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Original article



Evaluation of the Occurrence of Initial Failures from Stress Concentrators in Welded Joints and Structural Elements

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Abstract

Introduction. Data on the occurrence of initial failures obtained through testing on standard samples cannot always be extrapolated to real welded joints and structures. This is due to the difference between the concentrators in the joints, because after welding there is a significant structural and mechanical heterogeneity of the heat-affected and stress concentrator zone. Extended, deep concentrators are considered as crack-like defects, at whose vertices a volumetric, multiaxial stress state is formed. The paper addresses the issue of constructing critical diagrams of the onset of the limiting state at the concentrator vertex, which depends on the level of external load and the theoretical concentration coefficient.

Materials and Methods. Analytical methods were used to study the stress state. The literature on the topic was analyzed. The features of proven physical models and patterns of behavior of materials were taken into account. The characteristics of steel alloys were taken from open sources and summarized in a tabulated form. Nonlinear equations were solved in MATLAB applications. The diagrams constructed by the authors enable to track the correlation of the dangerous level of the theoretical stress concentration factor and the level of external load. Curve Fitting Toolbox MATLAB was used to design the graphic part of the work.

Results. The characteristic of damage from stress concentrators in welded joints was given. The crack propagation in the fusion zone was shown. The conditions stimulating and inhibiting destruction were indicated. The theoretical stress concentration factor α_T was specified. It was shown how this indicator depended on the width, the height of the seam and the thickness of the welded part. Acute stress concentrators with theoretical concentration factor $\alpha_T = 5 \dots 14$ and more were studied. For this case, an approximating formula was given that took into account the maximum stress in the concentrator in the first half cycle, the initial deformation, and the load ratio. Through those elements, an indicator of an increase in maximum stresses was set depending on the number of loading cycles. The flow condition, the stress state, and the overvoltage factor, which took into account the increase in the first principal voltage for a combined stress state, were analytically shown. A model of the critical state at the apex of an acute stress macro concentrator was described. It was presented as the dependence of the relative stresses of the initiation of destruction $\sigma_H^{bc}/\sigma_{0.2}$ on the concentrator. Possible variations of this model were analyzed. The dependences of relative values $\sigma_H^{bc}/\sigma_{0.2}$ on the theoretical concentration factor $\alpha_T^{bc} = \alpha_T$ were presented. To check the physical adequacy of this model, graphs were constructed that reflected changes in the relative stress of the external load at a critical state at the stress concentrator apex. The inevitability of bifurcation as a result of the studied processes was validated. Two directions of further development of events were indicated: brittle destruction and loss of stability of the stressed state with the transition to an increase in plastic deformations. The moment of bifurcation was defined as a critical state in the focus of the concentrator.

Discussion and Conclusion. The analysis and calculations performed within the framework of the presented scientific work enabled, in particular, to draw conclusions about the role of key factors of the processes under study. It was established, for example, that the operation of a steel alloy at a high theoretical stress concentration factor depended on the characteristics of the stress state. In a rigid state, it was possible to inhibit shear deformation and the onset of the limiting state at a lower value of the theoretical stress concentration factor. With the usual strength of steel (in comparison to high), a greater impact of the volume of the stress state on the value of the theoretical stress concentration factor was recorded. The probability of failure depended on the resistance of the material to the growth of a macrocrack. In future research, it is possible to refine analytical models and results, evaluate effective stress concentration factors.

Keywords: welded joint, theoretical concentration factor, defects of welded joints, volumetric stress state, stress concentration, yield strength, macrocrack.

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Научная статья

Оценка появления начальных разрушений от концентраторов напряжений в сварных соединениях и элементах конструкций

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Аннотация

Введение. Данные о возникновении начальных разрушений, полученные испытаниями на стандартных образцах, не всегда можно экстраполировать на реальные сварные соединения и конструкции. Это обусловлено отличиями концентраторов в соединениях, т. к. после сварки возникает значительная структурно-механическая неоднородность зоны термического влияния и концентраторов напряжений. Протяженные, глубокие концентраторы рассматриваются как трещиноподобные дефекты, в вершинах которых образуется объемное, сложное напряженное состояние. Решается вопрос построения критических диаграмм начала возникновения предельного состояния в вершине концентратора, которое зависит от уровня внешней нагрузки и теоретического коэффициента концентрации.

Материалы и методы. Для исследования напряженного состояния задействовали аналитические методы. Проанализирована литература по теме. Учтены особенности проверенных физических моделей и закономерности поведения материалов. Характеристики сплавов стали взяты из открытых источников и обобщены в виде таблицы. Нелинейные уравнения решались в прикладных программах Matlab. Построенные авторами диаграммы позволяют отследить корреляцию опасного уровня теоретического коэффициента концентрации напряжений и уровня внешней нагрузки. Для оформления графической части работы использовали Curve Fitting Toolbox Matlab.

Результаты исследования. Дана характеристика разрушений от концентраторов напряжений в сварных соединениях. Наглядно показано развитие трещин в зоне сплавления. Указаны условия, стимулирующие и тормозящие разрушение. Определен теоретический коэффициент концентрации напряжений α_T . Показано, каким образом данный показатель зависит от ширины, высоты шва и от толщины свариваемой детали. Рассмотрены острые концентраторы напряжений с теоретическим коэффициентом концентрации $\alpha_T = 5 \dots 14$ и более. Для этого случая приводится аппроксимирующая формула, которая учитывает максимальное

напряжение в концентраторе в первом полуцикле, исходную деформацию и коэффициент асимметрии цикла нагружения. Через эти элементы задается показатель повышения максимальных напряжений в зависимости от числа циклов нагружения. Аналитически показаны условие текучести, напряженное состояние и коэффициент перенапряжения, учитывающий повышение первого главного напряжения для сложного напряженного состояния. Описана модель критического состояния в вершине острого макроконцентратора напряжений. Она представлена как зависимость относительных напряжений зарождения разрушения $\sigma_H^{bc}/\sigma_{0,2}$ от концентратора. Проанализированы возможные вариации этой модели. Представлены зависимости относительных значений $\sigma_H^{bc}/\sigma_{0,2}$ от теоретического коэффициента концентрации $\alpha_T^{bc} = \alpha_T$. Для проверки физической адекватности данной модели построены графики, которые отражают изменения относительного напряжения внешней нагрузки при критическом состоянии в вершине концентратора напряжений. Обоснована неизбежность бифуркации как результата исследуемых процессов. Указаны два направления дальнейшего развития событий: хрупкое разрушение и потеря устойчивости напряженного состояния с переходом к росту пластических деформаций. Момент бифуркации определен как критическое состояние в очаге концентратора.

