LT0400057
STRENGTH, DURABILITY AND STABILITY OF MATERIAL
Proceedings of the 3rd international conference SDSMS'03, Klaip

INVESTIGATION OF THE FATIGUE CRACK OPENING UNDER LOW CYCLIC LOADING

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Abstract
Low cycle loading crack opening under various load levels were investigated. Analytical method of the fatigue crack opening investigation was described using relations of crack surface displacements. Calculated results of the crack surface displacement were compared with the experimental results.
KEY WORDS: *low cycle loading, crack, opening.*

Anotacija
Nagrinėjamas mažaciklio apkrovimo plyšio atsivėrimas, esant skirtingiems apkrovimo lygiams. Aprašytas nuovargio plyšio kontūro pasislinkimų analitinis tyrimas, pateiktos plyšio atsivėrimo dydžio skaičiavimo priklausomybės. Analitiškai apskaičiuoti nuovargio plyšio kontūro pasislinkimai yra palyginti su eksperimentiniais rezultatais.
PAGRINDINIAI ŽODŽIAI: *mažaciklis apkrovimas, plyšys, atsivėrimas.*

Introduction

Evaluating resistance of parts and structures to low cycle (cyclic elasto - plastic) deformation two types of damage are distinguished: the first is a formation of macro crack in the most loaded zones; the second is a growth of macro crack. In the first stage damage accumulation takes place in entire volume of the loaded part or specimen. In the stage of fatigue crack growth the damage accumulation process is localized in small region around the crack tip. When the crack appears the stress strain state changes: maximal strain localizes in a small volume, significantly increases its value and distribution gradient. Therefore the methods of investigation that are suitable in the first damage accumulation stage (when damage accumulates at large volumes) become incorrect. State of the part with a growing crack is characterized not only by straining nature but also by crack length, crack growth rate, crack opening size and all this makes the investigation very complicated.

Presented work deals with an analytical and experimental investigation crack opening in most common structural steel. The experimental investigation was performed measuring crack length and crack surface displacements at certain number of completely reversed tension - compression load cycles experienced by the specimen with central crack. The crack surface displacements were measured when the cyclic load approaches its' maximum. Crack opening displacements is easy to compare with experimental measurements and also with analytical solutions. This investigation can serve as an intermediate point to complete failure prediction model and also it may have a direct practical value, for example in determination of leak before break (LBB) in the pressure vessels and pipes [1].

Analytical investigation

Strength evaluation of the structural elements under static and cyclic load is based on the analysis of the operation of the structure and material properties. Evaluation of the structural element according cyclic fracture criteria is performed at crack formation and growth stages. Each of these stages have characteristic fracture criteria

Material experiences elasto - plastic strains when low cycle load is applied, therefore strain based fracture criteria are mostly used in this case [2, 3]. Comparing analytical solution and experimental results the simplest way is to compare crack opening and crack length. The main idea of the analytical stress and strain investigation method is to treat the crack as a very sharp notch (stress concentrator) and to use stress and strain concentration factors expressions. Using this method Neuber's or modified by Makhutov Neuber's metod is used in most cases.

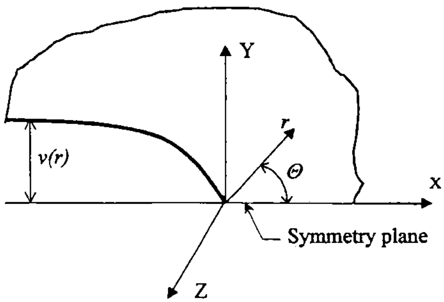


Fig. 1 Scheme of the crack and coordinate system

Fig. 1 presents rectangular and polar coordinate axis used in crack surface displacement calculation. Displacements were calculated in Y direction. Here and r are polar coordinates, $v(r)$ is a displacements of crack surface.

Theoretical solution obtained by Westergaard and others [2] gives the expression of crack surface displacement at the crack tip in elastic body. For the plane strain state

$$v=\frac{K_I 2(1+\mu)}{2E}\sqrt{\frac{r}{2\pi}}\sin\left(\frac{\theta}{2}\right)\left[3-4v+1-2\cos^2\left(\frac{\theta}{2}\right)\right] \tag{1}$$

and for the plane stress state

$$v=\frac{K_I}{2G}\sqrt{\frac{r}{2\pi}}\sin\left(\frac{\theta}{2}\right)\left[\frac{3-v}{1+v}+1-2\cos^2\left(\frac{\theta}{2}\right)\right], \tag{2}$$

if $\theta=\pi$, then

$$v=\frac{4K_I}{E}\sqrt{\frac{r}{2\pi}} \text{ and } v=\frac{4K_I}{E}\sqrt{\frac{r}{2\pi}}\left[1-v^2\right]. \tag{3}$$

Here v is a Poisons ratio; K_I is a first mode stress intensity factor.

