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Analytical model for assessing fatigue limit of welded joints of ferritic-pearlitic steels

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Introduction. Microdefects and zones with stress concentration in welded joints cause fatigue macrocracks. Such damage is potentially dangerous, especially if the fatigue life of the structure is almost exhausted. In this case, the crack size is close to the critical value, and it is crucial to determine its length. The paper considers the development of an engineering analytical model for assessing the critical crack length and endurance limit of weld joints with the formed grain in the structure of ferrite-pearlitic steels after welding.

Materials and Methods. The theory and methods of fracture mechanics at the mesoscale are used. A simple analytical dependence is obtained, which provides determining the critical dimensions of a macrocrack for ferrite-pearlite steels without using the Griffiths formula. . The calculation results of the critical crack lengths of various steels depending on their yield strength are presented. An analytical dependence of the endurance limit calculation for the most dangerous symmetric loading cycle, according to the standard set of mechanical characteristics and the average grain diameter of ferrite-pearlite steel, is presented.

Results. Structural deformation analysis of the crack propagation process has been performed. On its basis, an engineering technique for assessing the endurance limit is developed. A mathematical model that enables to calculate the endurance limit and the critical crack length in the components of welded assemblies of large-sized facilities, considering periodic loads of a symmetrical cycle, is developed. Using this model, it is possible to estimate the degree of metal sensitivity to the original characteristics (yield stress, Poisson's ratio, grain diameter, relative constriction, Young's modulus, power-law hardening coefficient, etc.).

Discussion and Conclusion. Under stresses corresponding to the steel endurance limit, the critical crack opening rates of the tip and edges approach each other. Energetically, this moment approximately corresponds to the transition of the crack to an unstable state. The accumulation of one-sided plastic deformations causes the limiting state of plasticity of the region adjacent to the crack tip and its avalanche-like or sharply accelerated motion. This critical area is interrelated with the grain diameter of the material, the characteristic of critical plasticity and the critical opening at the crack tip at the fatigue limit. The proposed analytical dependences can be used to assess the residual life and the fatigue limit of welded structures, the influence of various factors on the fatigue limit of welded joints of ferrite-pearlitic steels used in mechanical engineering, shipbuilding, pipeline transport, etc.

Keywords: welded joint, ferritic-pearlitic steel, crack length, endurance limit, critical deformation, mathematical model, structural damage.

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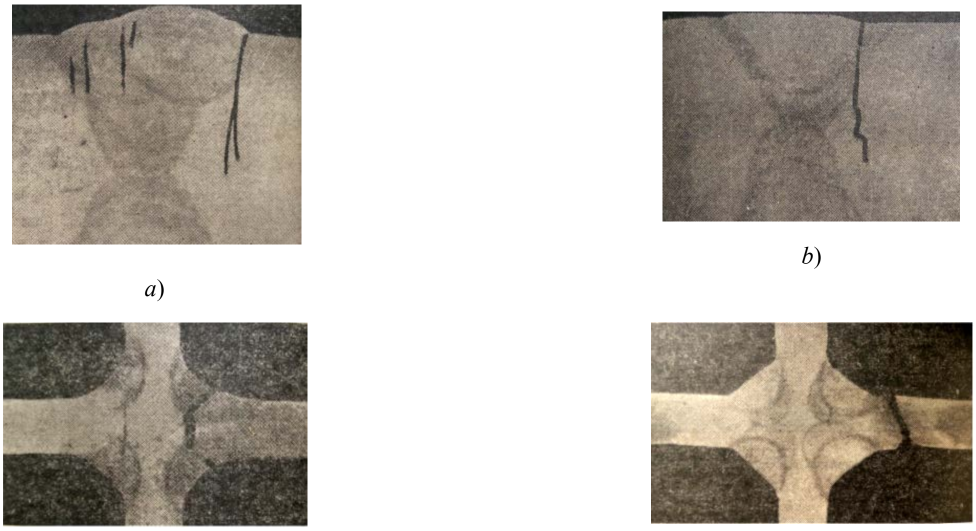
Introduction. Microdefects and stress concentration zones in welded joints cause fatigue macrocracks. Such damage is potentially dangerous, especially if the fatigue life of the structure is practically exhausted. In this case, the crack size is close to the critical value, and it is crucially important to determine its length. The paper considers the development of an engineering analytical model for assessing the critical crack length and endurance limit of weld joints with the formed grain in the structure of ferrite-pearlitic steels after welding.

