THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI.
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N^0. 1 – 2007, ISSN 1453 – 083X

EXPERIMENTAL AND THEORETICAL INVESTIGATIONS ON MODE I CRACK PROPAGATION IN NOTCHES UNDER CYCLIC LOADING

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ABSTRACT

Research works regarding crack opening stresses covering various types of Mode I cracks initiated and growing in notches under cyclic loading are shown. A large number of parameters influence the crack opening behavior, i.e. material, crack length, notch geometry, and load amplitude. The experimental results indicate uniform relationships cracks in notches and build the basis for developing improved formulae and algorithms to describe Mode I crack opening behavior. Theoretical calculations of crack opening stresses based on Newman's equations have been found out to be in good agreement with corresponding experimental data determined from thin, notched specimens subjected to fatigue loading with constant amplitudes.

KEYWORDS: Fatigue, notches, crack opening stresses, fracture mechanics

1. Introduction

Classical fatigue analyses discriminate between the phase of technical crack initiation, i.e. the lifetime till to the initiation of crack lengths of about 1mm, and the phase of crack propagation. The phase of technical crack initiation, however, is itself dominated by the growth of short fatigue cracks.

Since the work of Elber [3], it is confirmed that crack opening and closure are significant parameters controlling the growth behavior of cracks. Nowadays, various analytical models have been developed to calculate opening stresses for cracks growing in unnotched and notched material specimens [1,2], [4-7], [10, 12], [15]. A first discussion and assessment of the accuracy of the most favoured relationships to describe crack opening stresses in notches has been carried out in [8]. Though the experimental database used was not sufficiently large, from the statistical point of view, the assessment revealed and quantified certain prediction inaccuracies of the analytical formulae. The present paper deals with experimental and theoretical results regarding the opening and closure behavior of cracks growing in non-uniformly stressed fields of notched specimens. For this, experimental crack opening stress data determined from two specimen types with different notch geometries have been taken into account. The specimens were made of two materials, a fine-grained construction steel and an aluminum alloy. They were subjected to fatigue loading with constant amplitudes. In addition, theoretical results determined with Newman's crack opening stress equations [7] for un-notched specimens combined with the description of notch stress distributions according to the Theory of Elasticity are compared to the experimental ones.

2. Specimen geometry and load configuration

Two specimen types providing two different notch shapes and made of two materials have been considered in the present investigation. Figure 1 shows the geometry and the load configuration of the specimens used for the investigation.

The plates made of ductile steel FeE460 provide a central hole with a radius of ρ=12mm. The corresponding notch stress concentration factor amounts to K_t=2.5. The plates made of steel Al5083 provide a central, quasi-elliptical notch with a radius of ρ=4mm yielding a notch stress concentration factor of K_t=3.4. The notch surfaces were mechanically polished to avoid roughness-influencing effects on the crack initiation.

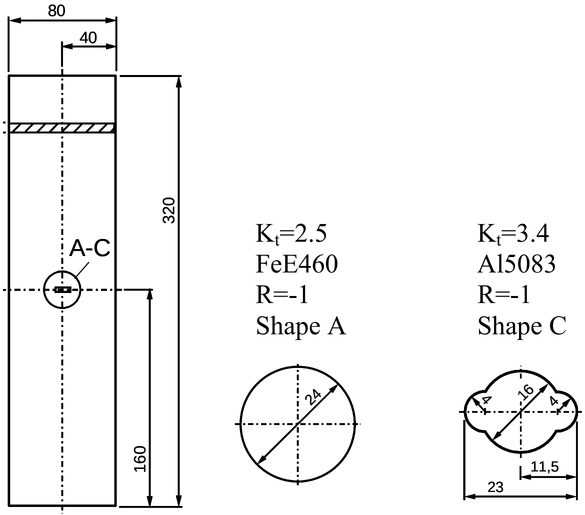

Fig. 1. *Specimen's geometry and load configuration, dimensions in [mm].*

The specimens were subjected to uniaxial, fully reversed cyclic loading (load ratio R=-1). The cracks were initiated as surface cracks at the very notch root of the specimens. They turned into corner and later into through-thickness cracks during the loading sequence.

Figure 2 illustrates the various crack types schematically. "2c" (surface cracks) or "c" (corner cracks) corresponds to the length of the crack lip at the very notch root surface, while "a" stands for the length of the crack lip at the specimen's face side.

