# Description of Fatigue Crack Growth Rate Notched Members under Tension and Bending Using the ΔJ - Integral Range

**G. Gasiak, D. Rozumek and R. Pawliczek**[1]

[1] Technical University of Opole, S.Mikołajczyka str.5, 45-271Opole, Poland

***ABSTRACT:*** *The paper contains the results of experimental tests of the fatigue crack behaviour examined for 10HNAP steel under tension and bending in the conditions of different stress ratios R. For the tests under tension the plane specimens with central, symmetric stress concentrator in the from of the slots with side notches were used, while for bending plane specimens with external unilateral V-notch as stress concentrator were tested. While testing a constant stress ratio R was kept, and accounted for -0.5, -0.3, 0, 0.5. The results of the experimental tests have been described by a nonlinear formula based on ΔJ-integral range. The change of the stress ratio R from the value of - 0.5 and - 0.3, 0 to 0.5 caused the fatigue crack growth rate in ΔJ-integral range for tension:* $4.5\cdot10^{-3}$ *MPa·m* ≤ *ΔJ* ≤ $1.78\cdot10^{-1}$ *MPa·m, and for bending:* $9\cdot10^{-3}$ *MPa·m* ≤ *ΔJ* ≤ $1.78\cdot10^{-1}$ *MPa·m. The proposed formula for the description of fatigue crack growth rate, including ΔJ-integral range, satisfactorily describes the results obtained experimentally for 10HNAP steel.*

## NOMENCLATURE:

| | |
|---|---|
| a | = length of crack |
| da/dN | = fatigue crack growth rate |
| N | = fatigue life cycles |
| ΔJ | = J-integral range |
| R | = stress ratio |
| $P_a$ | = the amplitude load |
| $M_a$ | = the amplitude moment |
| $P_m$ | = mean load |
| $M_m$ | = mean moment |
| $B_2$ | = coefficient in the authors` model |
| $n_2$ | = exponent in the authors` model |
| $J_{Ic}$ | = critical value of the integral |
| $K_t$ | = stress concentration factor |

## INTRODUCTION

Determination of the fatigue crack growth rate under different loads belongs to the basic problems of fracture mechanics. The authors decided to examine the fatigue crack growth rate in 10HNAP steel under cyclic amplitude bending for one-side restrained specimens and then compare the results with the results obtained for the specimens subjected to cyclic tension. Having the fatigue crack growth rate [1-3] we are able to estimate life of the material used for a specimen or a structure. The fatigue crack growth rate depends on many factors, for example a type of the material [4], the mean stress [5], cycle asymmetry [6,7], load spectrum [8], geometry of the specimen [9], microstructure or a type of the material treatment. The mentioned factors lead to formulation of various criteria, for example stress, strain or energy criteria describing the fatigue crack growth rate. Since the material tested is elastic-plastic, the energy criterion based on the $\Delta J$-integral range was applied for analysis of the experimental data. This criterion, formulated by J.R. Rice in 1968, concerns the crack front zone and is based on the J-integral. The cracking rate based on this criterion can be described by the Dowling-Begley relation [10] or the relation proposed by the authors of this paper [7]. The Dowling-Begley equation concerns the II linear range of the crack growth kinetics curve S and our equation concerns the II and III ranges of the fatigue crack growth kinetics on the graph $da/dN = f(\Delta J)$.

The aim of this paper is to determine influence of the stress ratio on the fatigue crack rate under cyclic tension and bending as well as a description of the process with use of the $\Delta J$-integral range.

