Influence of the slot inclination angle on crack path under cyclic tension

Dariusz Rozumek

Opole University of Technology, ul. Mikołajczyka 5, 45-271 Opole, Poland
e-mail: drozumek@po.opole.pl

ABSTRACT. *The paper summarizes the results of an experimental investigation of the crack path growth in plate specimens made of FeP04 steel under tension. For the tests under tension the plane specimens with central, symmetric stress concentrator in the from of the slots with side notches were used. The results of the experimental tests have been described by a formula based on J-integral.*

INTRODUCTION

During crack growth, we can observe three crack modes or their combinations coming from tensile (mode I), in-plane shear (mode II) and/or anti-plane shear (mode III) loading [1]. In practice, the fatigue crack growth is usually realized according to mode I [2], or the mixed mode I + II [3]. Therefore, under mixed mode loading conditions, not only the fatigue crack growth rate is of importance, but also the crack growth direction. One of the first criteria concerning the mode I + II was proposed by the authors of [4]. This criterion states that crack propagation starts from the crack tip along the radial direction and fracture starts when the maximum tangential stress reaches a critical stress equal to fracture stress in uniaxial tension. The J-criterion for mixed mode I+II was proposed by authors paper [5]. This criterion states that a crack extends along the direction of vector **J** and fracture occurs when this vector **J** reaches a critical value. Next J-criterion was used in paper [6] for modes I and II. For mode I load dominating cases, this criterion were satisfactory, but for mode II load dominating cases obtained deviate significantly from experimental data.

The aim of this paper is the fatigue crack growth path in FePO4 steel subjected to tension, with a slot at different angles, and describe its rate with use of the J-integral.

EXPERIMENTS

The specimens were characterised by a central notch having a length 2d = 10 mm and a notch tip radius $\rho = 0.2$ mm (Fig. 1). The notches were prepared by means of a cutter and their surfaces were polished after grinding. Some mechanical properties of the tested steel are given in Table 1. The tests were performed under different slot inclinations (0, 45°, 60°).

Table 1. Mechanical properties of the low carbon, deep-drawing, FeP04 steel

Yield stress σ_{YS} (MPa)	Ultimate stress σ_U (MPa)	Elastic modulus E (GPa)	Poisson`s ratio ν
210	330	191	0.30

The tests were carried out on two different testing systems, namely a Schenck PSA100 servo-hydraulic fatigue test machine available at the Department of Mechanical Engineering of the Padova University and MTS 809 servo-hydraulic axial test machine available at the Department of Management and Engineering in Vicenza. Both testing systems were equipped with a 100 kN load-cell. The tests were performed under force control with a load amplitude ranging between 6 and 8 kN and under displacement control with a maximum value equal to 0.21 mm. The test frequency ranged from 13 and 15 Hz. In any case the load ratio, R_σ, or the displacement ratio, R_δ was kept equal to 0. Crack initiation and propagation phases were observed on the specimen surface by means of a stereoscope having a magnification factor ranging from 6.5 to 64 times. Fig. 1 shows a sketch of the experimental set-up and of the specimen geometry.

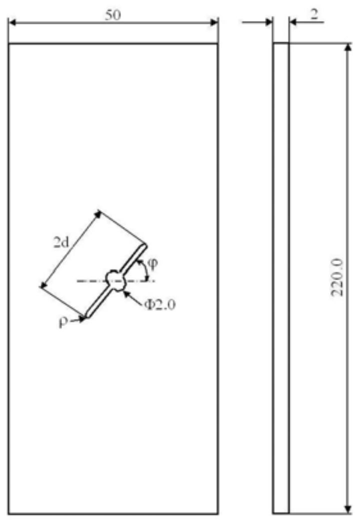


Figure 1. Adopted experimental set-up and specimen geometry

Due to the different notch inclination angle, pure mode I as well as combined mixed mode I+II fatigue tests were performed. Fig. 2 shows as an example the observed crack path occurring under mixed mode I + II loading.

THE TEST RESULTS AND THEIR ANALYSIS

The experimental data were collected in terms of crack lengths *a* versus number of cycles *N* and then were processed in order to derive the crack growth rate da/dN versus ΔJ-integral range. In the case of the mixed mode I+II with φ = 45° and 60°, both under force and displacement control, the specimens were seen to have an analogous behaviour. Fig. 2 shows the path of a crack about 0.4 mm long (mixed mode I+II – see the white arrow) observed by testing a notch characterized by φ = 60° under a load amplitude P_a = 8 kN. By increasing the crack length up to a ≅ 1 mm, a mode I crack path was observed.

