NUMERICAL AND EXPERIMENTAL STUDIES OF THE LAWS OF LOW-CYCLE FATIGUE CRACK PROPAGATION IN WELDED JOINTS

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ABSTRACT

The paper presents an application package simulating the fatigue crack propagation in welded joints in terms of the finite element method (FEM), using J-integral as the criterial parameter describing the elasto-plastic fracture process in the crack tip. The numerical study of J-integral invariance for certain types of welded joints was performed allowing for such factors as mechanical heterogeneity and geometrical non-linearity of the weld, residual welding stresses, loading biaxiality. Analyzed are the results of a set of experimental studies of the regularities of the main structural, technological and experimental factor effect on a stable propagation of the low-cycle fatigue crack. It was a basis to develop recommendations to evaluate the welded metal structure fatigue life at the stage of the low-cycle fracture propagation.

KEYWORDS:

welded joints, low-cycle fatigue, fatigue crack propagation, J-integral, kinetic diagram of fatigue fracture.

NUMERICAL SIMULATION OF WELDED STRUCTURE FRACTURE PROPAGATION

A FEM application package designed for PC was developed for the numerical simulation of a stable FCP in welded joints, using J-integral as the parameter describing the process of elasto-plastic fracture in the crack tip.

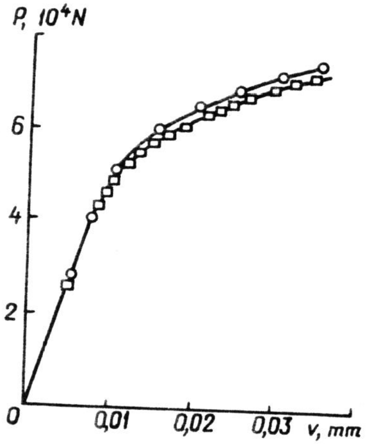

Fig.1. Diagram of loading the SENT-specimen of M16C steel. □ - experiment, ○ - numerical simulation.

The calculation of a uniaxial loading of SENT-specimen of M16C steel performed in order to test the developed FEM package revealed an acceptable agreement of the numerical simulation results with the experiment (Fig. 1). The performed series of numerical calculations confirmed the invariance of J-integral for welded joints. The maximum scatter of J-integral values, as shown by calculations, did not exceed 5% for different contours (Fig. 2). The mechanical properties of weld metal markedly affect the plastic deformation development in the zone of joints with cracklike defects. In case of an electroslag welded butt joint on low-alloyed 13ХГМФ steel (σ_Y= 636 MPa), with a transverse weld (σ_Y= 673 MPa), the loading diagram is located somewhat higher than that for the base metal (Fig. 3). The manual welding of the

given steel was performed using УОНИ 13/45 А stick electrodes

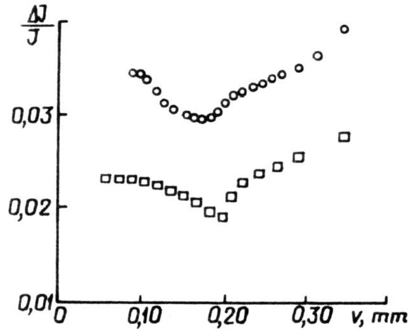

Fig.2. Relative error of J-integral evaluation. □ - welded joint, 13ХГМФ steel, manual welding; ○ - M16C steel, manual welding.

yielding a deposited metal with 440 MPa yield point. It determined a noticeable increase of plastic deformations under

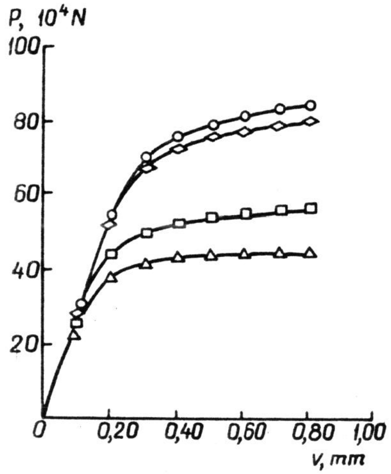

Fig.3. Diagram of loading the SENT-specimen with a weld. 13ХГМФ steel. ◇ - base metal; ○ - electroslag welding; □ - manual welding; △ - manual welding allowing for residual stresses.

the given joint loading as compared to the base metal at the same loading levels.

