac{(K_{Jci} - 20)^3}{(K_A - 20)^4} \exp\left[-\left(\frac{K_{Jci} - 20}{K_B - 20}\right)^4\right]$$

is the fracture probability density at the fracture toughness values less than or equal to K_{Jci};

$$S_i = p_a \exp\left[-\left(\frac{K_{Jci} - 20}{K_A - 20}\right)^4\right] + (1 - p_a) \exp\left[-\left(\frac{K_{Jci} - 20}{K_B - 20}\right)^4\right]$$

is the probability of no destruction.

The values of the parameters p_a, K_A, K_B corresponding to the extremum of the function $\ln L(X, p_a, K_A, K_B)$ are determined from solving the system of partial differential equations

$$\frac{\partial(\ln L)}{\partial p_a} = 0; \quad \frac{\partial(\ln L)}{\partial K_A} = 0; \quad \frac{\partial(\ln L)}{\partial K_B} = 0. \quad (9)$$

The integral curves and probability density curves of the bimodal distribution presented in Figs. 5 and 6 have been obtained using the maximum likelihood method for the entire data array for BM and WM ($n = 70$). It can be seen that the experimental data are significantly better described by the bimodal distribution than by the Weibull distribution.

The average values of $\overline{p}_a$, $\overline{K}_A$, and $\overline{K}_B$ obtained during statistical modeling for the base metal and weld metal (on the series from 70 and 24 values of K_{Jc}) are presented in Table 2. Here the values of reference temperatures $\overline{T}_a$ and $\overline{T}_b$ for modes A and B calculated using formula (7) are also given. The nature of the scattering of the parameter $\overline{p}_a$ during multiple repetitions of statistical tests (on the series of $n = 24$) depending on the test number N_i is shown in Fig. 7a. For 6% of the series, unimodal distributions turned out to be the most plausible ($\overline{p}_a = 1$).

The standard deviations of the parameters of relation (6) in accordance with ASTM E1921 are determined by the formulas

$$\sigma_{T_a} = \frac{22}{\sqrt{np_a - 2}}, \quad \sigma_{T_b} = \frac{16}{\sqrt{r - np_a - 2}}, \quad \sigma_{p_a} = \frac{0.35}{\sqrt{np_a - 2}}. \quad (10)$$

The values of the standard deviations given in Table 2 for the series of $n = 70$ were calculated using these ratios; for the series of $n = 24$, they were obtained from the results of statistical modeling.

The ASTM E1921 standard provides for the assessment of material homogeneity at a bimodal distribution on the basis of the criterion

$$NH = \frac{|T_a - T_b|}{\sqrt{\sigma_{T_a}^2 + \sigma_{T_b}^2 + 16}} < NH_{\mathrm{cr}},$$

where σ_{T_a} and σ_{T_b} are the standard deviations of temperatures T_a and T_b.

When $NH \le NH_{\mathrm{cr}}$, the material is considered homogeneous. The criterial level NH_{cr} depends on the number of samples in the series—at $n = 70$, it is 3.8; at $n = 24$, it is 2.5.

For the weld metal, all NH values obtained during statistical modeling ($n = 24$) turned out to be higher