It should be noted that an equally-strength weld joint for static loading does not guarantee its reliability under cyclic loads. This is due to local plastic deformations in stress points in discontinuities of the structures subjected to cyclic loads [1]. It can be assumed that for plastic materials, the maximum stresses in these zones will be constant and equal to the yield point if we neglect some strengthening of the material in the stress points and assume that the regions of disturbed stresses are relatively small compared to the material thickness [2].

Materials and Methods. The fatigue strength of structural steels corresponds approximately to the values of $\sigma_{-1} = 0.5 \dots 0.7\sigma_{\text{т}}$, and destruction under cyclic stresses, as a rule, occurs locally in the form of cracks originating from stress concentrators or defects in the weld joint (Fig. 1).



a) *b*) *c*) *d*)

Fig. 1. Cracks at undercut and in seam (*a, b*), destruction of cross joints from crack under incomplete penetration (*c*) and in heat-affected zone (HAZ) with full penetration (*d*) [2]

The stress concentration resulting from partial penetration during the formation of a weld joint can also play a decisive role in the formation of weak zones. This is facilitated by significant inhomogeneity of mechanical characteristics, major defects in the seam and near-weld zone.

In the corner and T-joints (with or without grooving), in most cases, the crack originates from the stress concentrator (see Fig. 1*c,d*). If the seam is convex, destruction can occur along the fusion zone or near it, along the base metal in the HAZ, whose structure has undergone changes [3].

Over time, microdefects cause fatigue cracks [4, 5]. Such cracks in the weld joints of some elements propagate slowly, so they may not be particularly dangerous. This is evident from the practice of using modern steel grades for ship hulls [6]. At the same time, fatigue cracks are potentially dangerous in two cases.

1. If the resource provided by the static indeterminacy of the structure and other factors is practically exhausted.

2. If the crack size corresponds to the Griffiths critical length in an infinite plate $L|_{\sigma_{-1}} = L_c$, determined from the dependence:

$$L = (K_{1c}/\sigma_{-1})^2/\pi, \quad (1)$$

where K_{1c} is critical stress intensity factor under plane deformation at the crack tip; σ_{-1} is stress of material endurance limit; L is half the length of the through-crack.

The coefficient K_{1c} can be calculated on the basis of a standard set of mechanical characteristics and average grain diameter of ferrite-pearlitic steel according to [7] for plane deformation and according to [8] for the planar stress state. However, to find the critical crack length of the fatigue limit, it is required to know value σ_{-1}.

The mechanism of the influence of the average diameter of steel grain at the moment of initiation of the transition of a crack into an avalanche-like advance is likely to differ from the mechanism that controls its movement at the stage of its formation. Such assumptions, based on the results of the studies [7, 9–11], motivate a more detailed consideration of the processes that control the end of the stage of stable development of macrocracks at stresses equal to the fatigue limit. It is not difficult to determine it at the critical crack size according to (1), if we find the pattern of the influence of the structure, plastic properties and mechanical characteristics of the material on the critical crack size.

The study objective is to develop analytical dependences that make it possible to establish the relationship between the critical crack length at stresses σ_{-1}, mechanical characteristics of ferrite-pearlite steel and the average grain diameter in the metal structure. The task is to bring the obtained dependencies to engineering formulas to estimate the endurance limit of ferrite-pearlitic steels.

The results of studying the cracking process at high nominal stresses indicate their discrete, jump-like development [12]. This character of growth is demonstrated through modeling at the final stage of fracture [7] under the load corresponding to the endurance limit. This suggests that, after the accumulation of one-sided plastic deformation, plastic deformation is restrained if large volumes of material with a fragmented structure are adjacent to the crack tip.

Results. At a high density of dislocations that create a fragmented structure, we will accept the conditions of plane deformation at the crack tip. Additional conditions will be provided due to constraint and accumulated one-sided plastic deformation under cyclic loads. Let us write the postulates for the moment when $L = L_{\text{кр}}$, $\sigma = \sigma_{-1}$.

1. One-sided plastic deformation reaches a critical value at the crack tip.

2. Fragmentation (cellularity) of the structure of the ferrite-pearlite material is limiting (located at the second level).

3. The function of the difference between the opening of the crack edges and the crack tip has an inflection at a point close to the state when $L = L_{\text{кр}}$, $\sigma = \sigma_{-1}$.

