CYCLIC CRACK RESISTANCE OF WELDED JOINTS WITH NON-UNIFORM FIELDS OF RESIDUAL WELDING STRESSES

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ABSTRACT

The correctness of using the linear fracture mechanics mathematics to describe the kinetics of fatigue fracture of welded joints with high residual stresses (RWS) is experimentally grounded in the paper. The correlation analysis is used to show that the kinetic diagrams of fatigue fracture (KDFF) of joints represented in the coordinates of the range of the factor of external alternating loading cycle stress intensity are linear in case of the fatigue crack propagation in the non-uniform fields of RWS for the range of Paris region rates. It is shown that the KDFF of joints with the high RWS are invariant to the characteristics of the alternating loading cycle, and the parameters of the Paris exponential equation are determined by the initial RWS equation, range of cyclic stresses and their asymmetry.

A method for calculation of cyclic crack resistance of joints is proposed, it explicitly allowing for the non-uniform field of RWS which influence the fatigue crack growth rate.

KEYWORDS

Cyclic crack resistance, residual welding stresses, kinetic diagram of fatigue fracture, stress cycle asymmetry, stress intensity factor, fatigue crack growth rate, correlation coefficient, non-uniformity of residual stress field.

The residual welding stresses (RWS) induced by the local thermoplastic deformations, can noticeably affect the cyclic crack resistance of welded joints at fracture rates corresponding to the average amplitude region of the kinetic diagram of fatigue fracture. The regularities of RWS influence on the kinetics of welded joint fatigue fracture are, mostly, determined by their features and mechanism of interaction with the cyclic stresses induced by external action. It is known that the RWS reach the values close to the base metal yield point, are distributed in a considerably non-uniform manner, and are redistributed in the process of cyclic loading and fatigue crack growth. The partial relaxation of initial RWS leads to the formation of a field of their stabilized values which actually influence the cracked welded joint viability (Trufiakov, et al., 1976). Here, the relaxation process is not accompanied by significant plastic strains. Accordingly, in the work by Makhnenko (1976) it is shown that when the specimens with high RWS are loaded up to the level of nominal stresses induced by external loading, equal to 0.8 σ_T the plastic deformation in the concentrator zones does not exceed 0.5...1 %. Therefore, in case of fatigue crack propagation in a welded joint with high initial RWS and action of nominal alternating stresses corresponding to the high-cycle fatigue region, no zones with high plastic deformations are found in the joints, and the maximum stress of the loading cycle formed under the effect of RWS does not exceed the σ_T the value of base metal. Therefore, the range of stress intensity factor (SIF) can be assumed to be the parameter controlling the fatigue crack growth rate in the welded joint with high RWS. However, the practical realization of the linear fracture mechanics methods aimed at forecasting the welded joint cyclic crack resistance, requires a number of special studies. One of the most important of these investigations is studying the problem of understanding the RWS kinetics during the fatigue crack growth. The non-uniform distribution of RWS makes it necessary to study the geometry of the curves representing the KDFF of joints in the coordinates of crack growth rate - range of external alternating loading SIF. The processes of RWS relaxation and redistribution do not provide an answer to the issues of joint KDFF invariance to the characteristics of external alternating loading cycle.

The regularities of RWS change with the fatigue crack growth were studied on model specimens of 15XSND steel (σ_T = 350 MPa, σ_b = 520 MPa) with artificially induced RWS. Tests were performed on 650 x 140 x 20 mm flat specimens with a centrally located cracklike defect in the form of a hole of r = 2 mm radius and initial "start" notches of 1 mm depth and ρ = 0.05 mm radius in the walls. To induce tensile RWS in the cracklike defect zone the longitudinal beads were deposited by manual arc welding in the middle of heat-treated specimens, from both sides. Near the defect the beads were interrupted at 5 mm distance from the hole edge, so that the notch tips would be in the zones of uniform distribution of the mechanical properties, which were determined by the appropriate measurements of the metal hardness. To induce the compressive RWS in the cracklike defect zone, the beads were deposited continuously on the side faces of the specimens. In the model specimens the RWS were measured by UT (Gushcha and Makhort, 1976). Fig. 1 gives the ensile RWS curves, reflecting their kinetics during the fatigue crack growth.