Обсуждение и заключения. Анализ и расчеты, выполненные в рамках представленной научной работы, позволили, в частности, сделать выводы о роли ключевых факторов исследуемых процессов. Установлено, например, что работа сплава стали при высоком теоретическом коэффициенте концентрации напряжений зависит от характеристик напряженного состояния. При жестком состоянии возможно сдерживание сдвиговой деформации и наступление предельного состояния при меньшем значении теоретического коэффициента концентрации напряжений. При обычной прочности стали (в сравнении с высокой) фиксируется большее влияние объемности напряженного состояния на значение теоретического коэффициента концентрации напряжений. Вероятность разрушения зависит от сопротивляемости материала росту макротрещины. В будущих изысканиях возможно уточнение аналитических моделей и результатов, оценка эффективных коэффициентов концентрации напряжений.

Ключевые слова: сварное соединение, теоретический коэффициент концентрации, дефекты сварных соединений, объемное напряженное состояние, концентрация напряжений, предел текучести, макротрещина.

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Introduction. Static and fatigue strength is reduced due to defects in welded joints. These can be:

- cracks formed during or after welding;
- stress concentrators (undercuts, incomplete fusion, pores, welding craters, high rippling, abrupt change in the shape of the weld, rolls, etc.)

In the latter case, the determining factors will be:

- shape, size of the concentrator and the position in the welded joint;
- stress state indicator at the top [1].

Under cyclic loads, cracks often occur and develop in welded joints, provoked by stress concentrators [2]. The risk also depends on how close the stress state of the welded joint with the concentrator is to the occurrence of a macrocrack and its spread at operating σ_H and cyclic loads σ_{-1} . Obviously, the latter depends significantly on the size, shape of the macrodefect and the stress state at its top. For example, an oblong and narrow macro stress concentrator is more dangerous than a rounded one. Probably, a crack is immediately formed at its top, and together with it, the initial concentrator will represent one long macrocrack [3]. The size of such a “total” macrocrack may be critical, which will

reduce the static strength [4]. It depends on its length and mechanical characteristics of the material at the top of the initial concentrator.

The study objective is to develop an analytical model for assessing the dangerous level of stress concentration. The case in hand is about the formation of a crack in the top of the concentrator, a sharp decrease in the bearing capacity of welded joints and structural parts.

Materials and Methods. Scientific research within the framework of the stated topic was based on known physical models and patterns of behavior of materials. The theoretical and applied literature was analyzed. Illustrative and reference materials were extracted from the sources.

The stress state was studied by analytical methods. The relationship between the rigidity of the stress state and the value of the theoretical stress concentration factor was established. The results were presented in the form of diagrams. This visualization method made it possible to track the correlation of the dangerous level of external load and the theoretical stress concentration factor.

To check the results of calculations based on the physical adequacy of the authors' model, dependency graphs for the critical state were constructed. The paper used information about widespread structural steels of ferrite-perlite class in the state of delivery (steel 10, 22K, 50, St3sp, 37KHN3A, 30KHGSA, etc.). Their mechanical characteristics were obtained from open sources¹ and summarized in Table 1. The data was visualized in the Curve Fitting Toolbox MATLAB.

Table 1

Characteristics of steels

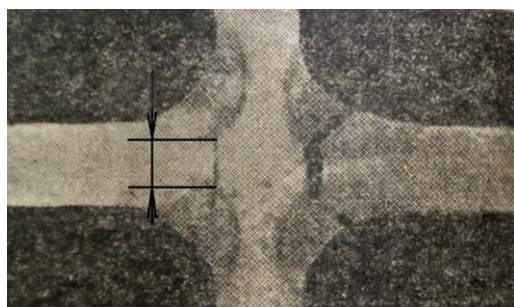
Steel grade	σ_B , MPa	σ_T , MPa	m	φ_k
10	320	190	0.17	0.73
15G	410	245	0.148	0.55
St3sp	450	270	0.16	0.71
22K	540	310	0.16	0.69
50	680	350	0.16	0.62
10KHSND	540	390	0.132	0.71
37KHN3A	1014	743	0.12	0.6
30KHGSA	1750	1360	0.09	0.44

Mathematical apparatus was applied to derive formulas. When solving nonlinear equations, the MATLAB application software package was used.

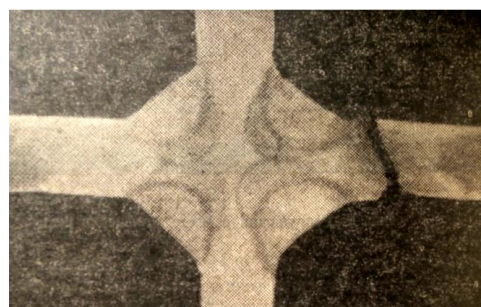
Research Results

Characteristics of damage from stress concentrators in welded joints. Since early 2000s, stress concentrations in welded joints and structures have been studied in relation to industrial tasks [2–3, 5–9].

Figure 1 shows examples of destruction of welded joints due to stress concentration.



a)



b)

¹ Sergeev NN, Sergeev AN. Mechanical Properties and Internal Friction of High-Strength Steels in Corrosive Media. Vologda: Infra-Inzheneriya; 2020. 431 p. (In Russ.)