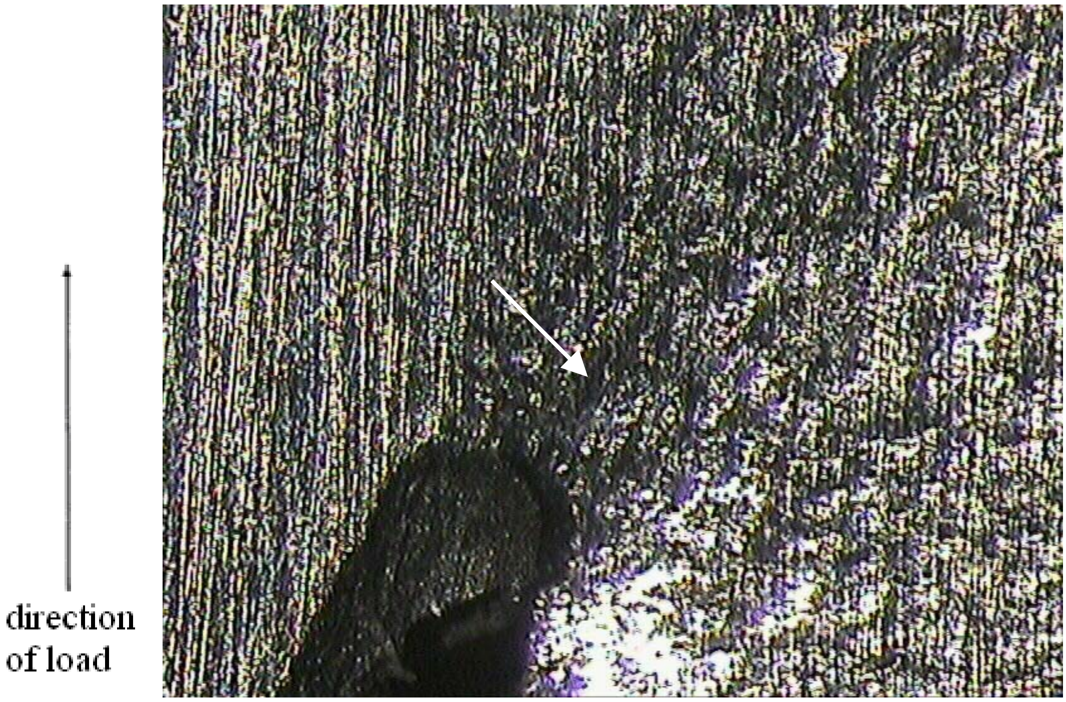
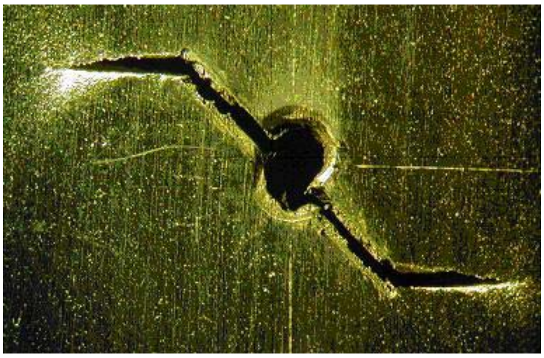


Figure 2. Crack path under mixed mode I+II in FeP04 steel for P_a = 8 kN and φ = 60°

Fig. 3 shows the specimens tested under force control P_a = 8 kN for two slot inclination angles, equal to φ = 45° and 60°, respectively.

Fig. 4 shows the specimens tested under displacement control with a maximum value of 0.21 mm for three different inclination of the slot φ = 0°, 45° and 60°. It can be observed that similarly to Fig. 3, mode I long cracks are formed.