When body experiences elasto - plastic strains, as it is under low cycle loading, this solution is not valid. It was proposed [2, 3] to obtain the solution of crack surface displacements by analogy with elastic solution but employing an expression of elastic plastic strain concentration factor. Having in mind that $e_i=\frac{K_I}{E\sqrt{2\pi r}}$ in the materials elastic state, the strain concentration factor K_e at the crack tip can be expressed by equations:

$$K_e=\frac{1}{\bar{\sigma}_{in}}\left(\frac{\bar{K}_I}{\sqrt{2\pi r}}\right)^{p_e}, \quad \text{when } \bar{\sigma}_{in}\leq 1 \tag{4}$$

and

$$K_e=\bar{\sigma}_{in}^{-\frac{2}{1+m_0}}\left(\frac{\bar{K}_I}{\sqrt{2\pi r}}\right)^{p_e}, \quad \text{when } \bar{\sigma}_{in}>1 \tag{5}$$

for the plane stress state.

Here $\overline{K}_I$ is a normalized stress intensity factor $\overline{K}_I = K_I / \sigma_{pr}$; m_0 is a power index of static stress strain curve approximation by power low; $\overline{\sigma}_{in}$ is normalized nominal static stress intensity in net cross - section;

$$p_e = \frac{2}{1+m_0} \tag{6}$$

in case if Neuber strain concentration factor relation is used and

$$p_e = \frac{2 - n(1-m_0)(1-\overline{\sigma}_{in})}{1+m_0} \tag{7}$$

if Makhutov [2] strain concentration factor relation is used. Using equations (4) - (7) and $\overline{e}_i = K_e \overline{e}_{in}$ normalized strain intensity can be expressed as follows:

$$\overline{e}_i = \left(\frac{\overline{K}_I}{\sqrt{2\pi r}} \right)^{p_e}, \text{ when } \overline{\sigma}_{in} \le 1, \tag{8}$$

$$\overline{e}_i = \left(\frac{\overline{K}_I}{\sqrt{2\pi r}} \right)^{p_e} \overline{\sigma}_{in}^{\frac{1-m_0}{m_0(1+m_0)}}, \text{ when } \overline{\sigma}_{in} > 1 \tag{9}$$

for plane stress state.

Further, using expressions (8) - (9), it was obtained that normalized strain intensity factor near the crack tip is [2, 3]:

$$\begin{aligned} \overline{K}_{Ie} &= \overline{K}_I^{p_e}, && \text{when } \overline{\sigma}_{in} \le 1 \\ \overline{K}_{Ie} &= \overline{K}_I^{p_e} \overline{\sigma}_{in}^{\frac{1-m_0}{m_0(1+m_0)}}, && \text{when } \overline{\sigma}_{in} > 1 \end{aligned} \tag{10}$$

for the static load, and

$$\left.\begin{aligned} \overline{K}_{I\varepsilon_k} &= \overline{K}_{Ik}^{\,p_{\varepsilon_k}}, && \text{when } \overline{S}_{ink} \le 1 \\ \overline{K}_{I\varepsilon_k} &= \overline{K}_{Ik}^{\,p_{\varepsilon_k}}\, \overline{S}_{ink}^{\frac{1-m_k}{m_k(1+m_k)}}, && \text{when } \overline{S}_{ink} > 1 \end{aligned}\right. \tag{11}$$

for the cyclic load.

Here $\overline{S}_{ink}$ is normalized nominal cyclic stress intensity in net cross-section; m_k is a power index of cyclic stress strain curve approximation by power low at k semicycle [3].