## EXPERIMENTS

Plane specimens, made of the low-alloy corrosion-resistant steel 10HNAP according to the Polish Standard PN-83/H-94017, were tested. The specimens were cut out from the sheets of 10 mm thick along the rolling direction. The specimen dimensions, length l, height b and thickness g, were 250 x 35 x 8 mm for tension and 120 x 20 x 4 mm for bending. In the centre the specimens subjected to tension had round slots, 4 mm in diameter, with lateral incisions 1mm in length ($2a_0 = 6$ mm) and the rounding radius $\rho = 0.125$ mm. The specimens for bending had the external unilateral notch, 5 mm in depth, with the radius $\rho = 0.5$ mm. The notches in the specimens subjected to tension were made by the electrospark method and in the specimens subjected to bending they were made with the milling cutter. The specimen surfaces were polished after grinding. The mechanical properties of the specimens are: Yield stress $\sigma_y$ = 418 MPa, Ultimate stress $\sigma_u$ = 566 MPa, Young`s modulus E = 215 GPa, Poisson`s ratio $\nu$ = 0.29. Chemical composition of the steel (%) is: 0.14 C, 0.88 Mn, 0.31 Si, 0.066 P, 0.27 S, 0.73 Cr, 0.30 Ni, 0.345 Cu. The critical value of the J-integral for 10HNAP steel, according to [11], is $J_{Ic}$ = 0.178 MPa·m. Some parameters of the cyclic strain curve for 10HNAP steel [2] are: the cyclic strength coefficient K' = 832 MPa, the cyclic strain hardening exponent n' = 0.133, the fatigue strength coefficient $\sigma'_f$ = 746 MPa, the fatigue strength exponent b = - 0.08, the plastic fatigue strain coefficient $\varepsilon'_f$ = 0.442, the plastic fatigue strain exponent c = - 0.601. The specimens subjected to cyclic tension were loaded with the constant amplitude $P_a$ = 15 kN corresponding to the stress amplitude to the crack initiation $\sigma_a$ = 65 MPa; the specimens subjected to cyclic bending were loaded with the constant amplitude $M_a$ = 18.91 N·m, corresponding to the stress amplitude to the crack initiation $\sigma_a$ = 126 MPa. The range of the stress ratio R was changed from - 0.5 to 0.5. The theoretical stress concentration factor for tension was $K_t$ = 8.87 and for bending $K_t$ = 3.27, and it was determined according to the model [12]. Tension was tested on the hydraulic pulsator [13] under the loading frequency of 13 Hz. The tests under bending were done on the fatigue test stand MZGS-100 [5, 14] under the loading frequency of 28.8 Hz. The fatigue crack increments were measured by using the digital micrometer included into the portable microscope with an accuracy of 0.01 mm. A number of load cycles $N_j$ was registered. The J-integral was calculated by applying the finite element method and the FRANC2D program. A value of the J-integral was determined taking into account a nonlinear model of the material.

## THE TEST RESULTS AND THEIR ANALYSIS

The paper contains the experimental data showing the phenomena proceeding in the 10HNAP steel while the fatigue cracking under cyclic tension and bending for different stress ratios R. The tests were conducted under the controlled load from the threshold value to failure of the specimen. The measurement results were presented as the graphs $a_j = f(N_j)$ where $a_j$ is the actual crack length measured from the concentrator tip after $N_j$ cycles. For example, Figure 1 shows a course of crack advance against the number of cycles a = f(N) for the tension specimens loaded at three