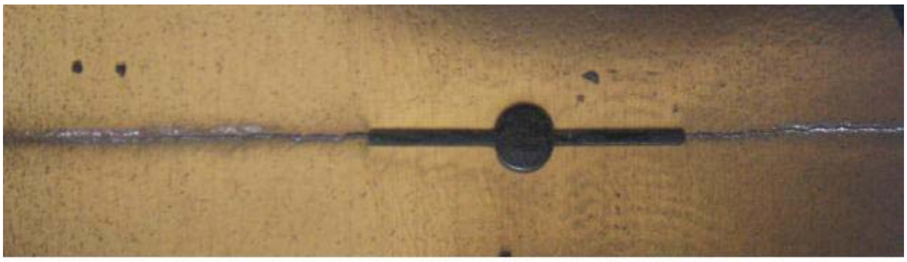


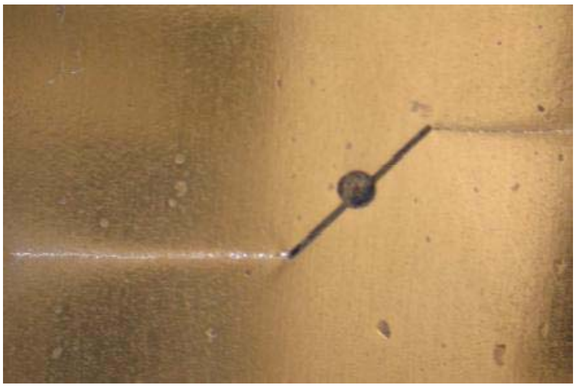
(a)

(b)

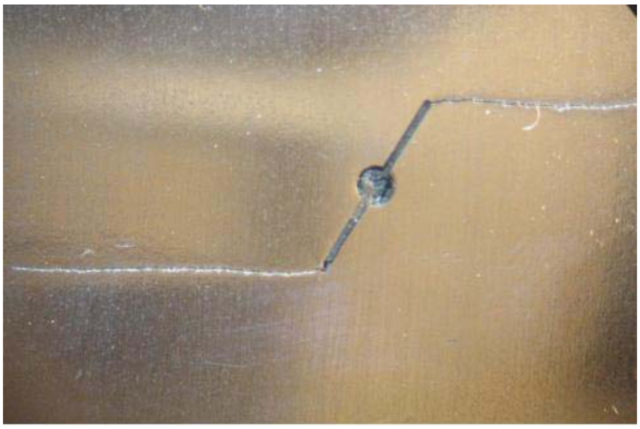
Figure 3. Crack paths under force control $P_a = 8$ kN ($R_\sigma = 0$) and angles: (a) $\varphi = 45°$ and (b) $\varphi = 60°$

(a)





(b)

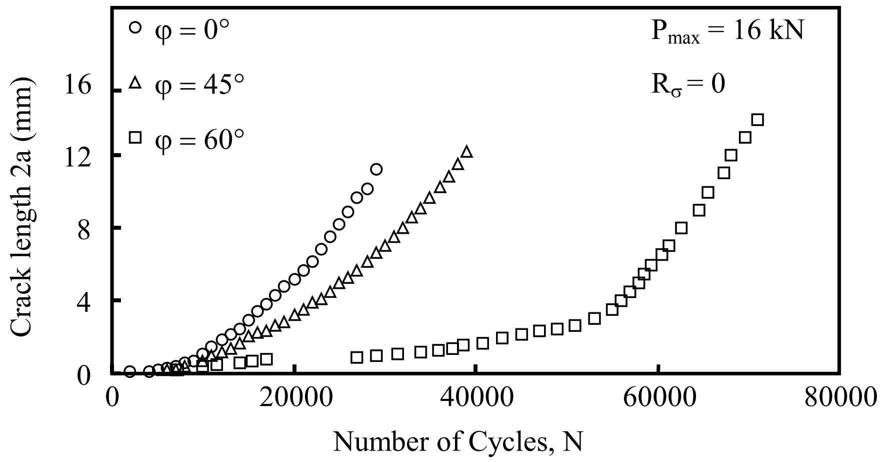


(c)

Figure 4. Crack growth under crack tip opening displacement control $\delta = 0.21$ mm ($R_\delta = 0$) and angles: (a) $\varphi = 0°$, (b) $\varphi = 45°$ and (c) $\varphi = 60°$

From the crack length versus number of cycles curves reported in Fig. 5, it appears that by changing the angle φ from 0° to 60° then fatigue life increases under both force and displacement control. Sometimes two phases were observed in cracks initiation and propagation; the first was characterized by initiation and propagation under a mixed mode regime whilst in the second phase the crack growth took place according to mode I. These two phases could not always be clearly observed and distinguished during the tests. From the test results obtained under force and displacement control it also appears that the specimen life is higher under force control (Fig. 5). This behavior could be due to the compressive part of the loading cycle present under the displacement-controlled cycle at R = 0, which could influence, in particular, the initial, mixed-mode crack initiation and short crack propagation.