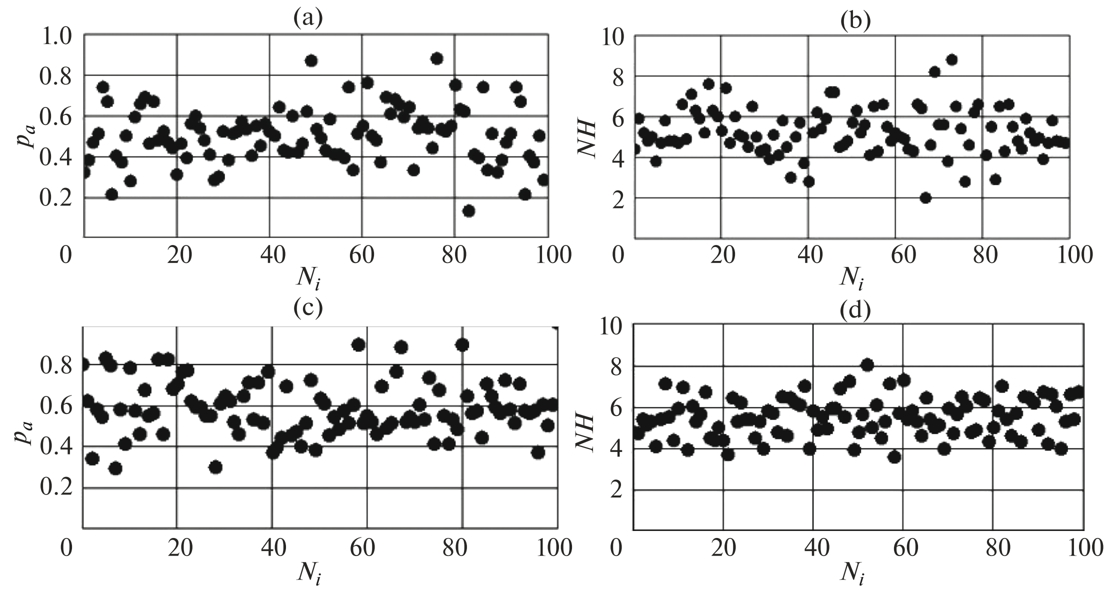

Fig. 7. Scattering of parameters p_a and NH depending on the test number at n = 24: (a, b) base metal; (c, d) weld-seam metal.

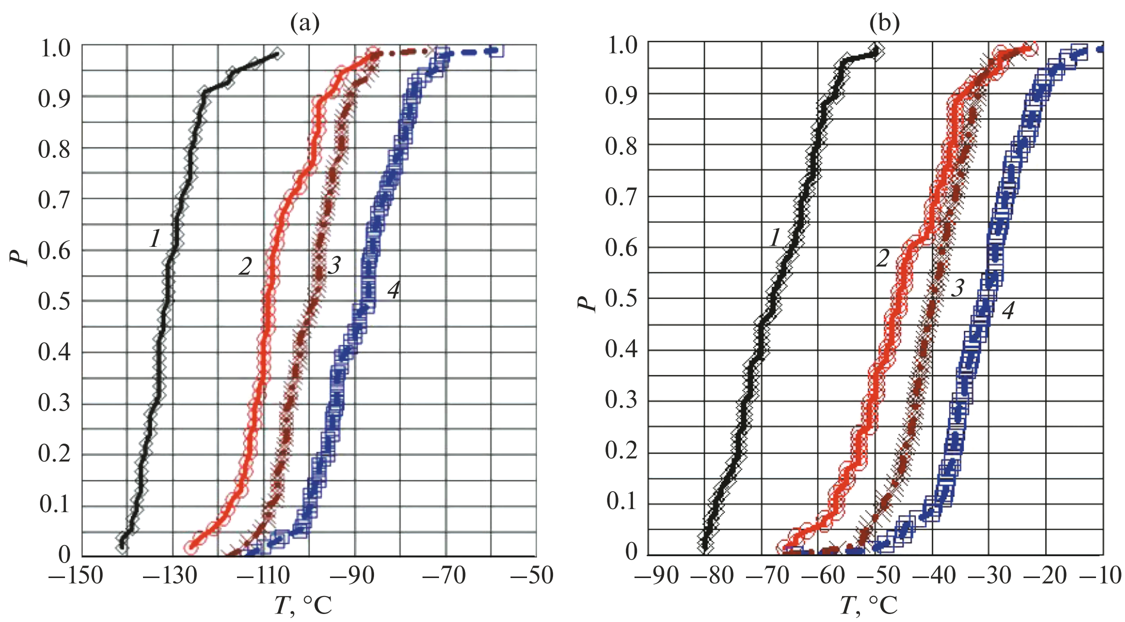

Fig. 8. Integral distribution functions (T_0) for the base metal (a) and weld-seam metal (b) without taking into account (*1*) and taking into account the inhomogeneity (*2*–*4*) at n = 24: (*2*) when determining T_0 by screening; (*3*) by bimodal distribution curves; (*4*) when determining T_0 by the reference temperature for the lower mode.

than the criterial values (the metal is inhomogeneous). For the base metal, criterion (9) was fulfilled for 5% of the series. Average values of $\overline{NH}$ are given in Table 2. The NH scattering pattern is shown in Figs. 7b and 7d.

In accordance with the ASTM E1921 standard for a heterogeneous material, the fracture toughness of which is described by a bimodal distribution, the value of T_0 can be determined through the value of K_{Jc} 0.05 corresponding to the lower limit of dispersion (fracture probability is P = 0.05), according to corresponding curves of the integral distribution of the fracture toughness (6). The distributions of T_0 obtained in this way (at the series size n = 24) for the base metal and weld metal are shown in Fig. 8 (curves *3*) in comparison with the distributions obtained without taking into account heterogeneity (curves *1*) and taking into account on the basis of screening (curves *2*).