The experimental data shows that the cyclic loading of metals causes a significant change in the structure, substructure, and affects all sensitive characteristics. For example, an increase in the number of loading cycles of cyclically hardening (or softening) metals contributes to an increase (or decrease) in hardness (primarily on the surface of the samples under study) [13, 14].

The results of the elastoplastic analysis of the plastic zones at the crack tip determined by the Panasyuk-Dugdale model [15], differ significantly from the real ones for materials with a hardening index $m > 0.05$. Nevertheless, we will assume that at low nominal stresses $\sigma_{\text{н}} = \sigma_{-1}$, the opening at the crack tip δ and the ratio δ/r_p can be determined quite accurately for the case of plane deformation from the formulas [16]:

$$\delta = 8\sigma_{\text{т}} \cdot L/pi/E \cdot \ln\sec[\pi\sigma_{\text{н}}/2/\sigma_{\text{т}}], \quad (1)$$

$$\delta/r_p = \frac{8e_{\text{т}} \ln\sec(\pi\sigma_{\text{н}}/2)}{\pi(\sec(\pi\sigma_{\text{н}}/2)-1)} \quad (2)$$

where r_p is the linear size of the plastic zone along the crack extension from its tip (Fig. 2); $e_{\text{т}}$ is deformation of the yield point.

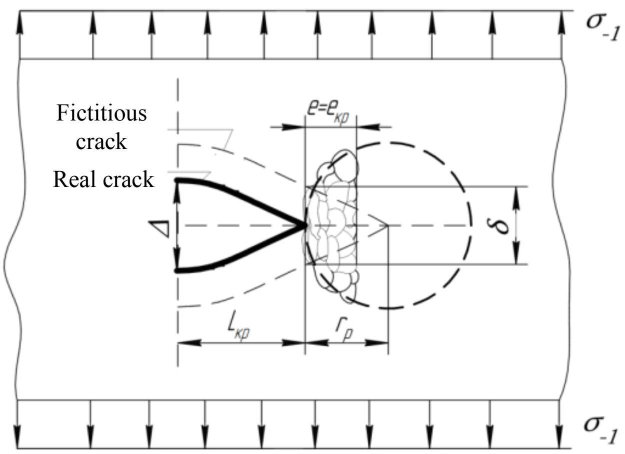


Fig. 2. State of metal at the tip of a critical opening mode crack under stresses of fatigue limit

Let us estimate the opening of the edges of this crack at rated stresses below the proportionality limit, allowing for some error [16]:

$$\Delta = \frac{4\sigma_{н}L}{E} \qquad (3)$$

After derivation of the difference between δ and Δ, we find that the voltages corresponding to the moment of accelerated convergence δ and Δ will correspond to the nominal ones determined from the expression:

$$\sigma_{н} = \sigma_{т}/2. \qquad (4)$$

With significant plastic deformations, the structure of the material undergoes fragmentation at the crack tip; therefore, the value $e_{кр}$ is associated with the staging and deformability of the fragmented structure. According to A.M. Glezer [17], the boundary between macroplastic and mega plastic deformations is conventional; it is at the level of relative deformation, equal to one hundred percent, or true. In this case, the critical deformation value:

$$e_{кр} \approx 1. \qquad (5)$$

A. N. Balakhnin[1] notes that self-organization of the structure with the cell formation (Fig. 3) starts already under the deformation of ferrite of 09G2S steel and with an average value of the degree of cold deformation ε 15–35%.