Using (10) and (11) relations, fatigue crack surface displacements in case of low cycle loading are determined by following expressions [3]:

$$\left.\begin{aligned} \bar{v}_0 &= 4\overline{K}_{I\varepsilon}\left(\frac{r}{2\pi}\right)^{p_\varepsilon/2}\left[f\left(\frac{r}{l}\right)f(K_I)\right]^{p_\varepsilon} \\ \bar{v}_k &= 4\overline{K}_{I\varepsilon_k}\left(\frac{r}{2\pi}\right)^{p_{\varepsilon_k}/2}\left[f\left(\frac{r}{l}\right)f(K_I)\right]^{p_{\varepsilon_k}} \end{aligned}\right\} \tag{12}$$

for plane stress state.

If plane strain state is used Eqs. (4), (5), (8), (9), (12) will be multiplied by $(1-\nu)^{p_\varepsilon}$. Here displacements normal to crack growth plane for zero and kth semicycle are normalized with respect to strain proportionality limit: $\bar{v}_0 = v_0 / e_{pr}$ and $\bar{v}_k = v_k / e_{pr}$. The power index

$$p_{\varepsilon_k} = \frac{2}{1+m_k} \tag{13}$$

in case if Neuber strain concentration factor relation is used, and

$$p_{\varepsilon_k} = \frac{2 - n(1-m_k)(1-\overline{S}_{ink})}{1+m_k} \tag{14}$$

if Makhutov [2] strain concentration factors relation is used.

The function $f(K_I)$ makes correction, evaluating geometry of specimen and crack [4]

$$f(K_I) = 0.38\left[1 + 2.308 \cdot \left(\frac{2l}{b}\right) + 2.439 \cdot \left(\frac{2l}{b}\right)^2\right]$$

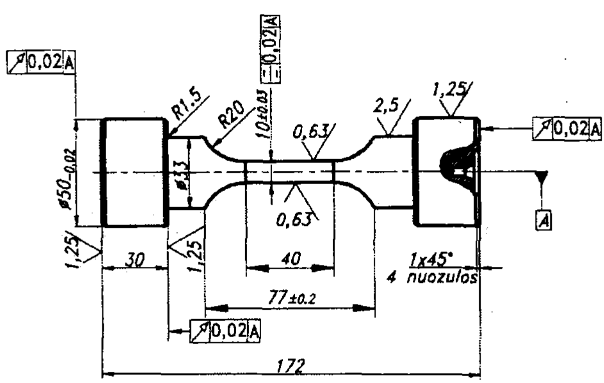
Here b is a width of the specimen, l is a half length of the crack.

Function $f\left(\frac{r}{l}\right)$ gives a correction for the solution when the solution point moves away from the crack tip [2, 3]

$$f\left(\frac{r}{l}\right) = \frac{1 + r/l}{\sqrt{1 + r/2l}}$$

Experimental investigation

Experimental investigation consists of two major parts: first part is a determination of material properties; the second part is an investigation of crack growth and opening. Specimens for both types of testing were produced from a rolled bar of structural steel 45 (brand according Russian standard GOST 1050-88). The normalizing heat treatment was applied for the bars which is a common procedure for this type of material. Initial diameter of the rod was 50 mm.



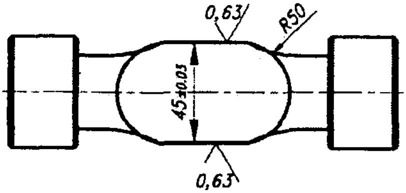


Fig. 2 Specimen for crack opening test

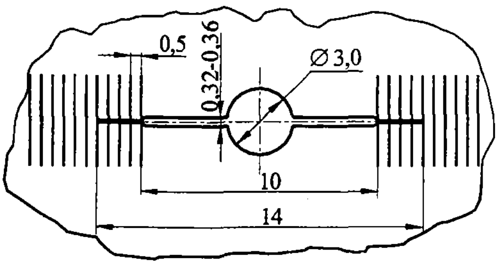


Fig. 3 Initial crack geometry

The two types of tests (static and cyclic) were performed to determine material properties. Three tests were performed for the determination of static properties and eleven tests to determine cyclic properties. The same types of cylindrical specimens with testing part diameter of 10 mm [4] were used for both test types. Cyclic tension - compression testing machine of 100 kN load capacity was employed for these tests. Determined material properties are: proportionality limit σ_{pr}=335 MPa, ultimate strength σ_u=820 MPa; cyclic proportionality limit S_T=422 MPa; Young's modulus E=197100 MPa; relative reduction of cross - section area at rupture ψ_u=39%.