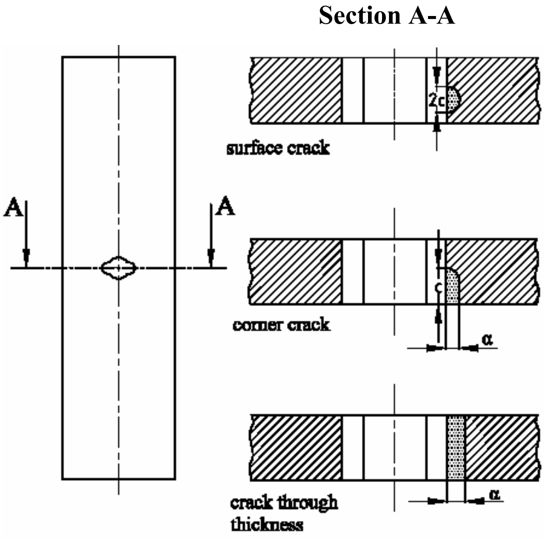

Fig. 2. *Definition of the various crack types.*

3. Crack opening behaviour

3.1. Measurement technique

Crack initiation can reliably be detected optically at lengths of about 0.2mm using a microscope. The measurement procedure suggested in [15, 9] was carried out to determine crack opening stresses. Figure 3 illustrates the measurement procedure.

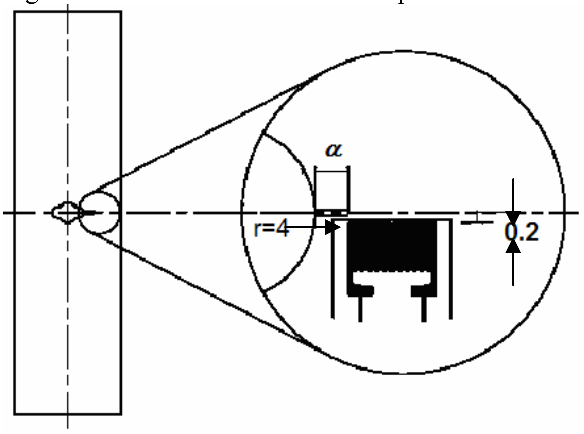

Fig. 3. *Measurement technique for crack opening and closure levels.*

Small strain gages with lengths of 0.6mm to 3mm were applied very close to the crack lips. The distance between the crack path and the grating of the strain gage did not exceed 0.2mm. The strain gage on the specimen surface is mounted so that the beginning of its grating is positioned directly under the crack tip.

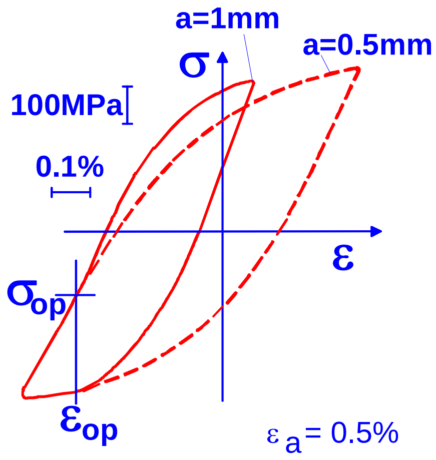

Fig. 4. *Stress-strain (σ-ε) paths measured under cyclic loading by means of strain gages.*

To illustrate the determination of crack opening stresses and strains, fig. 4 shows exemplary stress-strain paths measured during cyclic loading at crack lengths of ≈0.5mm and 1mm at a cracked smooth specimen made of FeE460 subjected to a fully-reversed total strain amplitude ε_a=0.5% [14].

When the crack is closed, its surface is able to carry stresses. Specific stress-strain behaviour is settled that obeys the Masing behaviour [5]. When the crack opens, the stresses get diverted around the crack tip, so that the local stiffness in front of the crack tip changes significantly. The change of the local stiffness reveals the crack opening point in the stress-strain diagram. The crack opening point is defined as the value, where the last contact of the crack surfaces at the crack tip vanishes. This definition is identical with the one of Newman [7], McClung and Sehitoglu [6], Vormwald [15] and Taylor [13].

It is essential that crack opening and closure occurs at the same strain level. Further experimental evidence for this behaviour is given in [9].