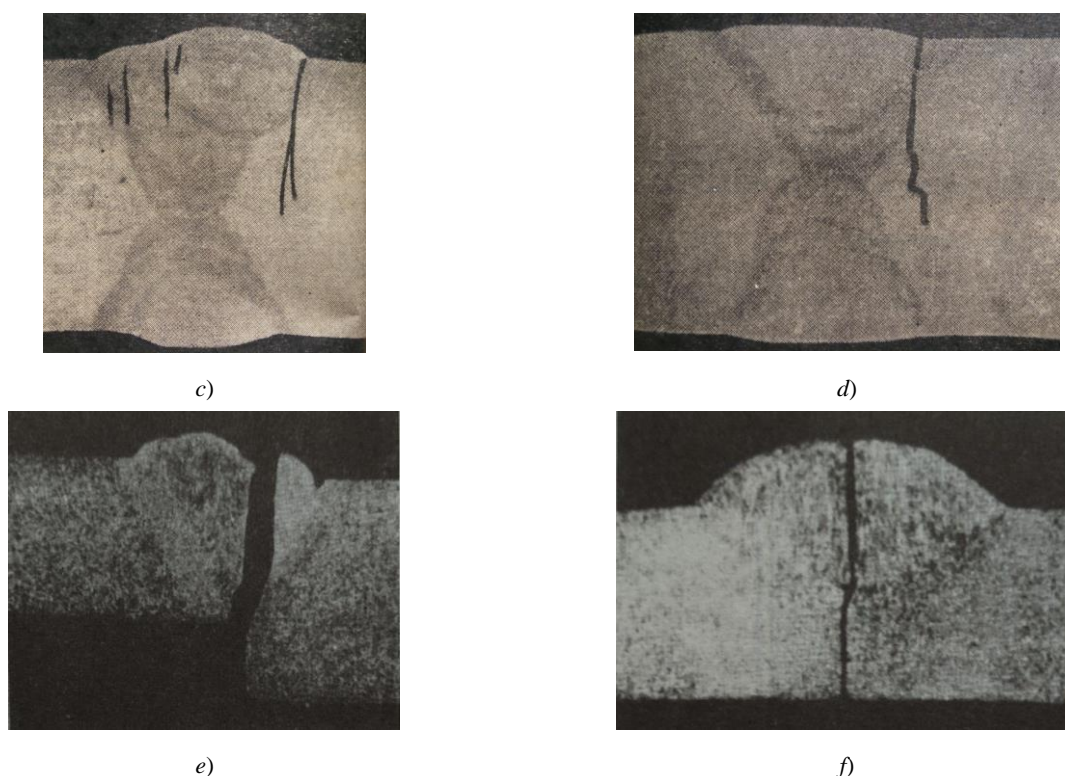


Fig. 1. Destruction of cross and butt joints² from stress concentrators:

a, f — from the incomplete fusion zone, square butt joint; *b* — from undercutting, V-weld; *c* — from a sharp transition in the fusion zone; *d* — undercut; *e* — from the concentrator formed by a step transition at the edge junction [10]

The destruction of cross joints with large non-fusion of the edges (indicated by arrows in Fig. 1*a*) is possible under the following loads:

- static (as a result of embrittlement of the fusion zone);
- cyclic (cause cracking at the tops of the concentrator).

In [5], the stress distribution for butt, corner, cross joints and intermittent connections of ship structures is analyzed. In butt and cross welded joints, the area of the base metal adjacent to the weld is of particular importance. This is the weakest cross-section that determines the strength of the joint at variable stresses. It should be noted that the welds are always quite long compared to the thickness of the metal and the stress concentrator (undercut in the butt or cross joint). This prevents a shift in the area of the concentrator and creates a biaxial, and more often a multiaxial stress state [11, 12]. When considering the destruction of welds with concentrators (see Fig. 1 *a, e, f*), we take into account the concept of the occurrence of plastic deformation in the top region [5, 7]. In addition, it should be noted that the concentrators are adjacent to the fusion zone, which, after welding, experiences longitudinal residual tensile stresses. They affect the degree of rigidity of the stress state in the concentrator focus [1, 13–14]. All this prevents the passage of shear in the concentrator focus and can contribute to the occurrence of a minimal brittle macrocrack with a high theoretical stress concentration factor α_T even from static load.

In [9], indicative failures from welded defects in large-diameter pipelines are described. It is established that with long-term operation (more than 20 years), fatigue cracks appear in the undercuts of longitudinal welded pipe joints. Cracks in undercuts in the fusion zone, as a rule, branch out and spread in two directions (fig. 2): one moves away from the fusion zone, the other develops along the fusion zone (along the weld). This indicates a strong impact of the

² Molokov KA, Novikov VV, Turmov GP. Fundamentals of Computational Design of Welded Structures. Vladivostok, 2019. T. 1. 204 p. (In Russ.)

mechanical, structural characteristics of the material³ and mechanochemical heterogeneity on the propagation of initial destruction [13, 14]. On the other hand, the crack branching can complicate the process of further destruction and the transition of the crack into the main one.

