A method for reducing the fatigue crack growth rate

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Abstract. On the basis of numerical modeling by the finite element method, a study was made of the influence of the field of local residual stresses, created by the action of a spherical indenter on the crack tip, on the fatigue crack growth rate. The problems of the fatigue growth of a flat semi-elliptic crack in a plate as well as a crack in a standard CT specimen are considered.

1. Introduction

Local indentation as a way for reducing the crack growth rate was considered in a variety of works over the recent years [1, 2], the results of which allow for the conclusion about the promising outlook on the practical application of this method for durability enhancement and service life extension of structural elements. The results of the research on the influence of local field of residual stresses created by means of depressing a spherical indenter onto the crack tip on the rate of its fatigue growth are presented in this paper.

The numerical modeling of the process of crack propagation is an indispensable stage of research, as a criterion of assessing the prospective viability of the practical use of this method for analyzing service life of structural elements with allowance for their actual loading. At that the consideration must be given to the influence of residual stress field within crack ingress to surface when these stresses are created by way of static or dynamic indentation. It is quite evident that the numerical modeling is an optimal way of estimating the general possibility of the practical use of this methodology for practical problem under consideration as well as of determining the optimal parameters of indentation (choice of indenter dimensions and material as well as value of the pressure on the indenter).

Below the results of numerical modeling of crack propagation processes are presented for two routine tasks:

- semi-elliptic crack in thick plate (semispace);
- crack in CT specimen for crack resistance test.

The calculations including the determination of residual stress fields appearing under indentation of researchable object as well as the subsequent process of crack fatigue growth were performed with the use of ANSYS software. The problem solver of this software ANSYS Explicit STR, fully integrated into the Workbench unified work environment, allows calculations of tasks for non-stationary and non-linear statics and dynamics in the Workbench Mechanical calculation module by explicit methods.
The Paris equation was used for numerical modeling the process of crack propagation under cyclic loading:

\[
\frac{dl}{dN} = C (\Delta K)^m
\]

with \( l \) is crack length; \( N \) is number of cycles; \( \Delta K \) is stress intensity factor range; \( C, m \) are constants of the material.

2. Plate with semi-elliptic crack

The first of the considered tasks is a plate with an edge semi-elliptic crack (Figure 1) \((a = kb; \ h = 6b; L = 30b; B = 50b; \ b = 2 \text{ mm})\). Plate material is AL 7075-T6. Its stress-deformation diagram can be treated as bilinear one. Parameters of the Paris equation are given in [3]. Cyclic load \( \pm \sigma_z \) is applied to the flat ends of the plate \( z = \pm L/2 \).

![Figure 1](image_url)

It should be pointed out that due to the particularities of the software package used, for instance the SMART Crack Growth module in the Fracture section which allows performing of the calculation of crack growth, the one and the other free surfaces of the crack (constructed with the help of Semi-Elliptical Crack built-in function) must be realized in a finite element model. Consequently, there is no possibility of fully using the task symmetry with constructing as little as a fourth of the zone under consideration. The tetrahedral finite element mesh was used for the calculation of fatigue crack growth. Taking into consideration the necessity of calculating the residual strains at the indentation zone (the zone where the crack crops out to free surface \( x = 0 \)) the finite element mesh had a local additional accumulation; the total amount of nodes was 128129.

The results of calculating the fatigue crack growth with initial sizes \( a = b = 2 \text{ mm} \) under cyclic load \( \sigma_z^{\text{max}} = \pm 50 \text{ MPa} \) for \( 0 \leq N \leq 1.8 \times 10^3 \) cycles are presented in the Figure 2. The stress intensity factor was determined by means of a \( J \)-integral.

At the second stage, the calculation of fatigue crack growth was performed for the case when a local field of residual stresses appears in the zones of crack ingress to the surface, obtained by means of indentation.

The small balls with the diameter of 5 mm made of structural steel were considered as indenters. The case was considered when the point of the first contact between the indenter and the plate is the point of crack ingress to surface \((0, a, 0 \text{ at Figure 1 (a)})\). It was accepted that the friction between surfaces of indenter and plate is absent. The value of static load \( P \) on indenter is varied from 200 N to
The displacement was $u^{\text{max}} = 60 \, \mu\text{m}$ and the maximal residual displacement was $u^{\text{res}}_{\text{max}} = 45 \, \mu\text{m}$ at the maximal value of load $P = 860 \, \text{N}$.

Inasmuch the calculation of fatigue crack growth (and, appropriately, the SMART Crack Growth procedure used for calculations) is applied only for linear elastic materials, it was accepted that the hardening is absent (which leads to somewhat greater stresses).

The results of calculations in the absence and in the presence of indentation are presented in Figure 2. It can be seen that the indentation can lead to a significant (in the considered example more than 50%) decrease in the crack growth rate. This applies not only to the indentation points that come to the surface, but also to the point $(b,0)$ farthest from the surface (Figure 3). Thus, indentation of the surface in the crack zone can help to reduce the crack growth rate in the depth of the part and, therefore, increase its lifetime.

![Stress intensity factor along crack front S](image1.png)

**Figure 2.** Stress intensity factor along crack front $S$

![Crack increment](image2.png)

**Figure 3.** Crack increment: $\square$ - at the point of indentation $(0, \pm \alpha)$; $\Delta$ – at deepest point of the crack front.
3. The CT specimen
The scheme of the CT specimen and its finite element mesh are presented in the Figure 4. With the purpose of increasing the zone of indentation influence on the rate of fatigue crack growth the relatively moderate thickness of specimen was adopted at \( h = 2 \) mm. The material of the specimen (7075-T6 aluminum alloy), the geometric and mechanical parameters of indenter are the same as in previous task.

![Scheme of specimen (a) and finite element mesh (b).](image)

Figure 4. Scheme of specimen (a) and finite element mesh (b).

The dependence \( l = l(N) \) obtained for the crack, on tip of which the indentation with forcing \( P = 100 \) N was performed, are presented in Figure 5. The indentation leads to the appearance of a residual stress field for which maximal value of residual displacement is \( u_{\text{res}}^{\text{max}} = 8 \) \( \mu \)m.

![Crack increment \( l = l(N) \).](image)

Figure 5. Crack increment \( l = l(N) \).

The symmetric cycle \( F^{\text{max}} = \pm 100 \) MPa was adopted to estimate fatigue crack propagation. The results of these calculations show that even under extremely small values of residual displacements the indentation on crack tip leads to the decrease of crack growth rate by more than three times on the basis of \( N = 2.5 \times 10^5 \) cycles. This allows us to conclude that the presented methodology is promising for extending the lifetime of thin-walled structural elements with through cracks.
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