(a)



(b)

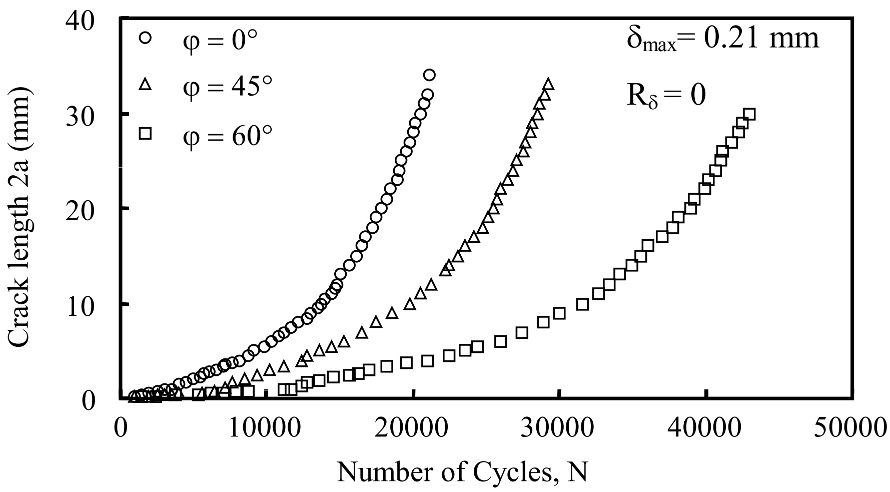


Figure 5. Comparison of experimental test results for φ = 0°, 45° and 60°: (a) force control and (b) displacement control

In Figs. 6 and 7 show fatigue crack growth rate da/dN versus ΔJ integral range for mode I, mode II and mixed mode I+II. In the elastic-plastic range, stresses and strains were calculated by means of the finite element program FRANC2D.