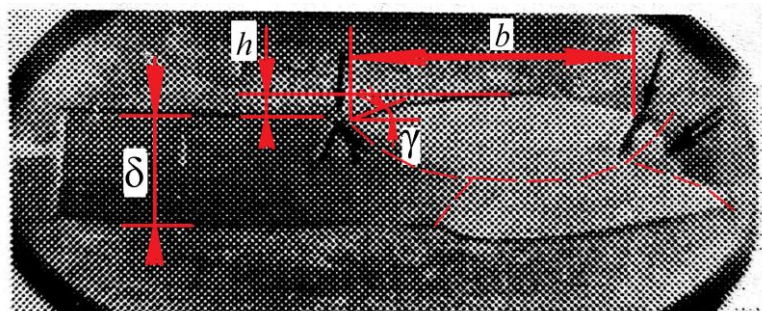


Fig. 2. Destruction in the pipe welded joint from the stress concentration in the fusion zone. Steel 14HGS. Single arrow shows fatigue cracks; double arrow — pipe burst edge; strokes — weld outlines. Here, b — weld width; h — weld height; δ — weldment thickness; γ — angle of transition from base metal to weld [9]

The theoretical stress concentration factor in the fusion zone can be determined from the formula that takes into account the concentration effect of a non-melting transition in this zone [5]:

$$\alpha_r = 1 + 1.1h \frac{(b/\delta)^2 + 1}{\delta} \sqrt{h/\ln(90^\circ/\gamma)}, \quad (1)$$

where $\gamma = A[90 \exp(-\rho/\rho_0) + B]$ — angle of transition from base metal to weld; ρ — radius of transition from base metal to weld; $\rho_0 = 1$ mm; $A = 0.94 \dots 0.17$; $B = 0.8$; b — weld width; h — weld height; δ — weldment thickness (fig. 2).

However, this dependence does not take into account the changed mechanical characteristics of the material. In these zones, hardening structures are usually present, whose mechanical characteristics can differ significantly (up to 30 %) from the characteristics of the weld and the base metal.

It is possible to indirectly control crack formation and the stress state in the region of the top of the stress concentrator through the concentration factor of their intensity. Accordingly, when a sample fails due to fatigue, one macrocrack is formed at the concentrator top, and in a corrosive medium — a group (fig. 3).

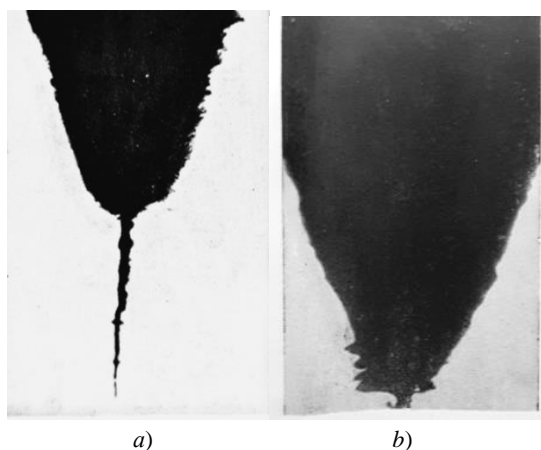


Fig. 3. Fatigue failure of steel 45 from a V-shaped stress concentrator: a — in air; b — in water — in a corrosive environment. An increase of 134 times⁴

After the formation of a group of macrocracks (fig. 3 b), the role of the macro-concentrator decreases, and further development of destruction can be suspended or inhibited. This was validated by experiments that indicated an increase

³ Molokov KA. Assessment of the Damage of Ferrite-Pearlite Steels under Low-Cycle Loading Conditions. In: Proc. Conf. "Science. Innovations. Engineering and Technology: Problems, Achievements and Prospects". URL: <https://elibrary.ru/item.asp?id=23752241&selid=46181945> (accessed: 31.10.2022). (In Russ.)

⁴ Molokov KA. Assessment of the Damage of Ferrite-Pearlite Steels under Low-Cycle Loading Conditions.

in fatigue strength in samples with stress concentration in a corrosive environment⁵. Such a group of cracks loosens the material, changes the stress state above and below the surface at the top of the macro-concentrator, which prevents the formation of a leading crack that can develop further at a lower level of cyclic loads.

Consider the situation on the surface or in the thickness of metal in massive bodies under stresses σ_H at infinity in a plane-stressed state. In this case, it is reasonable to use the Kolosov and Inglis's solution for an elliptical shape concentrator:

$$\alpha_T = \frac{\sigma_{max}}{\sigma_H} = 1 + 2\sqrt{a/\rho}, \quad (2)$$

where ρ и σ_{max} — radius of curvature and maximum component of stresses on the surface, respectively, at the top of the notch; a — semi-major axis, or half of the longest area perpendicular to the direction of the external load field.

Dependence (2) is well consistent with engineering practice. In accordance with the accepted concept, the theoretical stress concentration factor at the notch is determined by the depth of the notch and the contour curvature radius at its top, but does not depend on the shape of the contour.

Due to the development of information technologies, the evaluation of the theoretical stress concentration factor presents no great difficulty. The results of calculations of stress and strain concentrations in elastic and elastoplastic formulation of the problem can be obtained through the CAE finite element analysis [16–18, 12].

The experiments showed that at a certain stress concentration, external static load, and elastic-plastic stage of the material, an initial fracture crack appeared at the concentrator top at a certain distance from the surface. It rapidly propagated to an axis perpendicular to the direction of tension of the notched plates. The propagation is visible in the pictures (fig. 4). The process was fixed in the plates under a plane stress state and under a plane deformation. In the latter case, the appearance of a crack in the thickness of the metal under the surface was detected using an ultrasonic flaw detector.

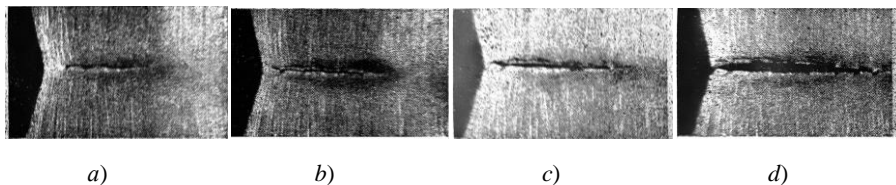


Fig. 4. Initiation of a subsurface crack at the top of the concentrator under static tension: *a* — macrocrack initiation; *b*, *c* — size increase in depth and towards the surface; *d* — crack exit to the surface [19]

Thus, under the given conditions and a sufficiently acute stress concentrator, a zone of a multiaxial stress state was formed, in which the continuity violation was possible. There would be a higher level of the onset of fluidity, and the tensile strength in a weakened place due to the concentrator could increase to 20-60 % (it depends on the material) [11].