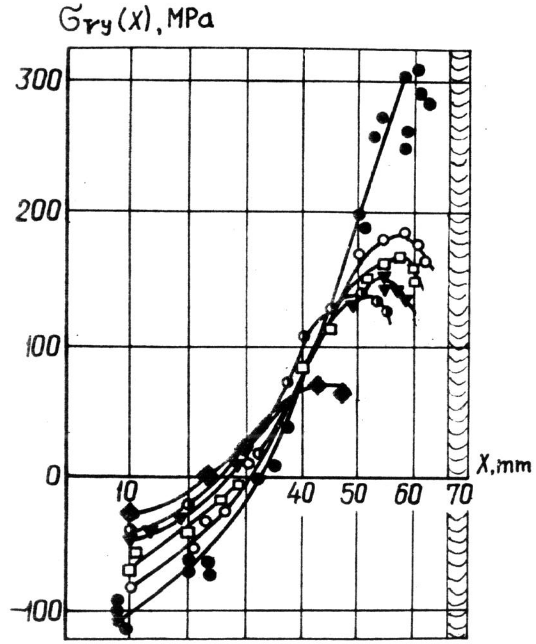

Fig. 1. RWS distribution in 15XSND steel specimens with a longitudinal bead along the central axis: ●- initial RWS; ○- RWS established after the first loading cycle; □- after 10 cycles; ▼- after 10 000 cycles, crack length is 1 mm; ◑- after 100 000 cycles, crack length is 6 mm; ◆- after 230 000 cycles, crack length is 25 mm.

After the first loading cycle the RWS relax and the degree of this relaxation depends on the cyclic stress range and cycle asymmetry. Then, already after the first 10 loading cycles, the RWS reach their stabilized level at which their distribution but slightly differs from distribution after the first cycle. Before the front of the propagating fatigue crack the established RWS have a maximum located at a certain distance from the crack tip, and the tensile stress zone is somewhat larger than the tension zone of the initial RWS. As the fatigue crack propagates, the tensile

RWS peak becomes smaller and is shifted farther from the crack tip with the simultaneous enlargement of the tensile stress zone. Here, the zone of the balancing stress distribution is reduced. Hence, the fatigue crack propagating in the non-uniform field of tensile RWS does not move into the region of reactive compressive stress distribution, but propagates all the time in the field of RWS of one sign. This result agrees with the data of other researchers (Mukai et al., 1986, Karzov et al., 1986), and seems to be important for understanding the process of welded joint fatigue fracture.

The derived experimental data on the RWS kinetics during fatigue crack propagation (Fig. 1) show that the crack propagating in the welded joint is influenced by RWS which are essentially non-uniformly distributed. In this connection there appears a need to study the linearity of correlation of the values of fatigue crack propagation rate, corresponding to the range of rates of the Paris region of KDFF, and the range of SIF due to the external alternating loading. The correlation analysis methods were used to study the pairs of random values, namely $\Delta l_i / \Delta N_i$ crack rate and values of SIF range ΔK_i, corresponding to it. The linear correlation was assessed by the values of correlation coefficient r, calculated by M pairs of $\{\Delta l_i / \Delta N_i, \Delta K_i\}$ points, where each increment was determined between two adjacent experimental points. In keeping with Taylor's recommendations (1985), a strong correlation is found if the correlation coefficient takes the value of $r > 0.7$. Besides calculation of correlation coefficient r, also the p_M probabilities of the significance of the studied correlation were calculated for M measurements of pairs of random values with the specified criterion of correlation r_o = 0.7 (Taylor, 1985). According to Taylor (1985), the correlation is to be considered significant, if the probability $p_M < 5\%$, and highly significant, if $p_M < 1\%$. Table 1 gives the data of calculations derived from interpretation of results of fatigue testing for cyclic crack resistance of 15XSND steel specimens with high tensile RWS at different values of the cycle stress asymmetry.