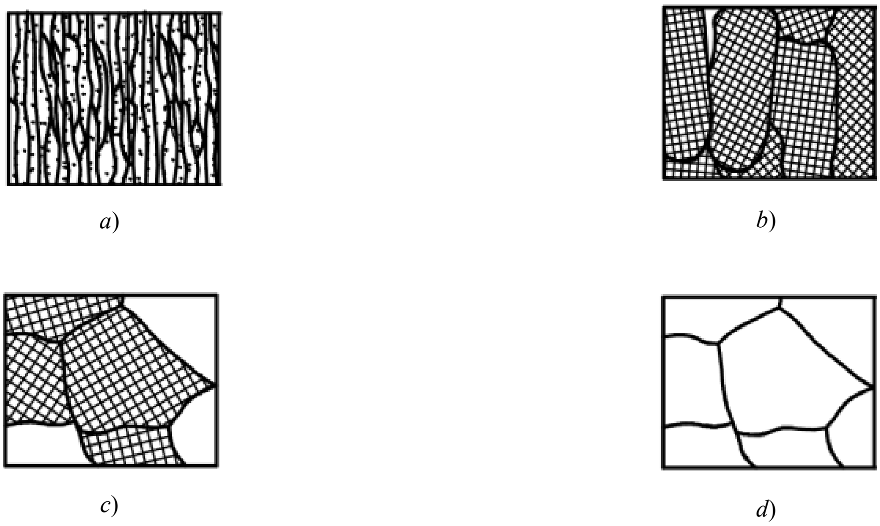


Fig. 3. Microstructure under plastic deformation: ε = 80 % (*a*), ε = 40 % (*b*), ε = 1 % (*c*), ε = 0 % (*d*) [11]

With a further increase in deformation, the cell walls become thinner, and their size decreases. The fragments acquire an elongated shape, and the grains stretch in the direction of the plastic flow (Fig. 3).

At critical crack opening in the region adjacent to the tip, the grain structure in the fictitious crack model should expand and pass into the pre-cleavage state (Fig. 3*a*). It is likely to be formed due to the containment of the influx of new dislocations and their transition across grain boundaries. The material in this area should be in a state of extreme critical plasticity, and the linear characteristics of its fragments should be at the second fragmentary level. Obviously, in the adjacent plasticity zone, the crack should also have a certain number of grains in their ultimate plastic state.

Thus, the zone can be formed due to the accumulation of a part of one-sided plastic deformation, covering practically all stages of crack propagation. However, the most significant contribution to the increase in such deformation is made at the final stage of fracture, when the plasticity region is large not only in relation to the crack length, but also to the linear characteristic of the metal structure. In this zone, the grains have a prolate shape in the form of an oblong grain of rice with a cross-sectional size $d_{к}$.

Let us refer the average grain diameter of the undeformed material d_z to $d_{к}$. Then, for the second fragmentary level:

$$d_z/d_{к} \cong 1/0{,}618/0{,}618 = 2{,}618, \qquad (6)$$

where $d_{к}$ is the fragment diameter.

[1] Balakhnin A N. Formation of the structure and properties of hardened sectional low-carbon steels under cold radial forging and subsequent thermal exposure: Cand.Sci. (Eng.) diss. Perm, 2015. 158 p. (In Russ.)

It is not hard to conclude that for this state, plastic deformation can be determined from the dependence of the maximum uniform elongation [3, 14]:

$$e_{кр} = 2\,ln(d_z/d_к) \cong 2. \tag{7}$$

For the same state, critical plastic deformation on the test specimen in the neck under rupture is expressed by the well-known dependence:

$$e_{кр} = k_н \cdot ln\left(\frac{1}{1-φ_к}\right), \tag{8}$$

where $k_н$ is the normalization factor introduced by the authors for the transition from the structure in the critical plastic state to the value of the critical plastic deformation of the sample under rupture.

Let us find this coefficient through the relative (critical) contraction of the sample under rupture, equating (9) to (8). Then, considering (6), the critical plastic deformation is determined by the expression:

$$e_{кр} = 2 = ln\frac{1}{1-φ_к} + ln\frac{1}{1-φ_к} = 2\,ln\frac{1}{1-φ_к} \tag{9}$$

For the critical opening at the crack tip, the structural-deformation criterion can be expressed:

$$δ_{кр} = d_з e_{кр} = 2d_z\,ln\left(\frac{1}{1-φ_к}\right). \tag{10}$$

As a result of the effect of the critical transverse narrowing $φ_к$ on the stress intensity factor at plane deformation K_{1c} for high-strength steels, the following is indicated [18]:

— significant spread of values K_{1c} and $φ_к$;

— satisfactory correlation between them.

At the same time, it is concluded that the relationship between K_{1c} and $φ_к$ can be applied only as a qualitative one. We can agree with such conclusions, but only if we discard the relationship with some other structural characteristics, for example, the average grain diameter of steel, etc.