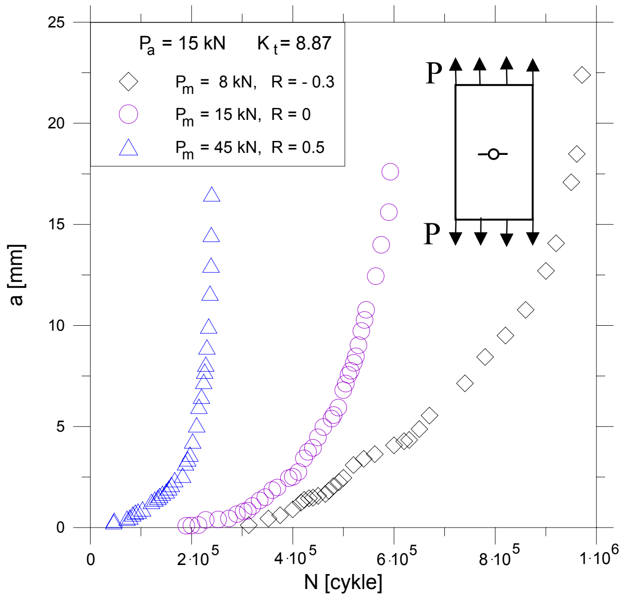


**Figure 1:** Crack growth length a versus number of cycles N detected in the specimens subjected to tension.

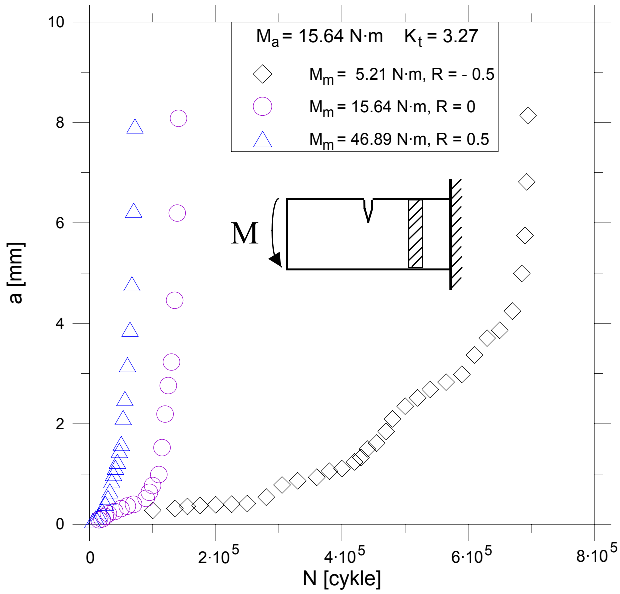


**Figure 2:** Crack growth length a versus number of cycles N detected in the specimens subjected to bending.

different values of the mean force $P_m$ = (8, 15, 45) kN and the constant amplitude of load $P_a$ = 15 kN. Figure 2 shows the relation a = f(N) for the specimens subjected to bending and loaded by three mean moments $M_m$ = (5.21, 15.64, 46.89) N·m and the constant amplitude of moment $M_a$ = 15.64 N·m. From courses of the relation a = f(N) in Figures 1 and 2 it appears that as the stress ratio increases, the fatigue life of the specimens decreases. Graphs of the fatigue cracking da/dN = f(ΔJ) for three values of the stress ratio for tension and bending are shown in Figures 3 and 4. It can be seen that the fatigue crack growth rate under tension for R = 0.5 (graph 3) is two times lower than the fatigue crack growth rate under bending; for R = 0 the fatigue crack growth rates are comparable. Moreover, in Figure 3, under tension (graphs 1, 2 and 3) as the stress ratio changes from - 0.3 to 0.5, the fatigue crack growth rate increases in the range $4.5 \cdot 10^{-3}$ MPa·m ≤ ΔJ ≤ $1.78 \cdot 10^{-1}$ MPa·m. Similarly, under bending (Fig. 4, graphs 1, 2, 3) for a change of the stress ratio from -0.5 to 0.5 we can observe increase of the fatigue crack growth rate in the range $9 \cdot 10^{-3}$ MPa·m ≤ ΔJ ≤ $1.78 \cdot 10^{-1}$ MPa·m. From Figure 4 it also appears that for R = 0.5 there is a small II range of the crack growth kinetics according to curve S (the curve is very flattened). It can be explained by large plastic strains around the slot top. In the case of tension (Fig. 3) such effect does not occur. The sets of measuring points in Figures 3 and 4 were described by a relation proposed by the authors (Rozumek and Gasiak)

$$\frac{da}{dN} = \frac{B_2 (\Delta J)^{n_2}}{(1 - R)^m J_{Ic} - \Delta J} \tag{1}$$

where $\Delta J = J_{max} - J_{min}$ is the range of the J integral.

Equation (1) is a result of modification of the Forman model applied in linear crack mechanics for description of the crack growth kinetics. The parameters ΔK and $\Delta K_{Ic}$ were replaced by the ΔJ-integral range and $J_{Ic}$, instead of the expression containing the stress ratio $(1 - R)\ K_{Ic}$ we introduced the relation $(1 - R)^2\ J_{Ic}$ resulting from analysis of equations of linear crack mechanics, assuming that $R = K_{min}/K_{max}$ and R = const. and knowing that $\Delta K = K_{max} - K_{min}$ and $\Delta J = \Delta K^2 / E$. In Equation (1), according to the Paris postulate, $B_2$ and $n_2$ are the material constants and they should be treated approximately in such a way. In practice, however, these constants depend not only on a material but also on some other

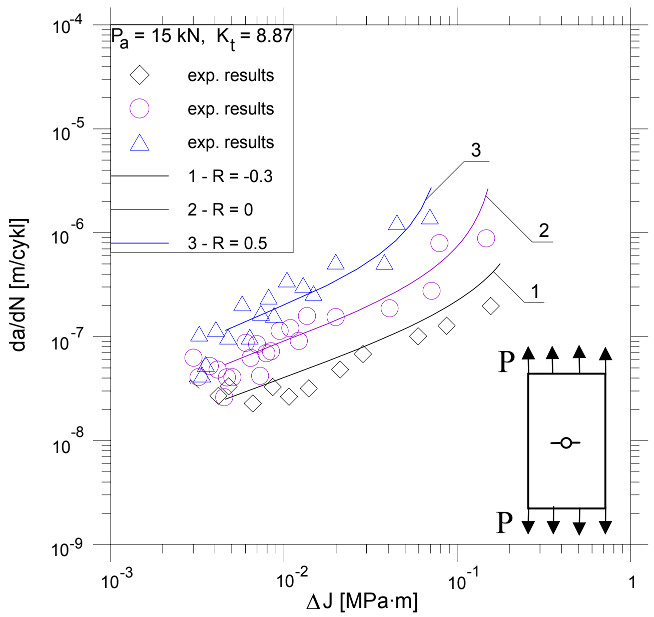


**Figure 3:** Fatigue crack growth rate versus ΔJ-integral range for the specimens subjected to tension at three different stress ratios R.

