Strength of welded joint under quasi-brittle fracture

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Abstract. In the study of the crack resistance of welded joints with constructive incomplete welds, which are regulated by welding GOSTs and have a wide practice of application, including for critical structures, it is necessary to keep in mind that these stress concentrators on the sharpness of their tops are significantly different from fatigue and operational cracks. Welding defects have the same difference: faulty welds, faulty fusions, undercuts. This paper shows that the strength of welded joints with structural faulty welds in addition to mechanical characteristics and the length of the faulty weld also depends on the radius at its top. Based on the ratios of fracture mechanics, a strain fracture criterion is proposed - the critical opening of the concentrator under consideration, depending on the radius at its top. At the same time, with the reduction of the radius at the top of the concentrator to a certain critical value, comparable to the radius at the top of the crack, the proposed criterion coincides with the material characteristic according to GOST 25.506-85 – the critical crack opening. Dependence for assessing the quasi-brittle strength of welded joints with faulty welds based on the critical disclosure of the concentrator under consideration satisfactorily corresponds to the experimental data on samples from the AMg6 alloy.

Keywords: Welding joints, Quasi-brittle fracture, Stress concentrators, Crack resistance, Faulty welds, Plastic strains, Fracture mechanics.

1. Relevance, scientific significance
Most welded structures are made of materials (alloys and steels) with a fairly high plasticity resource. Such materials include low-carbon, low-alloyed, medium-alloyed steels, titanium and aluminum alloys, etc. When loading structures made of these materials, a fairly developed plastic flow takes place at the top of crack-like defects. In general, this reduces the risk of brittle fractures, since some of the energy is spent on the formation of plastic zones. In these zones, stresses and strains are no longer controlled by stress intensity factors $K_{IC}$ [1], and are determined from the relations of the theory of plasticity. These fractures are usually called quasi-brittle (the prefix quasi denotes an approach to the brittle state). Thus, not all, but only a part of the net section of the welded joint is covered by plastic strain, therefore this circumstance must be taken into account when creating calculated estimates of the strength of welded joints. In the framework of fracture mechanics for models describing the behavior of materials beyond the elastic limit, a number of criteria are introduced: $\delta_C$ – critical crack openings [2], $V_C$ – critical strain rate coefficient [3], $J_C$ – critical value of the integral independent of the integration contour [4, 5], a two-parameter criterion based on a specific combination of the characteristics of crack resistance and plastic instability of the flow of metals [6]. These criteria and the practice of their application are most fully represented in the 4-volume directory of scientists edited by V.V. Panasyuk [7], in the works of Russian scientists: S.V. Serensen, V.P. Kogaeva, R.M.
Shnayderovich, N.A.Makhutov [8, 9, etc.]. With reference to the features of the fracture of welded joints and structures, the works of V.I. Makhnenko [10], L.A. Kopelman [11], G.P. Karzov [12], V.A. Vinokurov [13] and other scientists should be noted radius $\delta_C(\rho)$.

The purpose of this work is to further develop and apply the strain criteria of fracture for welded joints, taking into account their characteristic features.

2. Theoretical part

In the study of the crack resistance of welded joints with constructive incomplete welds, which are regulated by welding GOSTs [14, 15, 16 and others] and have a wide practice of application, including for critical structures, it is necessary to keep in mind that these stress concentrators on the sharpness of their tops are significantly different from fatigue and operational cracks. Welding defects have the same difference: faulty welds, faulty fusions, undercuts. In the framework of the formal approach, the direct use of fracture mechanics criteria for such concentrators leads to significant errors in assessing the quasi-brittle strength of welded joints [10]. In this regard, it is important to determine the effect of the severity of such concentrators on the stress-strain state in the zone of fracture. Following A. Kotrell [7], we take a certain radius $\rho$ for sharpness at the top of welding concentrators and investigate its critical disclosure. For this purpose, we use the results of [3], where $V_C$ - critical coefficient of strain intensity, which takes into account the change in mechanical properties in the zone of the concentrator during the thermoplastic welding cycle and the radius at its top $\rho$. The value of the parameter $V_C$ is equal to:

$$V_C = \varepsilon_{av} a_\varepsilon \sqrt{\rho} = \varepsilon_{1max} \varepsilon_{max} \sqrt{\rho}$$ (1)

Here $\varepsilon_{av}$ is the average strain obtained at some base away from the concentrator; $a_\varepsilon$ is the coefficient of concentration of strains at the top of the concentrator; $\varepsilon_{1max}$ - maximum strain at its top.