To find the required dependence, we substitute (5) into (2). We equate the resulting expression to (11) and write it with respect to L. As a result of calculations, we obtain the critical length of a macrocrack for nominal stresses equal to the endurance limit at the most dangerous asymmetry of the cycle:

$$L_{кр}\big|_{σ_н=σ_{-1}} = 0{,}3607\,\frac{π\cdot E}{σ_т}\,2d_z\,\ln\left(\frac{1}{1-φ_к}\right). \tag{11}$$

It follows from this that the length of the critical crack is directly proportional to the value of the critical logarithmic plastic deformation $e_{кр}$ of steel and is inversely proportional to the yield strain $σ_т/E$. Having transformed the numerical constant, (12) we can write in the form:

$$L_{кр}\big|_{σ_н=σ_{-1}} = 0{,}7214\,\frac{π\cdot d_z\cdot e_{кр}}{ε_т} \tag{12}$$

Using the empirical dependence of the resistance to micro cleavage of grain $R_{Mc} = σ_в/(1-φ_к^2)$, which is valid for the group of ferrite-pearlitic low-carbon steels, we find the average grain diameter:

$$d_z = [5{,}7(1-φ_к^2)/σ_в]^2. \tag{13}$$

Here, $σ_в$ is tensile strength of steel. Substituting d_z in (13), we can obtain the desired simple formula for estimating $L_{кр}$, which includes only the key characteristics of the material.

To calculate the endurance limit of a symmetric cycle, it is sufficient to equate (12) to (1). To find K_{1c}, we use the conclusion obtained in [7]. The final formula for calculating K_{1c} under the conditions of plane deformation at the crack tip, with mathematical rigor, has the form:

$$K_{1c} = \sqrt{\frac{π\;0{,}618\;d_z}{\left[{σ_т}^{1/m-1}\cdot(1-2μ)^2\right]/2}\left(\frac{R_{Mce}\cdot D}{q}\right)^{1/m+1}} \tag{14}$$

Here, R_{Mce} is resistance to micro cleavage of deformed metal, which for the class of ferrite-pearlitic steels $R_{Mce} = 1.618R_{Mc}$; R_{Mc} is resistance to micro cleavage of ferrite grain; m is the coefficient (indicator) of the power-law hardening of the material; q is the overvoltage factor equal for this case $1 - 2D/\sqrt{3}$; μ is Poisson's ratio. D is the coefficient that takes into account the increase in the first principal e $(1 + m)(1 - 2\mu)/2$.

The resistance of grain micro cleavage is calculated according to the classical relationship $R_{Mc} = 5.7/\sqrt{d_z}$ for cleavage of ferrite or ferrite-pearlite grains. Substituting (15) with all components from (12) into (1), we obtain the final value of the fatigue limit depending on the standard set of mechanical characteristics of the material and the average grain diameter:

$$\sigma_{-1} = \sqrt{\frac{1{,}091\left(\frac{4{,}611\cdot(1-2\mu)(m+1)}{\sqrt{d_Z}}\right)^{1/m+1}\cdot\sigma_{\text{т}}^{\,2-1/m}}{E(2\mu-1)^2\cdot e_{\text{кр}}\left(\frac{\sqrt{3}\cdot(2\mu-1)(m+1)}{3}+1\right)^{1/m+1}}} \quad (15)$$

If the value of the average grain diameter d_z is unknown, it can be calculated using (14).

The results of numerical testing of the endurance limit show that the dependence (16) is "sensitive" to some characteristics of the material. For example, varying the value of Poisson's ratio in hundredths can change the result by $\sqrt{2}$ times. Probably, such an error in calculations is associated with the unique features of the models used and the assumptions made when deriving (16).

Let us check the adequacy of the proposed analytical model through the example of a group of ferrite-pearlitic steels (Table 1).

Table 1

Basic experimental and calculated characteristics of steels

Steel grade	$\sigma_{\text{т}}, MPa$a	$\sigma_{\text{в}}, MPa$	μ	m	$\varphi_{\text{к}}$	$d_{з}, \mu m$	K_{1c}, MPa	σ_{-1}, MPa
10 steel	190	320	0.3	0.17	0.73	66	103.6	135.4[1]
St3sp	270	450	0.3	0.16	0.71	37	101	192[1]
22K	310	540	0.3	0.16	0.69	30	97	220[1]
50 steel	350	680	0.3	0.16	0.62	25	78	247[1]
37KHN3A	743	1014	0.26	0.12	0.6	14[3]	73	480[1]
15G	280	490	0.29	0.156[1]	0.65	45[4]	–	230
09G2	300	440	0.29	0.16	0.69	33	–	235
30KHGSA	1360	1750	0.26	0.13[2]	0.44	7[4]	–	490
16G2AF	417	600	0.29	0.16	0.5	22	–	255
10KHSND	390	540	0.29	0.132[2]	0.71	27[4]	–	284

[1] Values obtained by calculation [7].