Stress concentration and stress state conditions. Consider rather sharp stress concentrators with theoretical concentration factor $\alpha_T = 5 \dots 14$ and more. As a rule, the defects mentioned above act as such concentrators. At the top of the concentrator, the stress state can be considered the same as in plane deformation. In [18], the results of the analytical solution and experimental data for sharp concentrators under plane deformation were presented, the region of admissible values $[\alpha_T]$ and the radius at the top $[\rho]$ for steel 09G2S were established. However, the impact of its mechanical characteristics was not described. Moreover, it is not clear whether the analytical solutions are based on such initial parameters of 09G2S as the hardening coefficient m , yield strength $\sigma_{0.2}$, ultimate strength σ_B , critical fracture narrowing φ_k , etc. It is known that ductility and strength affect significantly the level of allowable stress concentration and the occurrence of brittle fracture at the top.

For hardening materials, cyclic stresses at the top of an acute concentrator aggravate the possibility of brittle

⁵ Sergeev NN, Sergeev AN. Mechanical Properties and Internal Friction of High-Strength Steels in Corrosive Media. Vologda: Infra-Inzheneriya; 2020. 432 p. (In Russ.)

fracture, therefore, we will take such α_T as a hazard criterion, at which brittle fracture is likely to occur under static load conditions. The increase in maximum stresses depending on the number of loading cycles N is given by the approximating formula:

$$\sigma_{\max} = \sigma'_{\max} + A \cdot \lg(N), \quad (3)$$

where σ'_{\max} — maximum stress in the concentrator in the first half cycle; A — coefficient depending on the level of initial deformation and the asymmetry coefficient of the loading cycle at the top of the concentrator.

We accept the obvious assumption that the appearance of brittle fracture may be due to the following reasons:

- an increase in the intensity of three-dimensional stretching in close proximity to the top of the concentrator;
- an increase in the resistance to plastic deformation of the material near the top as a consequence of shear resistance in acute stress concentrators.

The latter circumstance turns out to be the stronger the higher the loading speed and the sharper the stress concentrator.

Consider the elastic-plastic plane stress at the top of the concentrator and the elastic state in the gross section: $\sigma_{\max} = \alpha_T \sigma_H \gg \sigma_{0.2}$, $\sigma_H \approx \sigma_{0.2}$ and $\sigma_H < \sigma_{0.2}$. Here, $\sigma_{0.2}$ — conditional yield strength of the material under uniaxial tension. At $\alpha_T = 7.3$, stiffness of the stressed state is close to the state for a crack. Safety coefficient m_{FAD} for a crack-like defect with a plane deformation differs slightly (within 10 %) from $\overline{m_{FAD}}$ for a crack, i.e., for a state where there is an approximate equality $m_{FAD} \approx \overline{m_{FAD}}$:

$$\frac{\sqrt{1-(\sigma_0/\sigma_T)^2/\alpha_T^2} \cdot \sqrt{1-(\sigma_{0.2}/n_T/\sigma_0)^2}}{\sqrt{1-(\sigma_0 n_T/\sigma_T)^2/\alpha_T^2} \cdot \sqrt{1-(\sigma_{0.2}/\sigma_0)^2}} \approx \frac{\sqrt{1-(\sigma_{0.2}/n_T/\sigma_0)^2}}{\sqrt{1-(\sigma_{0.2}/\sigma_0)^2}}. \quad (4)$$

Here, n_T — yield strength margin coefficient, σ_0 — local strength of the material at the top of the crack or sharp concentrator.

In [11], the term “local yield strength” is applied to acute stress concentrators when the area of the concentrator adjacent to the top, experiences a complex stress state (CSS). Obviously, this term denotes the material flow stress on the concentrator circuit. There is plane stress state on the surface at its top, and a triaxial CSS appears under the surface. There, stiffness of the stress state increases sharply, therefore, the initial destruction of continuity is formed at some distance from the surface (fig. 4). It is established that the onset of local fluidity in the stress concentrator zone does not coincide with the level determined by the calculations based on strength criteria, particularly, according to von Mises–Huber–Hencky. As the stress concentration increases, the difference increases between:

- yield strength $\sigma_{0.2}$, theoretically calculated according to this criterion;
- experimentally determined stress value of the local flow of material $\sigma_{0.2}^*$ in the region adjacent to the top of the concentrator.

The results of experiments on plane samples of various steels and alloys [11, 16] show that ratio $\sigma_{0.2}^*/\sigma_{0.2}$ is well approximated by linear dependence on α_T . Then, the yield condition can be written as:

$$\sigma_i = \sigma_{0.2}(0.9 + 0.1\alpha_T), \quad (5)$$

where σ_i — von Mises stress intensity.

The authors limited their experimental studies to values $\alpha_T = 10$, and the tests were carried out only on plane samples with centrally located concentrators. In case of plane deformation, stiffness of the stressed state turns out to be slightly higher. Therefore, it is logical to assume that fluidity at some values α_T would occur no earlier than at the plane stressed state. And it is likely that the slope of the straight line according to equation (5) could be somewhat different [11]. However, we focus on this dependence.

For the moment of the beginning of yield, assume that with the transition from elastic deformations to elastoplastic, the ratio of the second and third main stresses to the first $\sigma_1 = \sigma_{\max}$ does not change. This has been proven

experimentally.