The performed calculations show that for the studied steel in case of the fatigue crack propagation in a non-uniform field of RWS a highly significant linear correlation is found between the fatigue crack propagation rate and range of SIF due to external alternating loading. The derived result indicates that the KDFF of welded joints with high RWS plotted in the coordinates of crack propagation rate - range of SIF due to external alternating loading, have the form of straight lines in the range of average amplitude region rates, and can be described by the Paris exponential equation for a broad range of the values of alternating stress cycle asymmetry factor. This, however, does not provide an answer to the question of the invariance of the Paris exponential law parameters to the alternating loading cycle characteristics.

Table 1. Coefficients of linear correlation of pairs of $\Delta l_i / \Delta N_i - \Delta K_i$ experimental values for 15XSND steel specimens with high tensile RWS.

Cycle asymmetry factor, R_σ	-1.0	-0.5	0.0	0.5
Number of experimental pairs, M	14	10	20	20
Linear correlation coefficient, r	0.86	0.87	0.85	0.90
Correlation significance p_M, %	<0.05	<0.05	<0.05	<0.05

As the relaxation of initial RWS in the welded joint is, mainly, determined by the properties of the joint material, range of cyclic stresses $\Delta\sigma$ and factor of cycle asymmetry R_σ, it is evident that the Paris equation parameters depend on the values of $\Delta\sigma$ and R_σ of external alternating loading. Fig. 2 gives the KDFF for 15XSND steel in case of the crack propagation in the tensile RWS fields, derived for different conditions of external alternating loading.

The KDFF given in Fig. 2 were plotted with fixed values of the cycle asymmetry factor R_σ=0 and two different maximum stresses of the alternating loading cycle: 150 MPa and 250 MPa. It can be seen, that with the greater stress range, the appropriate KDFF shifts downward along the ordinate axis, practically without changing the angle of inclination. Such a shifting is accounted for by the fact that with the increase of the $\Delta\sigma$ range, at the specified R_σ, the degree of high RWS relaxation is increased. Hence, under these conditions, the effect of RWS