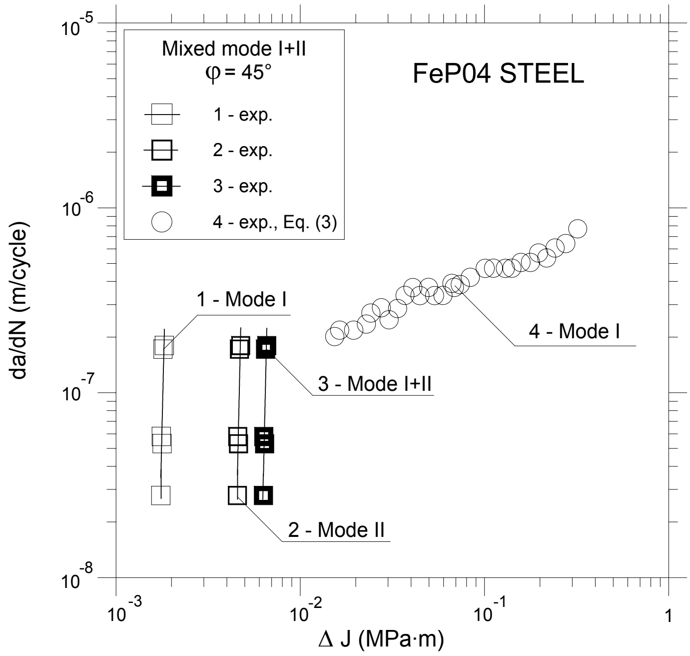


Figure 6. Comparison of experimental results for mixed mode I+II and φ = 45°

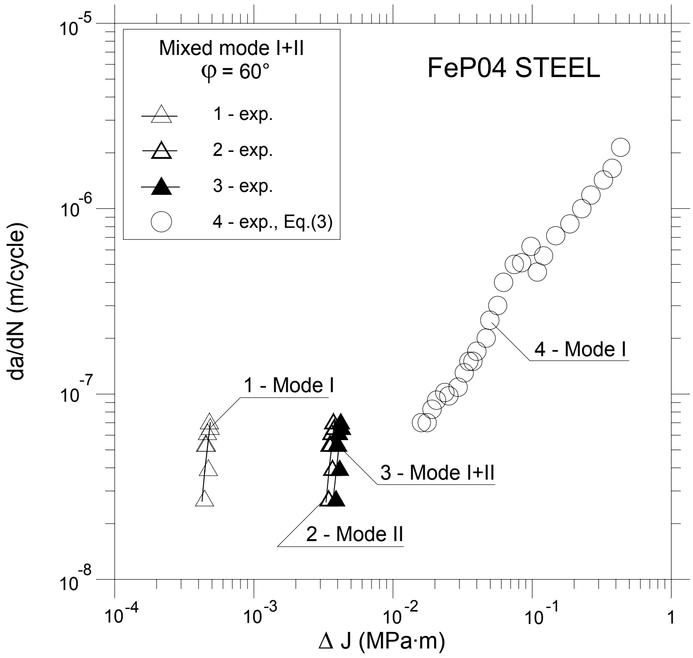


Figure 7. Comparison of experimental results for mixed mode I+II and φ = 60°

From the above figures 6 and 7 it appears that at the first crack stage the crack growth proceeds according to modes I and II. Next, the material is subjected to plastification and the crack growth stops. After a break, the fatigue crack growth rate proceeds only according to mode I for $\varphi = 45°$ and $60°$. The greater the slot inclination angle φ is, the longer time of the crack growth according to mode I + II is. In Figs. 6 and 7, the rate of fatigue crack growth for $\varphi = 60°$ is higher than for $\varphi = 45°$ in the FeP04 steel. Moreover, in the mixed mode I + II, ΔJ for both mode I and mode II is higher for $\varphi = 45°$ than for $\varphi = 60°$. For both considered angles, $\varphi = 45°$ and $60°$, mode II is dominating in the mixed mode I + II.

The ΔJ integral range for mode I and mode II is calculated from

$$\Delta J_I = \Delta\delta_I \, \sigma_{YS}, \tag{1}$$

$$\Delta J_{II} = \Delta\delta_{II} \, \sigma_{YS}, \tag{2}$$

where, from [7] $\Delta\delta_I = \Delta K_I^2 / \sigma_{YS} E$ and $\Delta\delta_{II} = \Delta K_{II}^2 / 2\tau_{YS}\mu = 2.6\left(\Delta K_{II}^2 / \sigma_{YS} E\right)$, E – Young's modulus, ν - Poisson's ratio, w – width, τ_{YS} – shear yield stress, μ - shear modulus, $\Delta J = J_{max} - J_{min}$, $\Delta K_I = Y_I \Delta\sigma \cos^2\varphi \sqrt{\pi(d+a)}$, $\Delta K_{II} = Y_2 \Delta\sigma \sin\varphi \cos\varphi \sqrt{\pi(d+a)}$ - stress intensity factors ranges for mode I and mode II, Y_1 and $Y_2 = 1 - 0.1\left(\frac{2(d+a)}{w}\right) + \left(\frac{2(d+a)}{w}\right)^2$ - correction coefficients for mode I and mode II [8].

ΔJ_I for mode I and plasticity was calculated by using the following relationship [9]

$$\Delta J_I = \frac{\Delta K_I^2}{E} + \pi Y_I^2 \frac{\Delta\sigma\Delta\varepsilon_p}{\sqrt{n'}} a, \tag{3}$$

where a – crack length, n' = 0.22 - cyclic strain hardening exponent, $\Delta\sigma$ - ranges of stress under tension in the notch root, $\Delta\varepsilon_p$ – ranges of plastic strains under tension in the notch root.

The test results for cyclic mixed mode I+II include the error not exceeding 5% at the significance level $\alpha = 0.05$ for the correlation coefficients r = 0.98 to 0.99.

For the controlled crack tip opening displacement, the J-integrals are constant, and their values are: $J_{maxI+II} = 0.0389$ MPa·m.

CONCLUSIONS

The results of fatigue crack growth tests on notched specimens made of FeP04 steel, all tested under tension loading, allow the following conclusions to be drawn:

1. The fatigue crack growth according to the mode I+II, for the slot inclination angles φ = 45° and 60°, was observed only in the initial stage of cracking up to 1 mm.
2. In the mixed mode I + II, the mode II was dominating for both considered slit angles.
3. After the material plastification, a higher crack growth rate was observed for φ = 60°.

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