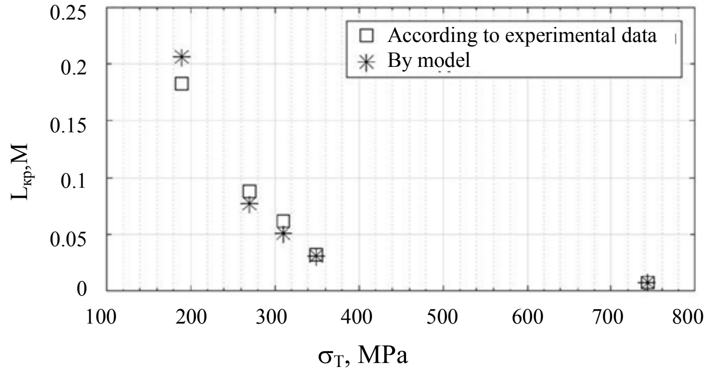
[2] Dependency calculation $m = \{0.75 \cdot lg[\sigma_{\text{в}}(1 + 1.4\varphi_{\text{к}})/\sigma_{0,2}]\}/lg\left[10^5 \cdot ln\left(\frac{1}{1-\varphi_{\text{к}}}\right)/(200 + 0.5\sigma_{0,2})\right]$ [2].

[3] Calculated from the data on the resistance of micro-cleavage of an undeformed material.

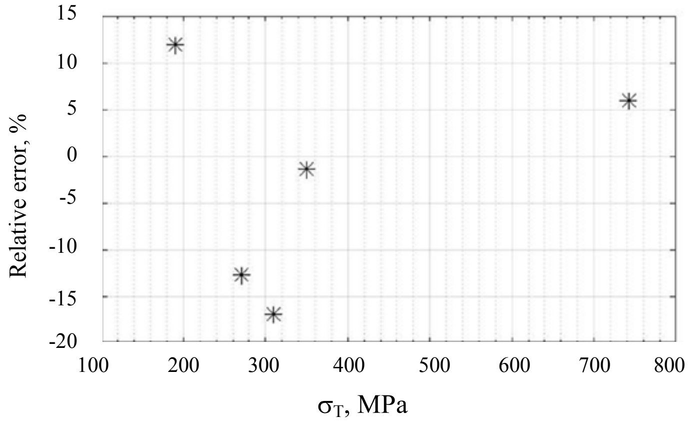
[4] Dependency calculation (14).

To compare the results obtained by (12), we find the critical crack lengths from the experimental data and with account for the formula (1). The endurance limits are calculated under the condition of plane deformation by the method [7], which considers the average grain diameter, the hardening rate m and other mechanical characteristics that significantly affect the endurance limit.

Fig. 4 *a* shows the values of the critical lengths of through-cracks at the fatigue limit for steels with different yield strengths. The calculated values according to (12) are compared to the experimental data. The comparison has shown a reasonably good agreement for ferrite-pearlitic steels of different strength, despite the numerous assumptions made (Fig.4 *b*).



a)



b)

Fig. 4. Values of critical crack lengths of steels depending on yield point (*a*), and relative error of the model (*b*)

Fig. 5 shows the results of comparing the fatigue limit of a symmetric cycle according to (16) for a group of steels (Table 1) to the experimental and known calculated values.