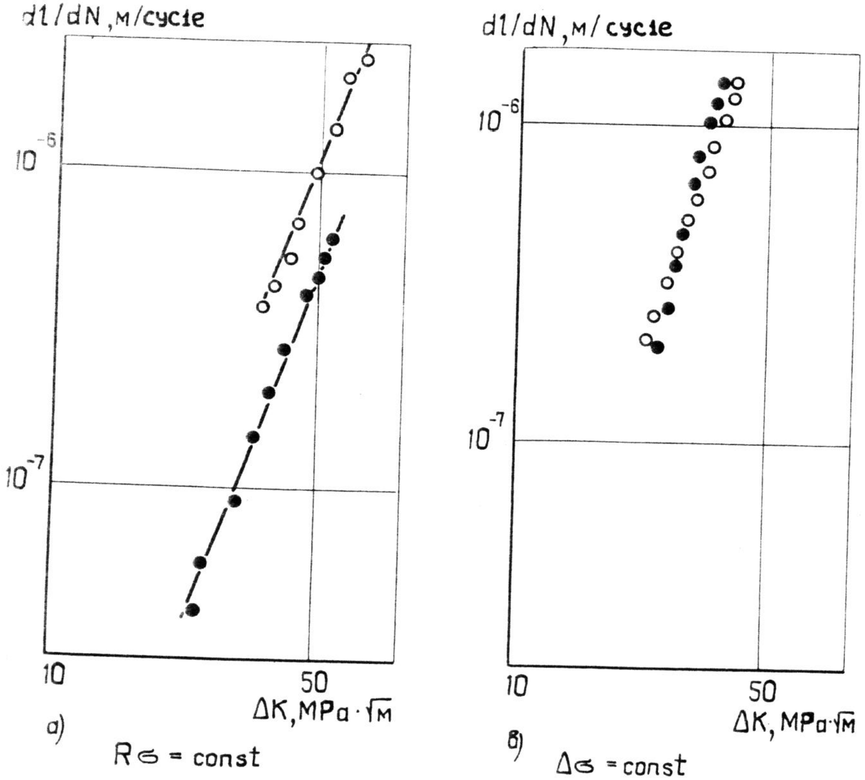

Fig. 2. The KDFF of specimens of 15XSND steel in the tensile RWS field
a) for R_σ=0: ○ - σ_{max}=150MPa, ● - σ_{max}=250 MPa;
b) for $\Delta\sigma$=150 MPa: ○ - R_σ=0, ●- R_σ=-1

on the cyclic crack resistance is reduced wih the increase of the cyclic stress range. Fig. 2b gives KDFF derived under alternating loading with the specified stress range, but with variable cycle asymmetry. The specimens were tested at the stress range of $\Delta\sigma$ = 150 MPa and two values of the cycle asymmetry factor: -1 and 0. The KDFF derived under such testing conditions form a single straight line within the range of experimental data scatter. Such a result is accounted for by the fact that irrespective of the cycle asymmetry a new stress cycle, with the maximum value equal to σ_T and the same range as that of the initial one, is formed for the specified cyclic stress range under the effect of high RWS. It is clear that for another value of the cyclic stress range, but the same values of the cycle asymmetry, the common KDFF will have other parameters in the Paris equation. The numeric values of the C and n parameters of Paris exponential equation for the KDFF given in Fig. 2: C=0.31*10^{-11} , n=3.01 at $\Delta\sigma$=150 MPa and C=0.23*10^{-11} , n=3.28 at $\Delta\sigma$=250 MPa for R_σ=0;

C=0.79*10^{-9} , n=1.69 at $\Delta\sigma$=150 MPa and R_σ=-1 and C=0.23*10^{-9} , n=1.96 at $\Delta\sigma$ =150 MPa and R_σ=0.

The given results of experimental studies show that in terms of linear fracture mechanics the calculated relationship for the fatigue crack propagation rate in the welded joint with high RSW should include the SIF range, cycle asymmetry factor and parameters invariant to the characteristics of the stress cycle of the external alternating loading. This relationship should also contain in the explicit or implicit form the SIF due to RWS action.

Earlier the work by Trufiakov et al (1987) has substantiated the expression for the fatigue crack growth rate, containing the cycle asymmetry factor in the explicit form:

$$\frac{dl}{dN} = C_{-1}\, e^{\lambda\,(R_\sigma+1)}\,(\Delta K)^{n_{-1}}, \qquad (1)$$

where C_{-1} and n_{-1} are Paris equation parameters, derived at $R_\sigma = -1$; λ is material constant characterizing its sensitivity to cycle asymmetry. This three-parameter equation described with satisfactory accuracy the experimental data on cyclic crack resistance of low-carbon and low-alloy steels in a broad range of variation of the asymmetry factor ($-1 < R_\sigma < 0.5$) .

The interaction of RWS and alternating loading cycle stresses leads to the formation of a new stress cycle with the same range as the initial one, but another asymmetry. In case of the propagating fatigue crack in non-uniform fields of RWS, the cycle asymmetry becomes the function of the crack length. This function can be assigned in the form of

$$R^r_\sigma(l) = \frac{K_{min}(l) + K_r(l)}{K_{max}(l) + K_r(l)}, \qquad (2)$$

where: $K_{min}(l)$ and $K_{max}(l)$ are the minimum and maximum values of SIF of external alternating loading; $K_r(l)$ is SIF due to the RWS action on the crack. The mathematical expression of $K_r(l)$ for a through-thickness isolated crack of 2l length, propagating in a non-uniform field of stabilized residual stresses $\sigma^{stb}_{ry}(x)$ normally oriented with respect to its plane, according to Wells (1977), has the form of

$$K_r(l) = 1/\sqrt{\pi l}\int_{-l}^{l}\sigma^{stb}_{ry}(x)\,\sqrt{(l\pm x)/(l\mp x)}\,dx. \qquad (3)$$

