METHODS FOR RESIDUAL LIFE ESTIMATION OF WELDED JOINTS

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ABSTRACT: *A calculational model to solve the problems about welded joints life has been formulated in this paper. A welded joint in this model is considered to be an inhomogeneous as to its physical-mechanical properties deformed solid with a lack of fusion, which develops under cyclic loading. An equation for determining the fatigue crack growth rate was obtained from the energy balance of fatigue fracture of a joint inhomogeneous material and reversible elastic-plastic fracture of the process zone at this defect tip.*

A direction of crack propagation with respect to the initial defect location plane is determined from the condition that this direction provides the maximum crack growth rate.

The proposed model has been used to evaluate the residual life of butt- and T-joints and a good agreement of the calculation and experimental data has been shown.

INTRODUCTION

Welded joints are widely used in many engineering structures, therefore the improvement of the methods for strength and durability calculation is very important for improving the structure quality. Since the majority of structures operate under alternating loading conditions, fatigue became one of the most important factors, determining the welded joints life. Here we should note that welded joints are complex

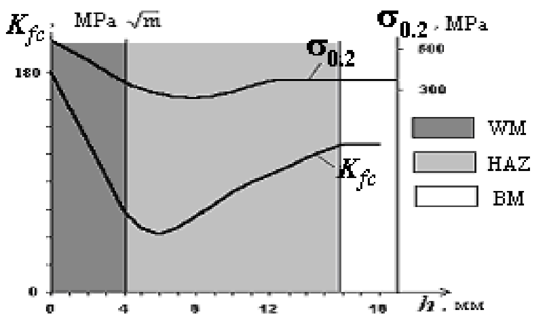


Figure 1: Distribution of physical-mechanical characteristics (K_{fc} is a fatigue threshold, σ_0 is an ultimate strength of material) in the vicinity of the 10XCHD steel welded joint: h is a distance from the weld middle part in the direction of the base metal.

objects for calculations because of the following causes. Welded joints often contain metallurgical or geometrical defects arising due to welding. Besides, significant inhomogeneity of the material is combined with high residual stresses [1]. As it is known [2-4], in the vicinity of the weld such zones are distinguished by the physical-mechanical properties of material [2-5]: a weld metal (WM), heat-affected zone (HAZ) and a base metal (BM) (Fig. 1). There exists a certain experimental experience in investigations of the field of welded structure failure; still there is no unique theory that allows the through study of fatigue fracture of welded joints. The known approaches usually do not account for the heterogeneity of the material in the vicinity of the weld and thus there appears a certain discrepancy between theoretical and calculated data. In this context a new method for assessing the durability of welded joints using data of papers [6-8] has been formulated in this paper. The method allows taking into account the variation of the physical-mechanical properties of material in the weld region.

CALCULATIONAL MODEL

Consider an elastic-plastic plate, weakened by a crack and introduce a rectangular Cartesian coordinate system *Oxy* (Fig. 2). Let this plate be subjected to cyclic tension. In this case a certain cyclic plastic zone of length l_{pf} is formed at the crack tip (Fig. 2, b). As known [9], l_{pf} is less than the length of the static plastic zone l_p, i. e. than the length of the plastic zone at the first loading cycle, and depends on the stress ratio R ($R=K_{\mathrm{I}min}/K_{\mathrm{I}max}$), while the characteristic length $l_{pf}=0.25(1-R^2)l_p$, where $K_{\mathrm{I}max}$, $K_{\mathrm{I}min}$ are maximum and minimum values of the stress intensity factor in a cycle. Consider now kinetics of fatigue macro crack growth rate. Let for ΔN number of loading cycles, the original crack increases by Δl in the direction that forms angle θ in the given coordinate system (Fig. 2, a). To establish the equations of the crack growth kinetics, use the energetic fracture criterion [10-12]. This criterion presupposes the existence for each material of the critical value of energy W_p, necessary for the elementary act of material fracture, that is formation of a free surface unit (material fracture energy). Thus to get the fatigue crack length increment Δl for ΔN loading cycles, the dissipation of the deformation energy in the material at points *(x,y)* on the crack growth path ($W=W(x,y)$) should be equal to the value of material fracture energy ($W_p = W_p(x,y)$) i. e. crack growth proceeds under condition