To establish the relationship between the critical values of the parameters $V_C$, $K_{ic}$, $\delta_C$ and the radius at the top of the concentrator $\rho$ we use the ratio of [3, 9]:

$$V_C = \frac{2K_{ic} \varepsilon'}{\sqrt{\pi E^*}}$$, (2)

$$\delta_C = \alpha \frac{K_{ic}^2 \varepsilon'}{E^* \sigma_T}$$ (3)

Here $E^* = E$ is the modulus of elasticity of the first kind for a welded joint in a plane stress state; $E^* = E((1-\mu^2))$ - under plane strain; $\mu$ is the Poisson's ratio (transverse strain factor); $\sigma_T$ - yield strength (ideal elastic-plastic model of the material is considered); $\alpha^*$ is a coefficient depending on the choice of correction for the plasticity zone near the concentrator.

It should be noted that the strain criterion $\delta_C$ is based on opening the crack edges to some constant critical values for the material under consideration, therefore this criterion was brought to the level of standardization [17]. Entering into the corresponding formulas the radius $\rho$ and the value of the maximum strain $\varepsilon_{21max}$, we abstract from $\delta_C$ as from the characteristics of the material and proceed to some constructive characteristic - critical disclosure of the concentrator of the finite radius, $\delta_C(\rho)$.

Taking into account (1-3), we obtain the following dependency:

$$\delta_C(\rho) = \alpha \frac{\pi E^*}{4\sigma_T} \rho \varepsilon_{1max}^2$$ (4)

The value of the coefficient $\alpha^*$ depends on the shape of the plasticity zone at the crack top adopted in the calculation scheme. For example, in the Dagdale model [18], the plasticity zone coincides with the direction of the crack. In this regard, when solving a problem, we obtain $\alpha^* =1$. There is also data from numerical calculations in which it was obtained that $\alpha^* =1...4/\pi$ [19]. According to many authors [8, 9, 10, 19 and others], and also relying on experimental data for processes associated with the developed plasticity zone at the top of the concentrator, we take the value $\alpha^* =1$. 

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The resulting expression (4) allows to relate the critical opening of the concentrator of the finite radius $\delta_C(\rho)$ with a metal plasticity resource $A_p$ in the fracture zone and at the same time determine the influence of the type of stress state in the zone of development of plastic strains [20]. This is possible due to the fact that both criteria ($\delta_C$ and $A_p$) determine the same moment: the moment of reaching the critical value of the resource plasticity of the metal $A_p$ during plastic strain corresponds to the moment of reaching the critical opening of the concentrator $\delta_C(\rho)$ and as a result – fracture. For this we use the connection between the maximum strain in the area of fracture $\varepsilon_{1\text{max}}$ and a resource of metal plasticity $A_p$ as follows [21]:

$$A_p = \frac{2}{\sqrt{3}} e_1 \max \left[ \frac{3+\nu_2^2}{3-\nu_2^2} \right]$$  \hspace{1cm} (5)

where, $\nu_2 = \frac{2(\sigma_2-\sigma_3)}{(\sigma_1-\sigma_3)} - 1$ is an indicator of the type of stress state (indicator Lode - Nadai); $\sigma_1, \sigma_2, \sigma_3$ are the principal stresses in the field of plastic strain.

Taking into account formulas (3– 5), we obtain a formula for the critical disclosure of a concentrator of the finite radius $\delta_C(\rho)$:

$$\delta_C(\rho) = \frac{\pi}{48} \frac{(3-\nu_2)^2 E^*}{3+\nu_2^2} A_p^2 \rho \delta_C(\rho)$$  \hspace{1cm} (6)

With decreasing of $\rho$ the value $\delta_C(\rho)$ decreases and at some critical values $\rho_0 = \rho_e$ achieves fatigue crack values. At the same time $\delta_C(\rho) = \delta_C$. In view of (6), we can write:

$$\delta_C(\rho) = \delta_C \frac{\rho_0}{\rho_e}$$  \hspace{1cm} (7)

where $\rho_e$ is the effective radius of the concentrator equivalent to the radius at the top of the fatigue crack:

$$\rho_e = \frac{48}{\pi} \frac{3+\nu_2^2}{(3-\nu_2)^2} \left( \frac{\sigma_T \delta_C}{E^* A_p^2} \right).$$  \hspace{1cm} (8)

If the concentrator has a radius $\rho \leq \rho_e$, the fracture process does not depend on this parameter, the fracture occurs during the critical opening of the concentrator (crack) equal to $\delta_C$. The effective radius $\rho_e$ is an important microstructural characteristic and is determined not only by the properties of the material, but also by its stress state.