We equate to (5), the intensity of the stresses of the beginning of von Mises yield according to the fourth (energy) theory of strength, and introduce the coefficients of the relationship between the main stresses under plane deformation: $\sigma_1 = \sigma_i/D$; $\sigma_2 = q\sigma_1$; $\sigma_3 = \mu_T(1+q)\sigma_1$ [15]. Here, $\mu_T = 0.5$ — Poisson's ratio in the plastic region, and D — overvoltage coefficient, which takes into account the increase in the first main voltage in the case of CSS. The equation obtained with respect to q has two solutions. The first is for tensile σ_2 component, the second — for the compressive one. Tensile component σ_2 increases stiffness of the stress state in the case of CSS. After transformations and compressions, we can express it like this:

$$q = 1 - \frac{\sqrt{3}\sigma_{0.2}}{15\sigma_H} \left(1 + \frac{9}{\alpha_T}\right). \quad (6)$$

For the limiting case $\sigma_H = \sigma_{0.2}$, it is possible to neglect the change in the radius at the top of the concentrator and the onset of some initial global fluidity for the net cross section. Then, the only value α_T , satisfying the stiffness of the stress state equivalent to the crack is 7.33. This validates approximate equality (4) obtained earlier. For other values, as can be seen from (6), proportionality q will vary depending on value α_T and σ_H .

For a crack, coefficient D is determined from the equilibrium condition in the elastoplastic region and is calculated for plane deformation from the formula:

$$D = \frac{(1+m)(1-2\mu)}{2}, \quad (7)$$

where m — power hardening coefficient; μ — Poisson's ratio in the elastic region.

For ferritic-pearlitic steels, this coefficient takes values from 0.22 to 0.26.

Multiplier before D in formula $q = 1 - 2D/\sqrt{3}$ for a crack is 1.156, and q for ferrite-pearlite steels is 0.73. Indeed, when substituting $\alpha_T = 7.3$ (6) for $\sigma_H = \sigma_{0.2}$, we get $q \cong 0.73$. Next, we find α_T , if $\sigma_{0.2}/\sigma_H > 1$, at which the same stress state is realized as at $\alpha_T = 7.3$ and $\sigma_{0.2}/\sigma_H \rightarrow 1$.

In [20], the impact of α_T on the effective stress concentration coefficient K_σ is investigated, and for a typical aluminum alloy, it is shown that, in the range α_T from 7 to 13, global extremum of the value K_σ is observed. It is quite probable that such a significant maximum value may indicate brittle fracture at the initial stages of cyclic loading or discontinuity at the top of the concentrator. In this case, the resource will depend only on the further ability of the material to prevent the propagation of macrocracks.

Model of critical state at the top of an acute macro-stress concentrator. Almost all defects in the welded connection of pipelines, hull ship structures, etc., create a stress concentration. An analytical model developed on the basis of the concept of “local stress concentration factor” is presented in [9]. In addition, a simple dependence was obtained based on the Neuber formula linking the theoretical generalized concentration factor and the concentration factors of the intensity of elastic stresses and deformations. As a result, for the critical value of plasticity in the concentrator focus, the following dependence was obtained:

$$\varepsilon_c = \frac{\sigma_B \alpha_c^{2/(1+m)}}{E}, \quad (8)$$

where α_c — critical value of the theoretical stress concentration factor; σ_B — modulus of rupture; E — modulus of elasticity; m — exponent of power hardening.

Dependence (8) gives such high values that are rarely found in practice. For example, with critical logarithmic deformation for steel 50, the critical concentration factor is 26, and for high-strength steel 37KHN3A with $\sigma_B = 1.014$ MPa — more than 18. It can be concluded that such plasticity is unattainable until continuity is broken in the first loading cycles. This is not surprising, since it is known that the maximum plasticity value for samples with stress concentrators is significantly lower than for samples without stress concentration. In addition, ε_c should be determined not only by the properties of the material, but also by the conditions for the development of plastic

deformation before destruction. Similar results are given by the dependence used in [9]:

$$\alpha_T = \frac{\sqrt{E \cdot \varepsilon_{\text{разр}} \cdot \sigma_{\text{разр}}}}{\sigma_H} \quad (9)$$

S.A. Kurkin used it for a comparative assessment of the material sensitivity to stress concentration. Here, α_T characterizes the concentrator in which the crack occurs at specific load σ_H . Next, we will use the concept of “the most probable initiation of a macrocrack in the concentrator” (born crack) α_T^{bc} for this case. The true deformation and stress at the moment of occurrence of the discontinuity at the top of the concentrator are denoted respectively by $\varepsilon_{\text{разр}}$ and $\sigma_{\text{разр}}$. They can be determined from the generally accepted formulas $\varepsilon_{\text{разр}} \cong \varepsilon_{\text{кр}} = \ln[1/(1 - \varphi_K)]$ and $\sigma_{\text{разр}} \cong S_{\text{отр}} = \sigma_B(1 + 1.4\varphi_K)$. Here, $S_{\text{отр}}$ — true stresses of destruction at uniaxial stress state. Note that the fluidity in the concentrator occurs according to (5). Replace $\sigma_H = \sigma_{0.2}$ and $\sigma_{0.2}$ with $\sigma_{0.2}^*$. As a result, we obtain for the critical states ($\alpha_T = \alpha_T^{bc}$) relative stresses of the nucleation of destruction $\sigma_H^{bc}/\sigma_{0.2}$ from the concentrator:

$$\frac{\sigma_H^{bc}}{\sigma_{0.2}} = \frac{\sqrt{E \cdot \varepsilon_{\text{разр}} \cdot \sigma_{\text{разр}}}}{\alpha_T^{bc}(0.9 + 0.1\alpha_T^{bc})\sigma_{0.2}} \quad (10)$$

Note that for a very small radius of the concentrator top ($\rho < 10d_z$, where d_z — average grain diameter), crack propagation is limited at constant α_T . As shown in [6], it depends on d_z of steel. Formulas (8) and (9) are attractive to an engineer because they provide comparing the material sensitivity to stress concentration and using the initial data of the mechanical characteristics of steel.

