Surface crack growth rate under tension and bending in aluminum alloys and steel

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Abstract

Fatigue surface crack growth is studied using FE-analysis and experiments for aluminum alloy D16 and low carbon steel under tension and bending. The subject for the study is central notched specimens with external semi-elliptical surface crack. Crack growth rate was determined on precracked specimens under tension and three point bend loadings. As experimental result the crack length increment on the specimen surface and crack edges opening displacement were obtained. A relationship between the crack form geometry and a number of loading cycles was obtained during tests by beach marks produced on each specimen. For the experimental surface crack paths in tested specimens the governing parameter for the 3D-fields of the stresses and strains at the crack tip in the form of \( I_\gamma \)-integral was calculated by finite element analysis along semi-elliptical crack front. The governing parameter of the elastic-plastic stress fields \( I_\gamma \)-integral was used as the foundation of the elastic-plastic stress intensity factor. The plastic stress intensity factor approach was applied to the fatigue crack growth on the free surface of the specimens and in the deepest point of the semi-elliptical surface crack front. A significant influence of material properties and loading type on crack growth rate characteristics was established in the present study. The experimental and numerical results of the present study shows that the elastic-plastic stress intensity factor, which is sensitive to elastic-plastic material properties, is attractive for fatigue crack growth rate characterization.

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Keywords: Surface flaw; crack growth rate; in-plane and out-of-plane constraint

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1. Introduction

Surface cracks of different shapes in the plan are the most widespread defects in metallic components. Pure tension and bending are common in engineering structures such as turbine disks, airplane fuselage skins, pressure vessels and so on. The problem of predicting the residual fatigue life of such type of structural element is complex and a closed solution is often not available because surface flaws are three-dimensional in nature. Numerical calculations of the stress intensity factors along the front of the surface flaw and crack growth rate study on this base were performed by Shlyannikov et al. [1,2].

In this paper, surface crack growth rate under tension and bending in aluminium alloy and steel is investigated by experiments and numerical calculations. A significant influence of material properties and loading type on crack growth rate characteristics is demonstrated.

2. Material properties and specimen geometry

The test materials used in this study are an aluminum alloy D16T and low carbon steel St3, and their main mechanical properties are listed in Table 1, where $E$ is the Young’s modulus, $\sigma_u$ is the nominal ultimate tensile strength, $\sigma_0$ is the monotonic tensile yield strength, $\sigma_t$ is the true ultimate tensile strength, $n$ is the strain hardening exponent, and $\alpha$ is the strain hardening coefficient.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_0$ MPa</th>
<th>$\sigma_u$ MPa</th>
<th>$E$ GPa</th>
<th>$n$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D16T</td>
<td>309</td>
<td>529</td>
<td>73.261</td>
<td>5.68</td>
<td>1.67</td>
</tr>
<tr>
<td>St3</td>
<td>294</td>
<td>487</td>
<td>215.655</td>
<td>5.19</td>
<td>10.47</td>
</tr>
</tbody>
</table>

The geometry of plate with central surface crack is shown in Fig. 1. The thickness of specimen is equal to 10 mm. The crack front is approximated by an elliptical curve with the major axis $2c$ and the minor axis $2a$. Surface edge cracks are cut with an initial flaw equal to 3.0 mm and $a/c=0.3$. The crack length on the free surface of the specimen $c$ is obtained by measuring the distance between the breakthrough points of the advancing crack and the notch.
Both optical microscopy and crack opening displacement (COD) method are used to monitor the evolution of the crack growth rate of the elliptical-fronted edge cracks in terms of the crack depth and crack length during the tests. The crack opening displacement is measured on the free specimen flat surface in the central plane of symmetry, as shown in Figs. 2. Pure tension or bending cyclic tests are carried out on a MTS Landmark servo-hydraulic test system with a maximal capacity of 100 kN at a frequency of 7 Hz and a stress ratio R=0.1.

Fig.2. Equipment for tension and bending tests

3. Surface crack paths

Two different stress ratios are applied several times to the specimens to fix and highlight the crack front geometry during propagation. Beach marks are produced on each specimen during each test by increasing the applied stress ratio from 0.1 to 0.5 at a constant value of the maximum cyclic nominal stress. Beach marks on the post mortem cross section of specimens are shown for pure uniaxial tension (Fig. 4), bending (Fig. 5).