3.2 Crack opening stress results

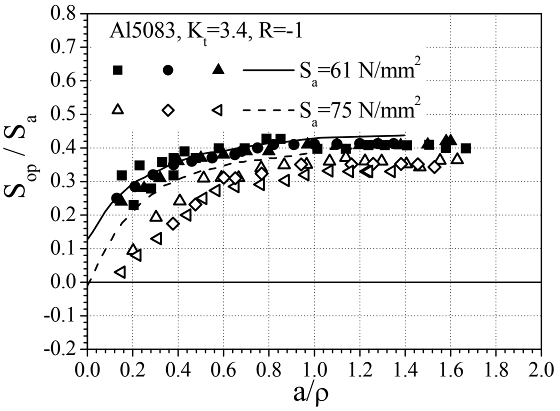

Fig. 5. *Calculated and measured crack opening nominal stresses in the notch area of thin plates made of Al5083.*

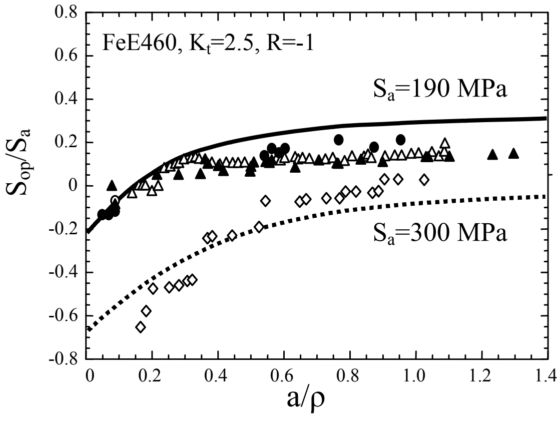

Fig. 6. *Calculated and measured crack opening nominal stresses in the notch area of thin plates made of FeE460.*

In fig. 5 and 6 measured nominal opening stress values S_{op} normalized by the applied nominal stress amplitude S_a are plotted versus the crack length a normalized by the notch radius ρ using marker symbols for both material/notch configurations, respectively.

The symbols in fig. 5 and 6 represent test results measured during cyclic loading at the various nominal stress amplitudes. Thereby, the results of two nominal stress amplitudes are shown for each material and notch case investigated. These figures contain results measured at the face side of the specimens, i.e. from corner and through-thickness cracks.

In the case of the quasi-elliptical, sharp notch (specimens made of Al5083), the black symbols stand for test results at S_a=61 MPa. The hollow symbols represent test results at S_a=75 MPa.

In the case of the mild notch (specimens made of FeE460), the hollow rhombs correspond to S_a=300 MPa, while the black symbols and the hollow triangles stand for the results at S_a=160 MPa .

In each case, the low S_a-level is slightly higher than the endurance limit of the corresponding specimen, where the notch strains are mainly elastic. The high S_a-level yields significant plastic strains at the notch leading to fatigue lives within the Low Cycle Fatigue regime of the corresponding specimen.

The experimental results derived from both specimen types show a clear tendency of decreasing S_{op}/S_a-values with increasing nominal stress amplitudes for particular crack lengths. This is due to the increase of the plastic deformation with increasing S_a.

In addition, the test results confirm that there is no influence of the crack type (corner, through-thickness) on the measured crack opening stresses.

Furthermore, for a particular nominal stress amplitude S_a, the S_{op}/S_a-values increase as the ratio a/ρ increases. This is due to the descending distribution of the local stress and, therewith, the decreasing plastic deformation with increasing distance from the notch root. Thereby, the crack front grows out of the highly stressed notch root into material areas with mainly elastic deformations. No significant changes of the S_{op}/S_a-values can be determined as the crack tip grows completely out of the notch area. At a/ρ≈1 a quasi stabilisation of the S_{op}/S_a-values can be observed. For higher values of a/ρ, the mechanisms controlling the crack propagation behaviour follow well-known propagation laws of long through-thickness cracks in materials under uniform stress distribution.

The solid and dashed lines in fig. 5 and 6 represent calculation results corresponding to the investigated nominal stress amplitudes for both specimens. These curves have been determined combining the Theory of Elasticity for the calculation of the elastic stress distribution along the notch section, Seeger's and Beste's [11] approximation formulae for the calculation of elastic-plastic stresses, and the well-known crack opening stress equations of Newman [7] as slightly modified by Savaidis et al. [8] to account for the notch influencing effect.