It can be seen that the average values of $\overline{T}_{0bm}$ established taking into account bimodality (curves *3*) are approximately 10°C higher than those obtained by screening. In the region of the upper scattering limit, which determines the position of the lower envelopes of the fracture toughness temperature curves, the discrepancy decreases, and the reference temperature values approach the values obtained during screening.

The reliability of determining the distribution parameters of inhomogeneous material depends on the series size n, the temperature difference $T_a - T_b$, and the value of the parameter p_a. In the case of insufficiently reliable estimates, which meets the conditions $T_a - T_b \leq 30$°C and $p_a \leq 0.2$ or $p_a \geq 0.8$, as well as $NH \leq NH_{cr}$, the value $T_0 = T_a$ corresponding to the mode with a lower level of the fracture toughness can be taken.

Using this approach in our case leads to a shift of the initial curves of the integral distribution T_0 (without taking into account heterogeneity) for the base metal and weld metal to the region of positive values by approximately 40°C (Fig. 8b, curves *4*).

In conclusion, it should be noted that a significant shift in T_0 when taking into account the heterogeneity of the material can be associated with the relatively small dimensions of the tested samples of the ST-0.5T type having a thickness of 12.5 mm.

The tip of a crack in small-section samples can be located in a zone with both reduced properties (with a high local concentration of brittle inclusions) and a low concentration of inclusions. In this regard, when testing small-sized samples, the scatter of the determined characteristics will be higher, and the minimum values will be lower than when testing large-section samples, since in the latter, the influence of local brittle inclusions is to a certain extent balanced by the viscous metal surrounding these inclusions. It is advisable to experimentally test this assumption on samples of large thickness.

CONCLUSIONS

(1) Representative arrays of data on the fracture toughness (K_{Jc}) were obtained for the base metal and the weld metal of a shell 200 mm thick made from steel of the Cr–Ni–Mo–V type (70 compact samples were tested). It is shown that, when assessing the reference temperature T_0 according to the ASTM E1921 standard, owing to the high dispersion of test results, it is necessary to take into account the structural heterogeneity of the base metal and the weld metal.

(2) Using the Monte Carlo method, analysis of the correctness of metal identification (homogeneous/inhomogeneous) was performed, and estimates of T_0 were obtained depending on the series size (12, 24, and 70 samples). It is shown that the series of 12 samples do not allow one to reliably determine whether the metal is homogeneous or inhomogeneous (in 50% of cases for the base metal and 37% of cases for the weld metal, incorrect results were obtained). When the series size was increased to 24 samples, incorrect results were obtained in 5% of cases.

(3) To account for heterogeneity, a screening procedure was used for the series of 24 samples. The value of the shift of average $\overline{T}_0$ towards positive values for the base metal and weld metal was 22°C. The T_0 value corresponding to the lower envelope of the master curve (for the probability of destruction $P = 5\%$) for the base metal was –92°C; for the weld metal, it was –30°C.

(4) When using a bimodal representation of data on the fracture toughness to take into account the heterogeneity (on the series of 24 samples), the reference temperature T_0 corresponding to the lower envelope of the master curve (for the probability of fracture $P = 5\%$) for the base metal turned out to be –86°C; for weld metal, it was –30°C, i.e., close to the results obtained upon using screening.

ABBREVIATIONS AND NOTATION

T_0	reference temperature
P	probability of failure
K_{Jc}	the elastoplastic equivalent of the stress intensity factor
υ	Poisson ratio
E	modulus of elasticity
P_f	the probability that the fracture toughness of the material will not be greater than K_{Jc}
K_0	scale parameter that depends on temperature and the sample thickness
$m^{0.5}$	minimum value of the fracture toughness
b	parameter
K_{Jc}^X, K_{Jc}^Y	values of the fracture toughness for the samples of thickness B_X and B_Y
t	the thickness of sample
a_0	the length of the initial fatigue crack
σ_{ys}	conditional yield strength
BM	base metal
WM	weld metal
$K_{Jcm} = 20 + 0.91(K_0 - 20)$	median value of K_{Jc}
r	the number of uncensored values of K_{Jci}
n	total number of samples in the series
β	coefficient depending on the level of K_{Jc} values
K_{cor}	correlation coefficient
W	relative frequencies of the fracture toughness

K_A, K_B	scale parameters
p_a	parameter for the redistribution of probabilities over modes A and B
T_a and T_b ($T_b \leq T_a$)	reference temperatures corresponding to mode A and mode B
MLM	the maximum likelihood method
$f(X, p_a, K_A, K_B)$	distribution density
δ_i	Kronecker symbol
σ_{T_a} and σ_{T_b}	standard deviations of temperatures T_a and T_b
NH_{cr}	the criterial level
Bm	bimodal

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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