Fig.3. Surface crack paths under tension for alloy D16T (a) and steel St3 (b)

Fig.4. Surface crack paths under bending for alloy D16T (a) and steel St3 (b)
The fatigue fracture process depends on the loading conditions. Under three-point bending crack growths only as the part-through-thickness surface flaw (Fig. 4). In contrary, the crack propagation process in the plate under uniaxial tension (Fig. 3) can be divided into two stages. In the first stage, the semi-elliptical crack is described by a part-through-thickness crack. In the second stage, the semi-elliptical crack completely crosses the specimen wall B and becomes a through-thickness crack.

Based on the periodically measured increments of the surface crack length $\Delta c$, the curve of surface crack propagation versus cycle number $N$ is obtained and represented in Fig. 5.a. The value of $N$ in Fig. 5.a is normalized by the maximum number of cycles corresponding to the fracture of specimen. In addition the relation between the relative crack depth $a/t$ and the aspect ratio $a/c$ is found and demonstrated in Fig. 5.b.

![Fig. 5. Aspect ratio versus fatigue life (a) and crack depth (b) under tension and bending.](image)

As it follows from Fig. 5 for the same plate configuration, the aspect ratio is an increasing function of number of cycles and the crack depth $a/t$ for pure tension, whereas the aspect ratio decreases under bending for both materials considered in the present study.

4. Numerical results

FEM calculations are performed to determine the displacement and stress distributions along the crack front under different loading conditions. Typical finite element mesh of the plate with central surface crack is illustrated in Fig. 6.

The governing parameter of the elastic-plastic stress fields $I_o$-factor are determined and analyzed on the base of stress and displacement data obtained through numerical calculations for aluminum alloy D16T and steel St3 under bending and tension.

![Fig. 6. FEM-meshes for tension/bending plate.](image)
The plastic stress intensity factor $K_p$ in pure Mode I can be expressed directly in terms of the corresponding elastic stress intensity factor using Rice’s $J$-integral as follows [3]:

$$
K_p = \left[ \frac{K_1^2}{\alpha \sigma \sqrt{J_{nFEM}^{FEM}(\theta, n, (a/w))}} \right]^{1/(1+n)} \left( \frac{\sigma}{\sigma_0} \right)^2 \pi (a/w) \frac{Y_1'(a/w)}{I_{nFEM}^{FEM}(\theta, n, (a/w))} \right)^{0.5/(1+n)}; \quad K_1 = \sigma \sqrt{\pi a} \cdot Y_1(a/w)
$$

where $K_1 = K_i / \sqrt{\pi w}$ is elastic SIF normalized by a characteristic size of cracked body, $\sigma$ and $n$ are the hardening parameters, $\lambda = a/w$ is the dimensionless crack length, $w$ is specimen width, $\sigma$ is the nominal stress, and $\sigma_0$ is the yield stress, $I_n$ is governing parameter for 3D-fields of the stresses and strains at the crack tip. Shlyannikov and Tumanov [3] suggested the procedure for calculating the governing parameter of the elastic–plastic stress–strain fields in the form of $I_n$ for the different specimen geometries by means of the elastic–plastic FE-analysis of the near crack-tip stress-strain fields. In this study, the numerical integral of the crack tip field $I_n$ changes not only with the strain hardening exponent $n$ but also with the relative crack length $c/w$ and the relative crack depth $a/t$.

More detail in determining the $I_n$ factor for different test specimen configurations are given by Refs. [3-5].

**Constraint parameter distributions along crack front in tension and bending plates**

The governing parameter of the elastic-plastic stress fields $I_n$-factor and plastic stress intensity factor distributions along crack front under bending and tension are plotted in Figs. 7 and 8. These distributions correspond to the different crack front positions, where 1 is initial front, 2 is intermediate front and 3 is a final failure front. These parameters are plotted against the normalized coordinate $\phi = 2\phi/\pi$. In these figures, $\phi = 0.0$ is the crack border (the specimen free surface), while $\phi = 1.0$ is the mid-plane of the specimen thickness.