In general, the calculation results are in satisfactory agreement with the measured ones for both notch geometries and all load levels, especially for the high ones yielding significant plastic deformations at the notch areas. This confirms the accuracy of the modified Newman's equations [7, 8] for predicting crack opening behavior in notched components. More detailed discussion of the calculation procedure and its verification is presented in [8].

4. Conclusions

The present paper deals with experimental and theoretical results regarding the opening and closure behavior of cracks growing in non-uniformly stressed fields of notched specimens. Two notch geometries and two materials have been considered in this investigation.

The test results show a similar crack opening behaviour between corner and through-thickness cracks in both notch types.

S_{op}/S_a increases with increasing crack length at a constant nominal stress amplitude S_a. It stabilizes when the crack propagates out of the notch area, i.e. at $a/\rho \geq 1$.

S_{op}/S_a decreases with increasing nominal stress amplitude S_a for a certain crack length a.

Newman's crack opening equations developed for un-notched specimens combined with the Theory of Elasticity and Seeger's and Beste's elastic-plastic notch approximation formulae in notches have been found out to evaluate crack opening load values successfully for both notch cases and all load values investigated.

Acknowledgement

The research activities have been co-financed by E.U.-European Social Fund (75%) and the Greek Ministry of Development-GSRT (25%).

References

[1]. **DeKoning A.U.**, 1981, *A simple crack closure model for prediction of fatigue crack growth rates under variable loading*, Fracture Mechanics 13th Symposium, ASTM STP 743, pp. 63-85.

[2]. **DuQuesnay D.L., Topper T.H., Yu M.T., Pompetzki, M.A.**, 1992, *The effective stress range as mean stress parameter,* Int. J. Fatigue, 1, pp. 45-50.

[3]. **Elber W.**, 1971, *The significance of fatigue crack closure*, Damage Tolerance in Aircraft Structures, ASTM STP 486, pp. 230-242.

[4]. **Ibrahim F.K.**, 1989, *The effect of stress ratio, compressive peak stress and maximum stress level on fatigue behaviour of 2024-T3 aluminium alloy,* Fatigue & Fracture Engng Mat. Struct., 12, pp. 9-18.

[5]. **Masing G.**, 1926, *Eigenspannungen und Verfestigung beim Messing*. Proc. 2nd Int. Congress Appl. Mech., pp. 332-335.

[6]. **McClung R.C., Sehitoglu, H.**, 1992, *Closure and growth of fatigue cracks at notches*, J. Engng Mat. Techn., 114, pp. 1-7.

[7]. **NEWMAN jr J.C**., 1984, *A crack opening stress equation for fatigue crack growth,* Int. J. Fatigue, 24, pp. R131-R135.

[8]. **Savaidis G., Dankert M., Seeger T.**, 1995, *An analytical procedure for predicting opening loads of cracks at notches,* Fatigue & Fracture Engng Mat. Struct., 18, pp. 425-442.

[9]. **Savaidis G., Seeger T.**, 1994, *An experimental study on the opening and closure behaviour of fatigue surface, corner and through-thickness cracks at notches,* Fatigue & Fracture Engng Mat. Struct., 17, pp. 1343-1356.

[10]. **Schivje J.**, 1981, *Some formulae for the opening stress level.* Eng. Fract. Mech., 14, pp. 461-465.

[11]. **Seeger T., Beste A.**, 1977, *Zur Weiterentwicklung von Näherungsformeln für die Berechnung von Kerbspannungen im elastisch-plastischen Bereich*. Kerben und Bruch, VDI-Fortschritt Berichte series 18, No. 2.

[12]. **Sun W.**, 1991, *Finite element simulations of fatigue crack closure.* Report 159, University of Illinois at Urbana-Champaign.

[13]. **Taylor D.**, 1992, *The definition and measurement of crack closure,* Eng. Fract. Mech., 16, pp 109-115.

[14]. **Vormwald M., Seeger T.**, 1991, *The consequences of short crack closure on fatigue crack growth under variable amplitude loading.* Fatigue & Fracture Engng Mat. Struct., 14, pp. 205-225.

[15]. **Vormwald M., Hertel O., Savaidis G.**, 2007, Modelling *fatigue crack growth in the elastic-plastic regime*, Bruchmechanik und Bauteilsicherheit, DVM, Dresden.