We can get a slightly different model that takes into account the CSS in the area of the top of the macro-concentrator. The author [12] uses the strength criterion of brittle fracture in the structural material $\sigma_1 > S_{\text{отр}}$, where $S_{\text{отр}}$ — stress of normal fracture in the approximation to a uniaxial stress state. Significantly, this characteristic of the material does not depend on the temperature of its test. We use this criterion in a slightly different way — for the moment of occurrence of a discontinuity in the area of the top of the stress concentrator. Suppose that $S_{\text{отр}}$ is achievable in the case of constant energy equality at CSS and uniaxial stress state, i.e., with loss of plastic stability and transition from a volumetric stress state (when σ_i is small) to a uniaxial stress state with an inevitable increase in deformations.

We use power approximation of the deformation diagram within the framework of the deformation theory of plasticity. We equate true stresses σ_i of the deformation diagram in the elastic solution function of the problem to $\sigma_i = F(\sigma_i^{(y)})$ to $S_{\text{отр}}$. As a result, we get:

$$\sigma_i = \sqrt{\frac{1}{m+1}} \sqrt{\sigma_{0.2}^{\frac{1}{m}-1} (\sigma_i^{(y)})^2} = S_{\text{отр}} = \sigma_B(1 + 1.4\varphi_K), \quad (11)$$

where $\sigma_i^{(y)}$ — uniaxial stresses in the elastic solution to the problem.

Writing (11) with respect to $\sigma_i^{(y)}$, we obtain an expression for the elastic solution to the stress concentration problem on the other hand: $\sigma_i^{(y)} = \alpha_T \cdot \sigma_H$. Thus:

$$\alpha_T \cdot \sigma_H = \sqrt{\frac{[\sigma_B(1+1.4\varphi_K)]^{\frac{1}{m+1}}}{\sigma_{0.2}^{\frac{1}{m}-1}}} \quad (12)$$

Here, σ_H — nominal workload on the welded joint. In hard points of welded structures, joints or under overloads, it can reach the value of the yield strength of the material. Let us imagine a special case under conditions of cyclic loading with hardening of the material for the moment of formation of the born crack discontinuity — failure initiation. After transformations (12), we write down a simplified formula:

$$\alpha_T^{bc} = \left[\frac{\sigma_B(1+1.4\varphi_K)}{\sigma_{0.2}^*} \right]^{\frac{1+m}{2m}}, \quad (13)$$

where α_T^{bc} — value of the theoretical stress concentration factor at which the nucleation of destruction occurs in the region of the top of the macro-concentrator; $\sigma_{0.2}^*$ — yield strength of the material at the top of the concentrator, which can be increased according to (5) in the case of CSS.

At the moment of equality $\alpha_T = \alpha_T^{bc}$, the nominal stresses must be equivalent to the nucleation (destruction) stresses σ_H^{bc} . For this situation (13), we can write in relative values $\sigma_H^{bc}/\sigma_{0.2}$ and construct the dependences of the relative values of the stresses of fracture formation on the theoretical concentration factor $\alpha_T^{bc} = \alpha_T$:

$$\sigma_H^{bc} = \frac{2 \cdot (\alpha_T^{bc})^{\frac{-2m}{m+1}} \cdot \sigma_B \cdot (7\varphi_K + 5)}{\alpha_T^{bc} + 9}. \quad (14)$$

Unfortunately, it is not possible to write (14) with respect to α_T^{bc} at $\sigma_H^{bc}/\sigma_{0.2} = 1$. However, α_T^{bc} can be found numerically for specific load σ_H^{bc} , or diagrams of the danger of discontinuities in the form of a macrocrack in the focus of the concentrator can be constructed.

Dependences are analytically obtained for calculating critical theoretical stress concentration factors related to the mechanical characteristics of the material and a given external static load under the condition of a volumetric stress state for concentrators in welded joints. It is shown that the volume of the stress state in the concentrator focus affects significantly the value of the critical theoretical stress concentration factor. It is established that the complex stress state in the concentrator focus can be controlled by the geometric characteristics of the concentrator itself and its location relative to the external stress field.

Experimental data of steels (see Table 1) are obtained from literary sources. These are ferrite-perlite materials for which formula (14) has shown good agreement. Dependence (14) is attractive because standard mechanical characteristics are used as initial data. It can also be used to assess the risk of defects in the fusion zone (fig. 1, fig. 2), where hardening structures are formed, whose properties differ significantly from the initial characteristics of the welded steel.

Solutions for (9) and (14) are used more often for the most brittle steels at low α_T^{bc} . However, in the area of high stress concentration, critical ratios $\sigma_H^{bc}/\sigma_{0.2}$ for different steels will be very close in values. This can be explained by the fact that with the CSS, a stress state similar to a dangerous case is created for all steels in the top region. In the region of small stress concentrations, solutions to model (9) show higher critical stress values σ_H^{bc} . Note that the average value α_T^{bc} at $\sigma_H^{bc} \approx \sigma_{0.2}$ is ~ 8.5 . For steels with different mechanical characteristics, it does not change as much as according to the calculated results of model (9).

Figure 5 is constructed to validate the calculation results based on the physical adequacy of model (14). These are graphs of critical state dependences $\sigma_H^{bc}/\sigma_{0.2}$ from α_T^{bc} .