$$W = W_p \ . \tag{1}$$

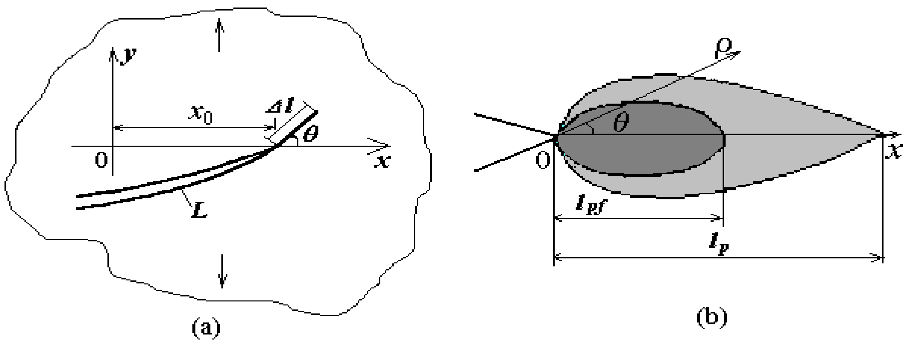


Figure 2: A plate with a crack (a) and a plastic zone at the crack tip (b) (schematically).

The character of elastic-plastic deformations of the material in the crack tip vicinity, as shown in Fig. 3, allows writing equation (1) as:

$$W_s + \Delta N W_c = W_p , \tag{2}$$

where $W_s = W_s(x,y)$ is the energy of elastic-plastic deformations of the material in the first cycle of a body loading up to the averaged amplitude values (σ_a); $W_c = W_c(x,y)$ is dissipation of plastic deformations energy for one loading cycle (starting from the second cycle). Since for one fracture event at energy point of section Δl the maximum opening δ_{max} at the moving (forwards θ) crack tip occurs, the energy W_s can be evaluated from the equation

$$W_s = \delta_{max}(\rho,\theta)\sigma_0 \Delta l, \quad x = x_0 + \cos\theta, \ \ y = y_0 \sin\theta, \tag{3}$$

where $\sigma_0 = \sigma_0(x,y) = \sigma_0(\rho,\theta)$ is the averaged stress value in the process zone according to the δ_c-model (this characteristic of the material is variable in case of its heterogeneity); ρ,θ are polar coordinates (Fig. 2, b) [13]. Cyclic tension diagram is modelled by a curve for a perfect elastic-plastic material (Fig. 3,b). Assume that $\sigma_0 = 0.5(\sigma_T + \sigma_S)$, where $\sigma_T = \sigma_T(x,y)$ is yield strength and $\sigma_S = \sigma_S(x,y)$ is ultimate strength of the material. During macrocrack growth, the plastic zone at its tip also moves and its elementary material volume at this tip undergoes all stages of plastic deformation, typical to the plastic zone of length l_{pf} ($l_{pf} < \Delta l$). Considering this fact and using results of [10] we obtain the correlation for evaluation the energy of cyclic deformations W_c

$$W_c = \int_0^{l_{pf}} \sigma_0(s,\theta)\Delta\delta(s,\theta)ds, \quad (4)$$

where $\Delta\delta(\rho,\theta)=\delta_{max}(\rho,\theta)-\delta_0(\rho,\theta)$ is the amplitude of the model crack opening according to δ_c-model [13] at point s of the plastic process zone ($0 \le s \le l_{pf}$):

$$\delta_0=(\delta_{min}, \delta_{op}, \delta_{th}); \quad (5)$$
$$\delta_{min}=[1-0.5(1-R^2)]\delta_{max}(\rho,\theta),$$

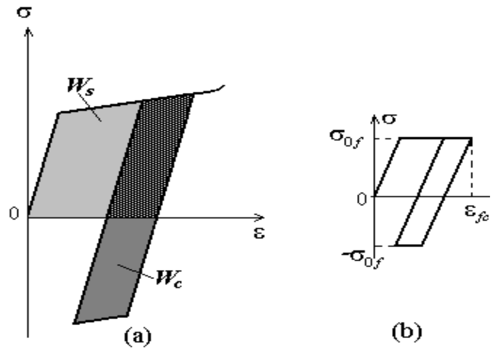


Figure 3: Tension-compression diagram of material in the process zone (a) and a diagram model (b).

where $\Delta\delta(\rho,\theta)=\delta_{max}(\rho,\theta)-\delta_0(\rho,\theta)$ is the amplitude of the model crack opening displacement in a cycle; δ_{op} is the residual crack opening [9]; δ_{th} is the threshold opening δ_0 (at $\delta_{max} \le \delta_{th}$ the crack does not propagate).