![Fig. 7. The $I_n$-factor (a) and plastic SIF (b) distributions along crack front under bending (1-initial, 2-intermediate, 3-final).](image-url)
As can be seen from Fig. 7 and 8 the $I_n$-factor and plastic SIF essentially change along the crack front from the free surface towards the mid-plane. A material properties as well as loading type has a significant influence on the distribution of the considered parameters. It can be observed that the plastic stress intensity factor distributions have a subsurface extremum for both of materials and loading types.

4. Experimental results and discussion

The experimental results of the present study are divided into two parts. The first part includes the data of the direct measurements of objective parameters, such as the crack length and the crack opening displacement, on the free surface of specimens. The second part of the experimental data relates to the interpretation of the crack growth rate in specimens under tension and bending using numerical results for SIF distributions.

Relations between the crack growth rate and COD under tension and bending cyclic loadings

Figure 9 represents the superficial crack growth rate $dc/dN$ versus COD on the rectangular plate from aluminum alloy D16T and low carbon steel St3 under three point bend.

Fig. 9. Crack growth rate on free surface of plate and under bending versus COD (St3 (a) D16T (b))
It is found that the crack growth rate along the external surface direction as a function of COD fits into a single curve with a small scatter band of the experimental results. This fact confirms the automation possibility for experimental studies of the crack growth rate of surface defects using the crack opening displacement.

**Crack growth rate under tension and bending for two types of material**

The main purpose of this section is to interpret the surface crack growth rate in terms of stress intensity factor for two types of material under different loading conditions.

![Fig. 10. Crack growth rate as a function of SIFs for St3 under tension (a) and bending (b) for different crack front points.](image)

![Fig. 11. Crack growth rate as a function of SIFs for D16T under tension (a) and bending (b) for different crack front points.](image)

Figure 10 shows the experimental fatigue fracture diagrams in the coordinates of the crack growth rate versus the values of the elastic stress intensity factors for the plate under tension and bending loading for low carbon steel St3.
Figure 11 represents experimental fatigue fracture diagrams for aluminum allow D16T. The left pictures in Fig. 10 and 11 depict the behavior of $\frac{da}{dN}$ and $\frac{dc}{dN}$ as under tension, whereas the right picture in Fig. 10 gives the crack growth rate under bending. To determine the experimental values of the elastic SIFs for two main points of the crack front, namely, the free surface $a$ and mid-plane section $c$, the distributions represented in Fig. 5 were used. It is clear in these fatigue fracture diagrams that two stages of crack growth can be distinguished under tension. The first belongs to the stage of surface flaw growth when the crack growth rate changes significantly for small changes in the elastic stress intensity factors. Furthermore, differences in the crack growth rate on the sample surface and the deepest point of the crack front depend on the initial value of the aspect ratio. The second stage of crack growth in the plate under cyclic tension with the initial surface flaw is related to the growth of through-thickness cracks with an inclined front. During the second stage, the crack growth rate is significantly less than in the first stage, and crack growth occurs in a wide range of elastic stress intensity factors.

The experimental data clearly illustrate the effect of loading conditions as well as material properties on the crack growth in the samples with the same geometries. It can be noted that a significant reduction of the crack growth rate is observed in the direction of the deepest point of the crack front with respect to the crack front intersection with the free surface of the specimens.

Further the crack growth rate interpretation in terms of plastic stress intensity factor will be performed on the basis of the data presented in this paper.

Conclusions

Fatigue crack growth for a semi-elliptical crack for two different types of materials in tension and bending plates was studied. Experiments and calculations made under uniaxial tension and bending, were described. The governing parameter of the elastic-plastic stress fields the $I_n$-factor distributions, along crack fronts was determined from the numerical calculations; this governing parameter was used as the foundation of the elastic-plastic stress intensity factor. Experimental results showed that uniaxial tension loading led to two main stages of cyclic fracture of surface flaws, while bending led to a uniform process of fatigue fracture with only one stage. A significant reduction of the crack growth rate was observed in the direction of the deepest point of the crack front with respect to the crack front intersection with the free surface of the tested specimens as a function of loading conditions. A significant influence of material properties and loading type on crack growth rate characteristics was established in the present study.

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References