At low cycle stressing were performed 14 tests. At this tests were estimated that steel 45 is cyclically stable material with power law $\bar{S}_{ik} = \bar{\varepsilon}_{ik}^{\,m_k}$ coefficient m_k=0.3 and cyclical proportionality limit $\bar{S}_T = \dfrac{S}{\sigma_{pr}} = 1.25$.

Tests on crack opening were performed using tension - compression testing machine which has 250 kN load capacity. General form of used specimens is shown in Fig. 2. In the center of the specimen 3 mm diameter hole was drilled and symmetrical 3.5 mm length notches produced using electric erosion machining. Specimen precracking was applied to have 2 mm initial cracks at notch tip (Fig. 3). Therefore the crack in the specimen can be divided into two parts: machined part (Fig. 4) $2a_m$=10 mm and the cracked part a_c, where $a_c = a - a_m$. Only a_c opening v was investigated. The scale consisting of vertical lines was made on a surface of the specimen. The lines were inscribed in to specimens' surface with a 0.5 mm pitch (Fig. 3). This was done in order to make easier crack length and opening measurements. These measurements were performed at every 0.25 mm distance of crack length. The applied load was completely reversed stress controlled cycling. The measurements were made at the moment of crack opening peak at 0, 4, 10 and then every 10 semicycles until the rupture of spacimen. The crack growth was not ideally symmetric therefore the left and right side was measured separately. The test results presented in this paper were obtained at initial load levels in net cross - section: $0.9\sigma_{pr}$; $1.0\sigma_{pr}$; $1.1\sigma_{pr}$ and $1.2\sigma_{pr}$. The results of crack growth and opening are presented in Fig. 4 - 7.

Comparison results of the analytical and experimental investigation

Investigation of crack opening consisted of calculation of crack surface displacements v_k, at the given crack length for certain semicycle k and nominal initial net load level $\overline{\sigma}_{in0}$. The calculations were performed for initial nominal load levels $\overline{\sigma}_{in0}$=0.8, 0.9, 1.0; 1.1; 1.2, 1.28 and a set of semicycles (10, 40, 80, 100, 160, 600, 800, 1000, 4000, 5000, 10000).

Because the experimental crack growth had some deviations from the ideal symmetry the mean value of the right and left side of the crack length was used in the calculations. However the experimental points are presented for both sides: left (e.g. left side at 100 semicycle: k=100 L) and right (k=100 R).

Fig. 4, 5 presents the results of an investigated crack opening displacements at 100th and 100000th semicycles under fully reversed cyclic load at the level $\overline{\sigma}_{in0}$=0.8. Fig. 6 presents the results at 40th semicycle under load $\overline{\sigma}_{in0}$=1.2 and Fig. 7 the results at 10th semicycle under load $\overline{\sigma}_{in0}$=1.28. The calculations at this load case were performed for plane stress (curves *1*, *2*) and plane strain (curves 3, *4*) states.

From the presented results it is evident that analytical expressions did not describe the entire crack surface at the opening but matches the last point at the end of crack where the displacements have a maximum. Also it was found that employing the expression (14) analytically calculated results are slightly close to experimental ones for shorter cracks ($l \leq 2.5$mm) and when crack length increases the better results were obtained using expression (13).

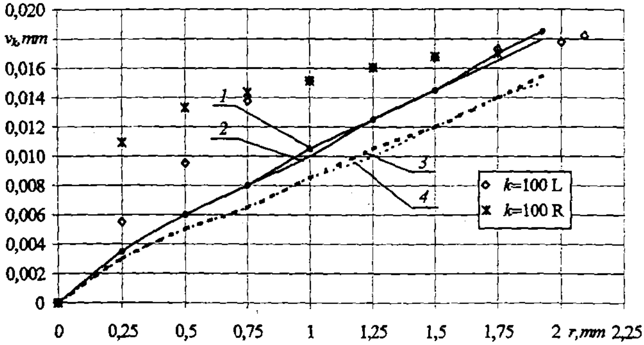


Fig. 4 Displacements of the crack surface at k=100 semicycle under nominal load $\bar{\sigma}_{in0} = 0.8$

In Fig. 4 – 7 curves *1* and *3* presents the results calculated by Makhutov's expressions; curves *2* and *4* - the results calculated by Neuber's expressions.