The material fracture energy W_p, needed the crack area of length Δl, is defined as $W_p=\beta\gamma\Delta l$, where γ is specific energy of fracture of the given volume of the material, that is necessary to create the formation of a unit of the crack length; β is a Morrow's coefficient [14], that shows the difference between cyclic and static fracture energy; it is determined as : $\beta=\sigma_s^4\sigma_a^{-4}$. Specific fracture energy is determined by the equation: $\gamma=\sigma_0\delta_c$, where $\delta_c=\delta_c(x,y)$ is the critical opening of the fatigue crack, $\sigma_0=\sigma_0(x,y)$. In this case we get

$$W_p=\beta\sigma_0\delta_c\,\Delta l. \quad (6)$$

By substitution (3), (4) and (6) into equation (2), we get the following relationship: $\Delta l \sigma_0 \delta_{\max}(0,\theta) + \Delta N \int_0^{l_{pf}} \sigma_0(s,\theta)\Delta\delta(s,\theta)ds = \beta \Delta l \theta_0 \delta_c$. Thus it is easy to find that:

$$\Delta l \Big/ \Delta N = \int_0^{l_{pf}} \sigma_0(s,\theta)\Delta\delta(s,\theta)ds \Big/ \left(\beta\sigma_0\delta_c - \sigma_0\delta_{\max}(0,\theta)\right).$$

Putting $\Delta N \to 0$ in this equation, get the kinetic equation for assessing the crack growth rate V ($V=V(x,y)=dl/dN$) under cyclic loading of a body:

$$V = \int_0^{l_{pf}} \sigma_0(s,\theta)\Delta\delta(s,\theta)ds \Big/ \left(\beta\sigma_0\delta_c - \sigma_0\delta_{\max}(0,\theta)\right). \qquad (7)$$

Note that the rate V depends on the orientation angle θ of fatigue crack growth with respect to the chosen coordinates system (Fig. 2, b).

Let θ be the angle between the crack propagation and the abscissa of the chosen coordinate system (Fig. 2). Since, we further assume, that the crack propagates in the direction of the maximum rate, i. e. ($\partial V/\partial\theta=0$), then from equation (7) we get the second kinetic equation for evaluation of the crack propagation direction:

$$\frac{\partial}{\partial\theta}\left(\int_0^{l_{pf}} \sigma_0(s,\theta)\Delta\delta(s,\theta)ds \Big/ \left(\beta\sigma_0\delta_c - \sigma_0\delta_{\max}(0,\theta)\right)\right) = 0. \qquad (8)$$

To get equations (7) and (8) it is necessary to add the initial and terminal conditions, namely:

$$N=0 \text{ at } l=l_0\,;\ N=N_d \text{ at } l=l_* , \qquad (9)$$

where l_* is the critical crack length, achieved for N_d loading cycles and is determined by the criterion of critical crack opening [15]:

$$\delta_{max}(\, l_*)=\delta_{fc}(x,y)\ . \qquad (10)$$

So, kinetic equations (7), (8) and conditions (9), (10) determine the calculation model for the investigation of the subcritical fatigue crack growth in heterogeneous plates. Below the results of the proposed model application to the calculations of residual life of the butt and cruciform joints are presented.

CALCULATION OF THE RESIDUAL LIFE OF BUTT AND CRUCIFORM WELDED JOINTS

To solve the concrete problems at first the distribution of residual stresses in the welded joint region has been found using calculational and experimental method of Ignatieva [16]. Here equations (7), (8) of the calculational model after mathematical transformations have been reduced to the form:

$$v = \frac{0{,}01}{\sigma_0^2}\frac{\left(K_{\mathrm{I}\max}^4\left(1 + c_1 d c_0 \sigma_0^{-3} K_{\mathrm{I}\max}^2 \sin\theta\right) - K_0^4\left(1 + c_1 d c_0 \sigma_0^{-3} K_0^2 \sin\theta\right)\right)}{\beta K_c^2 - K_{\mathrm{I}\max}^2},$$

