INFLUENCE OF NOTCH RADIUS ON FATIGUE CRACK PROPAGATION IN BEAM SPECIMENS OF 2017A-T4 ALLOY

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The paper presents experimental tests results of the fatigue crack growth in 2017A-T4 aluminium alloy under bending in specimens with rectangular cross-section. The specimens were weakened by sharp and blunt one-sided notches (for notch root ρ = 0.2; 5; 10 and 22.5 mm). The tests were performed on the fatigue test stand MZGS-100 in the low and high cycle fatigue regime, by imposing a constant value of the nominal load ratio $R = -1$; 0 and a moment amplitude $M_a = 15.84$ N·m. The results of the fatigue tests were then analysed in terms of the parameter ΔK including influence of the notch.

Keywords: *fatigue crack growth, notch, bending, stress intensity factor range.*

The fatigue crack growth rate is directly related to existing stress concentrators in the elements studied [1, 2]. Fatigue crack initiation usually occurs at the notch root. In many cases the shape of the notch influences the fatigue life and fatigue crack growth rate [3, 4]. The paper [5] presents a model for the description of the fatigue crack growth rate including the notch shape and crack length in the specimen. The proposed model describes correctly the fatigue crack growth rates in the specimens and in the actual machine parts of various shapes and sizes. The paper revealed that the model applied enables also the determination of a critical crack length. The authors of the paper [6] proved the influence of the notch and stress ratio on the fatigue life in the scope of crack initiation and propagation for the 7075-T6 aluminium alloy. Two parameters were proposed to specify the maximum local stress by means of which fatigue crack initiation and propagation in the element studied can be determined. In paper [7] a solution of the plane problem of the theory of elasticity for a plane with a semiinfinite rounded V-shaped notch under antisymmetric loading was obtained. On this basis the relations between the stress intensity factor at the vertex of a sharp V-shaped notch, the maximal stresses on the boundary contour or stress gradient at the vertex of the corresponding rounded V-shaped notch, and its rounding-off radius were determined.

The main aim of this paper is characterisation of fatigue crack growth rates in terms of the parameter K taking into account the shape of the notch, by using experimental data from specimens with rectangular cross-section.

Material, properties and test stand. The tested material was aluminum alloy 2017A-T4 (Polish standard PN-EN 573-3: 2010), which belongs to non-weldable, averagely workable and cyclically hardening group of materials. This kind of material is widely used in aircraft and aerospace structures. Rectangular cross-section specimens of size 8×10 mm were used in fatigue tests (Fig. 1). The specimens were made of a drawn bar 16 mm in diameter. The specimens had an external, unilateral notch, which was $a_0 = 2$ mm deep and its radii ranging from 0.2 to 22.5 mm (Fig. 1). The notches in specimens were cut with a cutter and their surfaces were polished with finer and finer emery papers.

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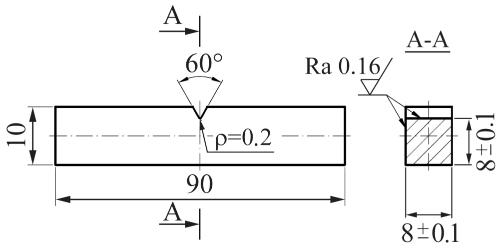

Fig. 1. Test specimen dimensions in mm.

The theoretical stress concentration factor in the specimen was estimated with use of the model presented in [8], under bending K_t = 3.76 (for ρ = = 0.2 mm), K_t = 1.24 (for ρ = 5 mm), K_t = 1.11 (for ρ = 10 mm) and K_t = = 1.04 (for ρ = 22.5 mm). Chemical composition of the tested 2017A-T4 alloy is the following (wt.%): 4.15 Cu; 0.65 Mn; 0.50 Zn; 0.69 Mg; 0.70 Fe; 0.10 Cr; 0.45 Si; 0.20 Ti; bal. Al. The monotonic quasi-static tension properties of 2017A-T4 are the following: yield stress σ_y = 382 MPa, ultimate stress σ_u = 480 MPa, Young's modulus E = 72 GPa, Poisson's ratio ν = 0.32. Alloys of aluminium with copper and magnesium, that is duralumin, belong to the alloys characterised by supreme strength properties. Elements of such shape are used, among others, in cars (by Renault Co.), trucks and tanks (attaching springs) as torsion bars, and as indirect beams used in drilling for oil and natural gas [9]. Figure 2 shows a microstructure of the aluminium alloy.