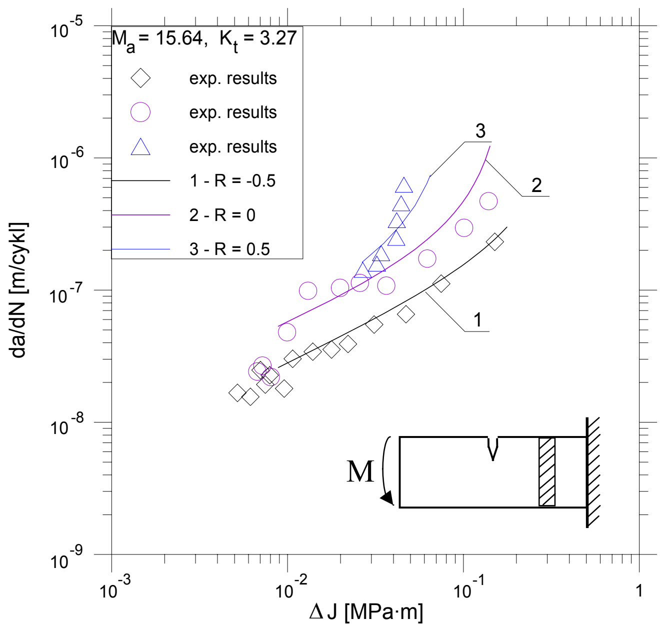


**Figure 4:** Fatigue crack growth rate versus ΔJ-integral range for the specimens subjected to bending at three different stress ratios R.

factors, for example the stress ratio (Figs. 3 and 4). It was found also in [1, 2], in the case of the Paris model. For the presented Equation (1) for 10HNAP steel the material constants are $B_2$ = 3.0 · $10^{-7}$ $\mathrm{m}/(\mathrm{MPa}\cdot\sqrt{\mathrm{m}})^{n_2-1}$ cycle and $n_2$ = 0.63. For the stress ratios R = - 0.3 and 0 (Fig.3) under cyclic tension and the stress ratios R = - 0.5 and 0 (Fig.4) under cyclic bending, a satisfactory agreement between the experimetal data and the data obtained according to the proposed relationship (1) was obtained for m = 2. For the stress ratio R = 0.5 and m = 2 the theoretical and experimental data are different for both cyclic tension and cyclic bending. Thus, a correction of the exponent m was proposed. Namely, its value was matched to the obtained experimental results. After correction it appeared that for cyclic tension and cyclic bending the exponent m should be 1. The maximum relative error of the experimental results for the fatigue crack is 15% under correlation at the significance level $\alpha$ = 0.05: $r_2$ = 0.78 for R = - 0.3, $r_2$ = 0.85 for R = 0 and $r_2$ = 0.90 for R = 0.5. Under cyclic bending the maximum relative error is 17 % under correlation at the significance level $\alpha$ = 0.05: $r_2$ = 0.85 for R = - 0.5, $r_2$ = 0.88 for R = 0 and $r_2$ = 0.89 for R = 0.5, where $r_2$ is a coefficient of correlation. The constant $B_2$ and the exponent $n_2$ included in the presented model were determined by means of the least square method. In Figures 3 and 4 we can observe little scatters of the experimental results resulting from the method of discontinuous measurements (an optical method with use of a microscope).

## CONCLUSIONS

The analysis of the test results leads to the following conclusions:

1. Change of the stress ratio from - 0.5 to 0.5 under tension and bending causes increase of the fatigue propagation rate.
2. A little greater increase of the fatigue crack rate is observed for bending in comparison to tension.
3. The proposed equation describes the fatigue crack growth rate well.
4. The experimental results are well estimated by the Equation (1) with the power exponent m equals 2 when R = - 0.5, R = - 0.3 and R = 0. For the stress ratio R = 0.5 the exponent m is 1.
5. In the presented relation (1) the parameters $B_2$ and $n_2$ depend not only on the material, but on the other factors (for example the stress ratio) as well.

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