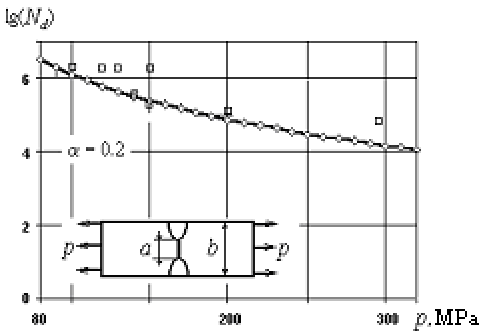
$$\frac{\partial}{\partial\theta}\left(\frac{0{,}01}{\sigma_0^2}\frac{\left(K_{\mathrm{I}\max}^4\left(1 + c_1 d c_0 \sigma_0^{-3} K_{\mathrm{I}\max}^2 \sin\theta\right) - K_0^4\left(1 + c_1 d c_0 \sigma_0^{-3} K_0^2 \sin\theta\right)\right)}{\beta K_c^2 - K_{\mathrm{I}\max}^2}\right) = 0 \quad (11)$$

where c_1=0,663; $c_0 = 0{,}6(1-\mu^2)\left(2(1+\mu)(1+\eta)\sigma_0 \big/ 3\sqrt{\eta}E\right)^{\eta}$, μ is Poisson's ratio, η is coefficient of deformation hardening of material; $d = \partial\sigma_0(0,y)\big/\partial y$; according to relation (5) $K_0 = \max(K_{\mathrm{I}min}, K_{op}, K_{th})$.

Using the method, proposed in paper [17] for determination of the stress intensity factors [SIF] at curvilinear cracks, equations (11) have been solved numerically for the examples given below. So two types of butt joints of CT3 steel with incomplete penetration (Fig. 4, 5) and X-welded joint of E355 steel with a faulty fusion (Fig. 6) were studied. Experimental characteristics for the joint materials are presented in Table. Here K_{fc} is the material fatigue threshold, which is quite close to K_c for materials considered. The results, calculated by the proposed model, have been compared with data of large-scale experiments of the same joints as those given in the paper of V.I.Makhnenko and V.E.Pochynok[18](see Fig. 4,5,7).

TABLE: Mechanical and fatigue properties of different regions of Ст3 and E355 steels welded joint.

Joint region	Steel **Ст3**			Steel **E355**		
	σ_T, MPa	σ_B, Mpa	K_{fc}, MPa√m	σ_T, MPa	σ_B, MPa	K_{fc}, MPa√m
WM	250	490	35	579	680	62
HAZ	167	388	23	395	540	41
BM	194	446	27	449	620	48



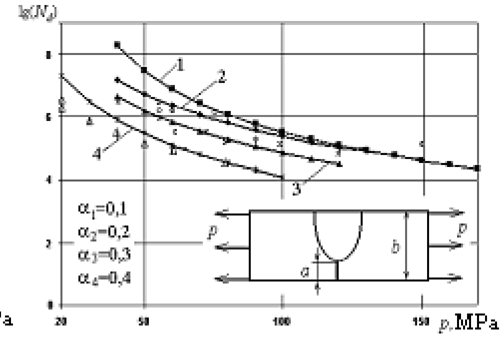
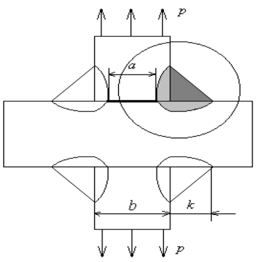
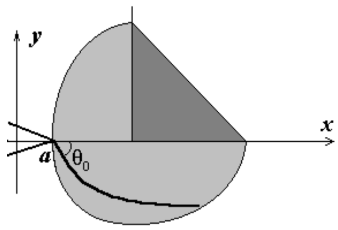


Fig. 4. Fig. 5.

Figure 4: A welded joint with a lack of fusion and comparison of the calculational (◊) and experimental [19] data ([]) of the residual life (N_d) (schematically).

Figure 5: A welded joint with a lack of fusion at different values of α_i (i=1, 2, 3, 4) and comparison of the calculational (lines 1, 2, 3, 4 respectively) and experimental [18] data of the point of residual life at α_1=0,17…0,20 ([]); α_2=0,26…0,31 (◊); α_3=0,44…0,49 (Δ).





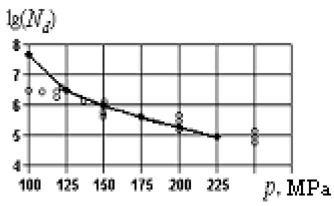


Fig. 6 a Fig. 6 b Fig. 7.

Figure 6: Cruciform joint with a lack of fusion (a) and a path of fatigue crack growth from this flaw (b).

Figure 7: Comparison of the values of the life (N_d) obtained for cruciform joint, using calculational (solid line) and large-scale testing data (points) [18] for E355 steel.

The analysis of the data in Fig. 4, 5 and 7 allows drawing a conclusion that the calculated values of the residual life agree well with experimental results. Thus we can speak about the correctness of the usage of the proposed method for residual life estimation of welded joints.

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