As can be seen from Fig. 3, the effect of residual stresses is manifested, mainly, in the increase of the plastic deformation level as compared to the initial specimen. The loading biaxiality produces a more complex effect on the welded joint deformation. As can be seen from Fig. 4, in the elastic region the additional tensile stresses in the direction normal to the main load diminish the measured longitudinal deformation of specimens, as they cause the opposite sign deformation in the main direction. Conversely, the compressive additional stresses, due to the same effect, increase the longitudinal deformation of the specimen. In the

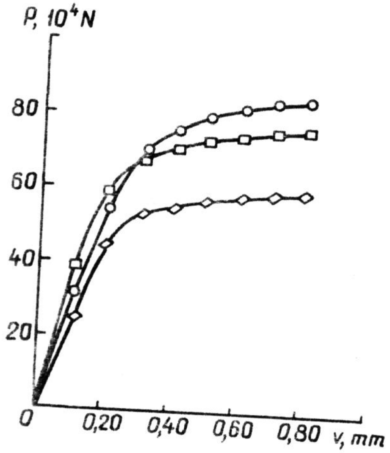

Fig.4. Diagram of loading the SENT-specimen of 13ХГМФ steel. Biaxial loading. ◇ — $\sigma_1 = -\sigma_2$; ○ — $\sigma_2 = 0$; □ — $\sigma_1 = \sigma_2$.

region of plastic deformations the presence of both the compressive and tensile additional stresses leads to the increase of plastic deformations.

EFFECT OF THE PRINCIPAL STRUCTURAL AND TECHNOLOGICAL FACTORS ON RESISTANCE TO STABLE FCP

The numerical simulation was performed in parallel with a series of experimental studies on the effect of the main structural, technological and service factors on the resistance to stable FCP in welded joints using SENT-specimens made of low-carbon Ст3 steel, low-alloyed 14ХГНМД and 12ХГН2МФДРА steels and their welded joints.

The speed of the FCP was assessed on basis of kinetic equation of the type of

$$\frac{dl}{dN} = C\cdot(\Delta J)^m \qquad (1)$$

The analysis of the performed experimental study results

Table 1. Parameters of kinetic equation.

Steel	Welded joint zones	Parameters	
		$C\cdot10^8$	m
Ст3, Welding in CO_2	BM (Base Metal) HAZ(Heat-Affected zone) WM (Weld Metal)	4,07 1,10 0,53	1,26 1,50 1,52
14ХГНМД	BM	0,27	1,83
X-70 submerged arc welding	BM HAZ WM	1,28 1,06 1,04	1,35 1,30 1,30
12ХГН2МФДРА	BM(hardening + tempering)	3,50	1,09
	BM (temp.+ hard.+temp.)	11,00	0,79

enabled to reveal the tendency to m exponent lowering with the improvement of steel mechanical properties (Tabl.1) and to establish the dependence of C constant on the steel strength:

$$C_{eff} = C \cdot 10^{-\eta_W} \qquad (2)$$

where $\eta_W = 1.86 \div 0.78 \cdot 10^{-5} \cdot W_{st}$, W_{st} is specific fracture energy under static loading.

The loading cycle asymmetry is one of the most essential factors affecting FCP in metals by means of so-called crack closure effect (Shih and Wei,1974). The effective value of J-integral range should be used for taking into account the influence of the given effect on FCP rate in case of elasto-plastic deformation:

$$J_{eff} = \frac{\Delta K^2}{E} \cdot U_\sigma^2 + \frac{[\,\eta_{pl} \cdot U_\sigma \cdot S_{pl} - (\,2 - \eta_{pl} \cdot U_\sigma\,) \cdot S_1]}{t \cdot (\,b - 1\,)} \qquad (3)$$

, where

$$U_\sigma = \frac{\sigma_{max} - \sigma_{op}}{\sigma_{max} - \sigma_{min}} = \frac{P_{max} - P_{op}}{P_{max} - P_{min}}$$