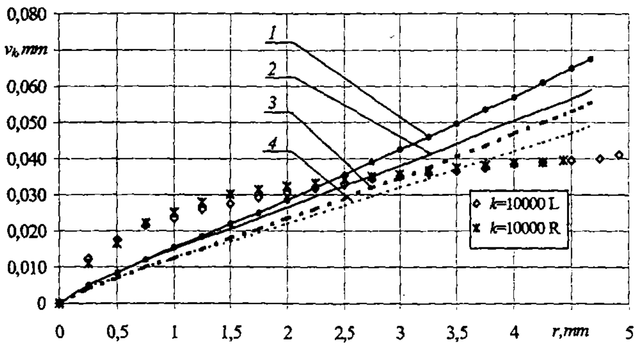


Fig. 5 Displacements of the crack surface at k=10000 semicycle under nominal load $\bar{\sigma}_{m0} = 0.8$

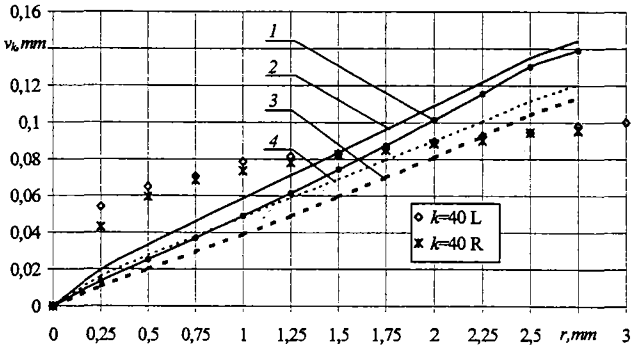


Fig. 6 Displacements of the crack surface at k=40 semicycle under nominal load $\bar{\sigma}_{in0} = 1.2$

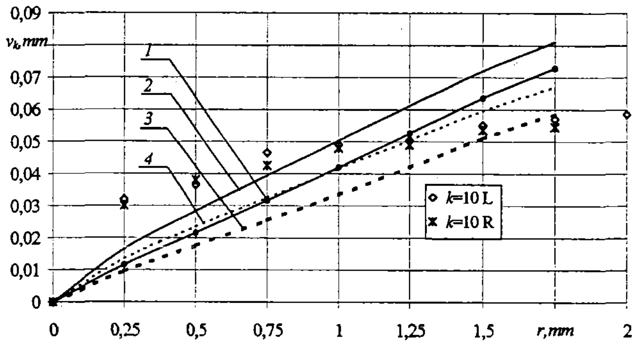


Fig. 7 Displacements of the crack surface at k=10 semicycle under nominal load $\bar{\sigma}_{in0} = 1.28$

Conclusions

At comparison crack surface displacements v_k, obtained by analytical investigation with experimental data it was found that:

1. analytical expressions do not describe the entire crack surface geometry at the opening but matches the last point at the middle of the crack where the displacements have a maximum;
2. the worse coincidence of calculated and experimental results was obtained for long cracks;
3. while the crack length is relatively small the better results were

obtained by expressions obtained using Makhutov's stress and strain concentration factor relations. For longer cracks, the expressions obtained using Neuber stress and strain factor relations give better coincidence.

4. for the short cracks Neuber's and Makhutov's methods makes a negligible influence on the final result. For long cracks Neuber's method better suites the experimental data.

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NUOVARGIO PLYŠIO ATSIVĖRIMO TYRIMAS ESANT MAŽACIKLIAM APKROVIMUI

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Santrauka

Nagrinėjamas mažaciklio nuovargio plyšio atsivėrimas bei plyšio užsivėrimo įtempiai, esant skirtingiems apkrovimo lygiams. Aprašytas nuovargio plyšio kontūro pasislinkimų analitinis tyrimas, pateiktos plyšio atsivėrimo bei užsivėrimo įtempių skaičiavimo priklausomybės. Plyšio kontūro poslinkių bei užsivėrimo įtempių skaičiavimuose buvo panaudotos Machutovo bei Neuberio pasiūlytos įtempių ir deformacijų koncentracijos koeficientų išraiškos. Plyšio kontūro poslinkiai ir užsivėrimo įtempiai apskaičiuoti esant skirtingiems apkrovimo lygiams ir plyšio ilgiui. Analitiškai apskaičiuoti nuovargio plyšio kontūro pasislinkimų rezultatai palyginti su eksperimentiniais ir skaitiniu metodu apskaičiuotais rezultatais.