Substituting the expression $R^r_\sigma(l)$ in the form (2) into the equation (1) instead of R_σ, and leaving the SIF range unchanged, we shall have a relationship describing the rate of fatigue crack propagation in a non-uniform field of RWS:

$$\frac{dl}{dN} = C_{-1}\, e^{\lambda\,[R^r_\sigma(l)+1]}\,(\Delta K)^{n_{-1}}. \qquad (4)$$

Integration of equation (4) by l in the range from the initial length l_0 to its current value l_i, allows to determine the number of stress cycles required for the fatigue crack growth:

$$N_i = \int_{l_0}^{l_i}\frac{e^{-\lambda(R^r_\sigma+1)}\,(\Delta K)^{-n_{-1}}}{C_{-1}}\,dl. \qquad (5)$$

Fig. 3 a and b give the calculated by equation (5) and experimental data on the fatigue crack length dependence on the number of stress cycles. The calculation was performed for cracks propagating in the field of tensile (Fig. 3a) and compressive (Fig. 3b) RWS, at the symmetric ($R_\sigma = -1$) and asymmetric ($R_\sigma = 0.5$) cycle of external loading, respectively.

The calculated values of fatigue life turned out to be somewhat lower as compared to the experimental ones. It is connected with the fact, that in order to reduce the scope of preliminary experimental studies of RWS kinetics and simplify the engineering calculations, it is proposed to use the curve of $\sigma_{ry}^{stb}(x)$ stresses stabilized after the first 10 cycles of stress alternations, when calculating Kr from the equation (3). With such a simplification, the calculation yields a conservative estimate of fatigue life.

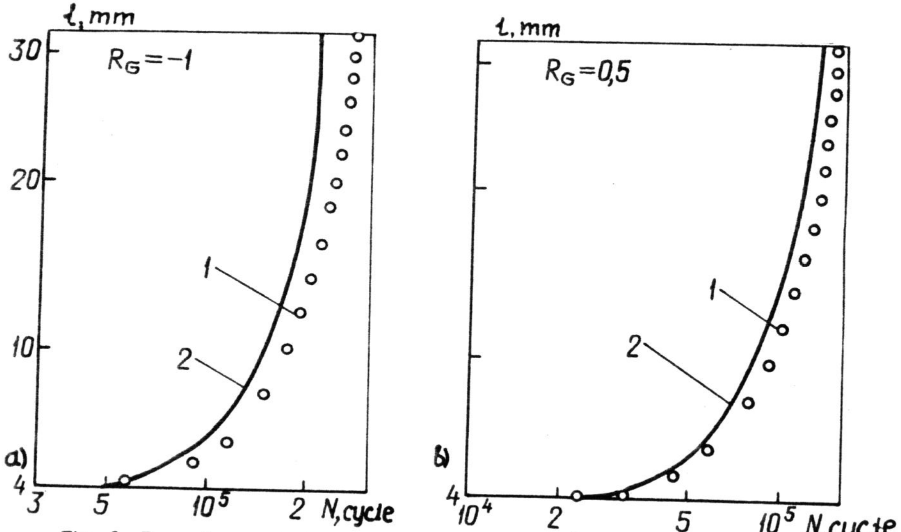

Fig. 3. Dependence of the length of fatigue crack on the number of loading cycles when it propagates in specimens of 15XSND steel in the field of tensile (a) and compressive (b) RWS: 1 - experiment; 2 - calculation by equation (5).

Thus, the experimental studies described in the paper and the calculations performed prove the effectiveness of applying the mathematics of linear fracture mechanics to assess the cyclic crack resistance of welded joints with high RWS.

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