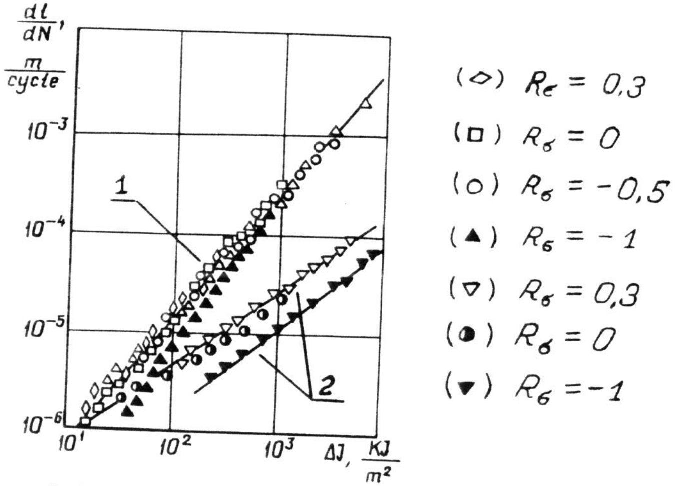

Fig.5. Diagram of fatigue fracture propagation. 1 - Ст3 steel; 2 -12ХГН2МФДРА steel.

is a relative effective stress range; S_{pl}, S_1 are plastic components of the area under and above the "P-v" diagram, respectively, b and t are width and thickness of the specimen, respectively; P_{op} is load level corresponding to the moment of

crack closure, which is determined from the "P-v" diagram,by the inflection point. For the low-carbon ductile Ст3 steel a gradual diminution of the crack closure effect is observed because of the increase of plastic deformations at the crack tip. With the increase of the alternating load level a gradual drawing together of kinetic diagrams of fatigue fracture (KDFF) of low-carbon Ст3 steel is found (Fig. 5). In high-strength steels the nature of the stress cycle asymmetry effect is reduced to practically parallel shifting of KDFF (Fig. 5).

Proceeding from the derived results of experimental studies the evaluation of the effective values of J-integral can be performed on the basis of the expressions of the following kind:

$$\Delta J_{eff} = \Delta J \cdot e^{\lambda_j (R_\sigma + 0,5)} \cdot a_j \cdot (\Delta\Phi)^{b_j} \qquad (4)$$

$$\Delta\Phi = \Delta J \cdot E / (\pi \cdot l \cdot \sigma_Y^2) \qquad (5)$$

where λ_j is the factor of steel sensitivity to stress ratio at the fatigue fracture propagation stage; a_j and b_j are constants (Table 2); R_σ is the stress ratio.

Table 2. Parameters of the equation (4).

Parameter	Ст3	12ХГН2МФДРА
λ_j	2.13	2.76
a_j	1.66	0.97
b_j	0.18	0.15

The effect of creep on the cyclic crack resistance depends on the maximum values of J-integral (Audo and Ogura,1978):

$$\frac{dl}{dN} = \left(\frac{dl}{dN}\right)_{fat} + \left(\frac{dl}{dN}\right)_{cr} = C \cdot (\Delta J)^m + C^* \cdot (J_{max})^{m^*} \qquad (6)$$

Approximation of the design-experimental data array by the exponential expression of the type (1) yielded the following parameter values for the low-carbon CT3 steel:

$$C^{*} = 4,6\cdot 10^{-12}\ \frac{M^{(2m+1)}}{KJ^{m}}\ ;\ m^{*} = 2,98$$

The number of regular loading cycles corresponding to the stable FCP stage up to the moment of fracture, on the the basis of (4), can be written as:

$$N = \frac{10^{\eta_w}\ (\pi\sigma_T^2)^{b_j}}{C\cdot e^{\lambda_j (R_\sigma + 0,5)}\cdot a_j\cdot E^{b_j}}\cdot\int_{l_o}^{l_{cr}} \frac{1^{b_j}}{\Delta J^{b_j+1}}\,dl \qquad (7)$$

where l_o is starting length of initial defect, l_{cr} is critical length of defect at which the condition is fulfilled; and the value of J_{fc} parameter is established from the experimental KDFF for SENT-specimens. When performing the numerical integration, the values of J-integral range are substituted into the integrand of the expression (7), these values having been derived during numerical simulation using the FEM program package.

Thus, the results of the performed numerical and experimental studies and the generalized estimates derived on their base allow to forecast the fatigue life and service life of complex-shaped welded metal structures at the stage of fatigue fracture propagation in the elasto-plastic loading region.

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