Based on the criterion $\delta_C(\rho)$ in [22, 23] there are proposed formulas for assessing the quasi-brittle strength of welded joints from plates $\nu_2 = 0$ (plate strain at flat stress state) For plates with structural faulty welds, critical stresses $\sigma_k$ are equal to:

$$\sigma_k = \frac{E \sigma_B \delta_C(\rho)}{0.89 \rho l} \cos \frac{\pi l}{2B}$$  \hspace{1cm} (9)

where $l$ is the length of constructive incomplete weld; $B$ is the weld width; $\sigma_B$ is the temporary resistance of the weld metal. (Since an elastic-plastic model of a material was considered ideally, the corresponding real diagram of the material stretching was approximated by an ideally elastic-plastic to the level of the values of the temporal resistance $\sigma_B$ [23, 24]).

3. Results of experimental studies

Figure 1, 2 shows the results of the experiment for welded joints from the AMg6 alloy. The straight line in Figure 1, 2 corresponds to the viscous nature of the fracture, the static strength of the samples decreases in proportion to the decrease in net sample cross section $\sigma_k = \sigma_B (1-l/B)$. At the same time the gap $\Delta = 2\rho = 1\, \text{mm}$ between end (connected) surfaces was created with spec Dial templates.
Experimental data corresponding to the viscous nature of fracture are shown in Figure 1, 2 in white circles.

By reducing the radii at the top of the faulty weld to $\rho = 0.08 - 0.16$ mm, at a test temperature of 77K, quasi-brittle fractures were obtained (Figure 1 the calculated curves using formula (9) and experimental data are filled circles). With a decrease in radii to a value of $\rho = 0.02-0.04$ mm, quasi-brittle fractures (triangles in Figure 2) were obtained already at a normal test temperature of 293 K (+20°C).

Figure 1. Comparison of calculated and experimental values of strength for welded joints from the AMg6 alloy $\sigma_{B}$=260 MPa at 293°K.
The value of the radii \( \rho = 0.02–0.16 \text{mm} \) was obtained on the basis of the state of the joined surfaces, which were evaluated by the roughness class \( R_Z \) (\( R_Z \) – height of the roughness profile of the surface). With a dense imposition of surfaces on each other and subsequent welding, the parameter of the top of the penetration \( \Delta = 2 \rho = 2 R_Z \). As a result of measurements, it was obtained that for a batch of samples with processing according to the second roughness class (\( R_Z = 80...160 \text{ um} \)) \( \rho = 0.08...0.16 \text{ mm} \); for the fourth class (\( R_Z = 20...40 \text{ um} \)) \( \rho = 0.02...0.04 \text{ mm} \). The material characteristic - the critical crack opening \( \delta_C \) was determined experimentally with reference to the standard [17]. At normal test temperature \( \delta_C = 0.022 \text{ mm} \); at \( 77 \text{K} \) \( \delta_C = 0.0074 \text{ mm} \). To calculate the effective radius \( \rho_e \), plasticity diagrams were constructed according to the method [20], of which, with the stress state value \( \Pi = 3.08 \) the value \( \Delta \rho = 0.12 \) at normal temperature; at \( 77 \text{K} \)–\( \Delta \rho = 0.06...0.065 \). The calculation of the effective radius by the formula (8) for the weld metal from the AMg6 alloy showed approximately the same value \( \rho_e = 0.023 \text{ mm} \) regardless of the temperature of the test, which indirectly indicates that \( \rho_e \) – microstructural characteristics of the material.

4. Conclusion
The strength of welded joints with structural faulty welds depends on the mechanical characteristics of the material, the length of the faulty weld, as well as on the radius at its top. Based on the ratios of fracture mechanics, a strain fracture criterion is proposed: the critical opening of the concentrator depending on the radius at its top. At the same time, with the reduction of the radius at the top of the concentrator to a certain critical value comparable to the radius at the crack top, the proposed criterion coincides with the material characteristic according to GOST 25.506-85 – the critical crack opening. The dependency for assessing the quasi-brittle strength of welded joints with incomplete welds based on the critical disclosure of the concentrator under consideration satisfactorily corresponds to the experimental data on samples from the AMg6 alloy.

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