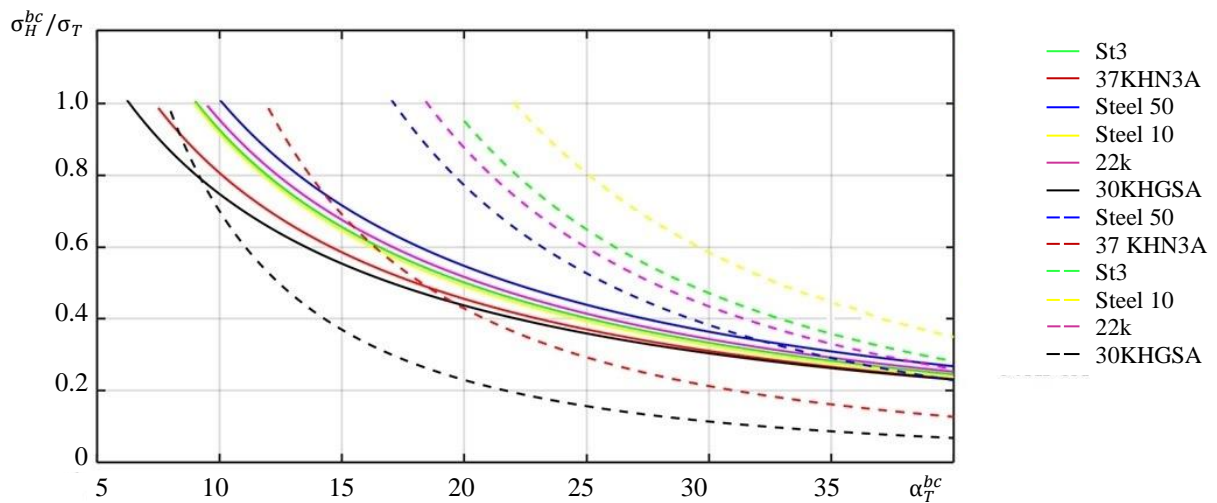


Fig. 5. Dependences of changes in the relative voltage of the external load $\sigma_H^{bc}/\sigma_{0.2}$ from α_T^{bc} for the critical state at the top of the stress concentrator. Solid curves — formula (14); dotted curves — formula (10)

Model (9), which does not take into account the volume and increase in yield stresses at the top of the concentrator, gives $\alpha_T^{bc} = 91$ at stresses $\sigma_H^{bc} = 0.5\sigma_{0.2}$ for steel 10, which is unlikely. If we take into account the volume in this

model, then $\alpha_T^{bc} = 33$, which is significantly less. Taking into account the volume of the stressed state, the critical plastic deformation is reduced to the occurrence of destruction during static tensile of the samples. This was validated by experiments with various steels and alloys⁶. Moreover, the researchers obtained less ductility of the steels on corroded samples. Here, it was shown that a volumetric stress state was created at the tops, and the volume prevented the free flow of plasticity. The plasticity before the destruction of these samples was 40 %, and the yield strength increased to 27 % [21]. It can be concluded that deeper concentrators cause a greater increase in the yield strength. The results of indirect experiments allowed us to assert that under hydrostatic load, the fluidity is not fixed, in this case the material only embrittles. However, in the focus of the concentrator, with an increase in the external load, the volumetric stress state cannot remain stable enough for the development of a higher volume level. Therefore, bifurcation is inevitable. Further, the development can go in two directions:

- fragile destruction or its beginnings in the focus;
- loss of stability of the stress state and, as a consequence, the transition to a sharp increase in plastic deformations.

Probably, the moment of bifurcation should be considered a critical state in the focus of the concentrator. Perhaps, this moment depends significantly on the depth of the concentrator, its relative length and depth to the thickness of the part, orientation to the external stress field, as well as on the mechanical characteristics and extent of the concentrator focus. All this requires additional research and more precise solutions.

Discussion and Conclusions. Defects and design features of welded joints (weld groove geometry, incomplete penetration, undercuts, pores, hardening structures, etc.) reduce static and fatigue strength. Stress concentrators are typical for welded joints, having a long and shallow shape relative to the thickness of the parts being connected (undercuts) or long and deep (incomplete penetration, etc.). All of them reduce fatigue strength. The analytical models obtained in the presented work allowed us to draw a number of conclusions.

1. The operation of the material at high values of the theoretical stress concentration factor depends on the stress state and its rigidity, as well as on mechanical and structural characteristics. The latter may differ from the parameters of the source material, since the tops of the concentrators may be located in the fusion zones of welded joints.

2. A rigid stress state in the stress concentrator focus can cause an increase in the yield strength. In this case, the passage of shear deformation is restrained, and the onset of the limiting state is achieved at a lower value of the theoretical stress concentration factor and is characterized by discontinuity at a constant value of the external load.

3. Comparison of high-strength steels with ductile and ordinary strength steels at the same level $\sigma_H^{bc}/\sigma_{0.2}$. In the second case, the formation of the volume of the stress state will have a more significant effect on the change in the critical value of the theoretical stress concentration factor, at which the nucleation of destruction occurs in the region of the top of the macro-concentrator α_T^{bc} (fig. 5).

4. Comparison of models (14) and (10) allows us to draw a certain conclusion. Taking into account the rigidity of the stress state and the increase in the yield strength at $\sigma_H^{bc}/\sigma_{0.2} \rightarrow 1$ from below, (10) gives estimate α_T^{bc} with a margin of safety, if we are talking about $\sigma_H^{bc}/\sigma_{0.2} = 0.8$ (30KHGSA). For less durable steel (14), the margin of strength at $\sigma_H^{bc}/\sigma_{0.2} = 0.5$ (37KHN3A), etc. Thus, it is preferable to take into account the volume and use model (14).

5. The dependences on the diagram of the theoretical stress factors are more densely grouped in (14), than in (10) due to very similar stress states in the region of the tops of acute stress concentrators. Therefore, the mechanical characteristics of steels have a secondary effect on α_T^{bc} .

6. With an increase in the theoretical stress concentration factor and a decrease in α_T^{bc} at the same level $\sigma_H^{bc}/\sigma_{0.2}$ of the external load, the influence of the structural factor in steel on the occurrence of initial destruction (formation of discontinuity) reduces. However, for further destruction, the resistance of the material to macrocrack growth is essential. After its occurrence, other criteria of mechanics and kinetics of destruction are triggered.

The presented study can serve as a prerequisite for the development of analytical models to assess the residual life of welded joints and structures exposed to cyclic loads. Further research will presumably refine the analytical models. The authors will check and test the results through CAE modeling and proceed to the evaluation of effective stress concentration factors.

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