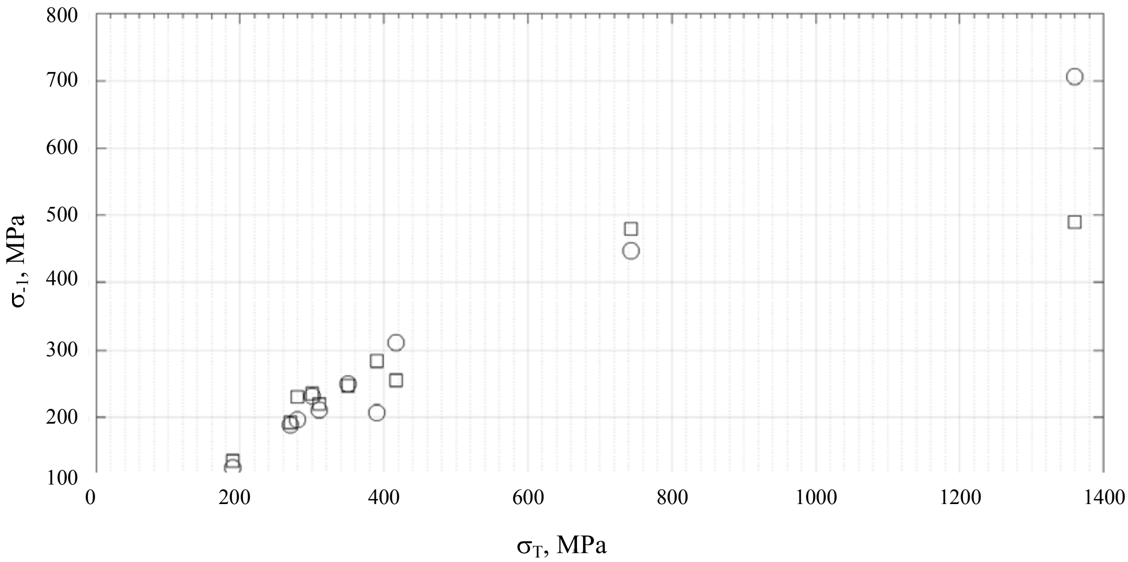


Fig. 5. Comparison of endurance limits of symmetric cycle and yield strength: ○ is calculation according to the model (16); □ is known data (Table 1)

Based on the comparative analysis results, conclusions can be drawn.

1. The stronger the steel, the more the “sensitivity” (16) affects the initial data, and the calculation error grows.

2. For ferrite-pearlite steels with $\sigma_т < 400$ MPa, the results of calculating the fatigue limits are in satisfactory agreement with the initial data in Table 1.

The dependence (16) has high “sensitivity” to some initial parameters, so, at this stage of the study, it is impossible to more accurately assess the results.

When the crack length approaches the critical value $L_{кр}$, it starts to grow stepwise. Therefore, the deterministic model cannot accurately determine the number of cycles after which this crack propagation will end and it will propagate at the speed of sound. The average grain diameter of a material can vary significantly in areas of welded structures, for example, in the HAZ and the material that is not affected by welding.

It should be noted that the stage of the macrocrack development in air for elements of large-sized parts without stress concentrators takes almost 20% in time.

In this regard, when determining $L_{кр}$, the relative error up to $\sim 15\%$ can be considered a positive result. The period of the so-called "cyclic breakdown" [11] falls within the framework of this error, where for low cyclic fatigue stresses, $\sim 1/10$ a part of the residual life corresponds to an increase in the crack length about two fold.

Thus, the analytical dependences proposed on the basis of the structural-deformation analysis criteria can be used in calculating the endurance limit of the ship and other large-sized structures.

Discussion and Conclusions. A safe operation of ships requires up-to-date and adequate information on the condition of the hull structures including metallurgical defects and structural stress concentrators. It is important to assess the residual life and, accordingly, to determine the critical dimensions of fatigue cracks. At the top of a critical developing macrocrack under stresses corresponding to the endurance limit, one-sided plastic deformation, which reduces the plasticity of the highly fragmented zone, is accumulated. At the same time, the number of residual life cycles remains insignificant and strongly depends on the yield point, defects, grain diameter of the steel of the structure in which the crack develops.

The study results show that under stresses corresponding to the endurance limit of steel, the rates of the critical crack opening of the tip and the edges approach. Energetically, this moment corresponds approximately to the transition of the crack to an unstable state. The accumulation of one-sided plastic deformations causes the limiting state of plasticity of the region adjacent to the crack tip and its avalanche-like or sharply accelerated motion. This critical area is related to the material grain diameter, critical plasticity characteristic and critical opening at the crack tip at the fatigue limit.

The analytical dependences obtained allow us, with account for the average grain diameter of ferrite-pearlite steel and critical narrowing, to calculate the endurance limit of the most dangerous loading cycle according to the classic Griffith relationship between the crack length, stresses and the stress intensity factor.

The proposed mathematical model and the approach based on structural-deformation analysis criteria can be used in engineering calculations of machine-building, ship structures and their connections to assess the service life.

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