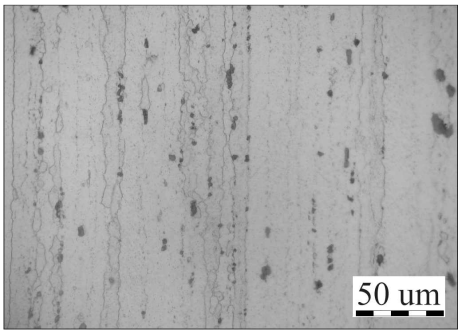

Fig. 2. Microstructure of 2017A-T4 alloy.

The microstructure heavily dominated by elongated grains of the solid solution α of various sizes, and a width of about 50 μm. Between large elongated grains is a cluster of very small equiaxed α phase grains in the system band also visible. On a background of solid solution α, there are many precipitations of intermetallic phases, particularly Al_2Cu, as well as Mg_2Si, AlCuMg. Precipitation phase Al_2Cu occurs mainly in the chain system at the grain boundaries of the solid solution, and their size does not exceed 5 mm. The test results of fatigue crack growth under bending were obtained at Opole University of Technology in Department of Mechanics and Machine Design. The tests were performed on the fatigue test stand MZGS-100 [10, 11] enabling to carry out cyclically variable (bending, torsion and proportional bending with torsion) and static (mean) loading. The tests were performed under controlled loading and at load frequency 28.4 Hz.

Unilaterally restrained specimens were subjected to cyclic bending with constant amplitude of moment M_a = 15.84 N·m (which corresponded to the nominal amplitude of normal stress σ_a = 185.63 MPa before the crack initiation) and stress ratio R = –1; 0. Crack growth was observed on the specimen surface with the optical method. The fatigue crack increments were measured with a digital micrometer located in the portable microscope (telescope) with 25-fold magnification and accuracy 0.01 mm. At the same time, a number of loading cycles N was recorded.

The analytical models. ***Concept of the ΔK-criterion.*** Stress intensity factor (SIF) range ΔK_I, which could be written for bending as:

$$\Delta K_1 = Y_1 \Delta\sigma_n \sqrt{\pi(a + a_0)}\,, \tag{1}$$

where $\Delta\sigma_n$ – range of nominal stresses for bending (is evaluated on the gross area); a – crack length; Y_1 – correction factor dependent on specimen geometry and loading type (other symbols in Fig. 3).

The correction factor for bending is calculated from equation [12]

$$Y_1 = 5/\sqrt{20 - 13((a+a_0)/h) - 7((a+a_0)/h)^2}\ , \qquad (2)$$

where h – height of the specimen.

The authors propose to introduce a correction factor Y_{2FR}, which takes into account the impact of the notch shape in equation (4)

$$Y_{2FR} = \sqrt{e^{\beta}}\ , \qquad (3)$$

where $\beta = \dfrac{0.1\sqrt{\rho}(h-a_0)}{\sqrt{a}(1.4\rho + 2.5a)}$.

In order to include the influence of crack length on the gross area ratio as well as on the non-uniform stress distribution due to the notches (Fig. 3), the stress intensity factor range was evaluated according to the following expression:

$$\Delta K_1 = Y_1 Y_{2FR} \Delta\sigma_n \sqrt{\pi(a+a_0)}\ . \qquad (4)$$

Results from Eq. (4) are plotted in Fig. 4. The effect of the non-uniform stress distribution due to different notch root radii on Y_{2FR} is evident there. In this case $\rho \to \infty$ and $Y_{2FR} \to 1$.

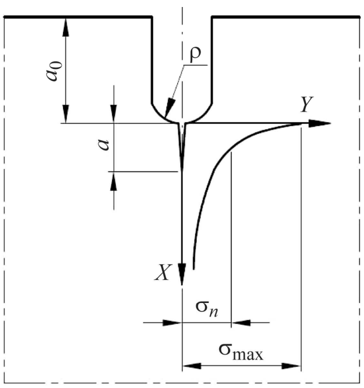

Fig. 3.

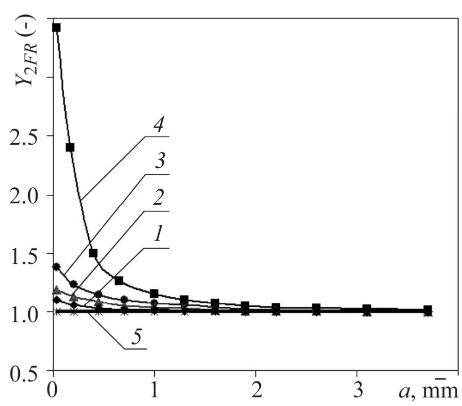

Fig. 4.

Fig. 3. Description of the symbols used for ΔK_I (Eq. (4)).

Fig. 4. Correction factor for different values of the notch root radius:
1 – 0.2 mm; *2* – 5; *3* – 10; *4* – 22.5 mm; *5* – $\rho \to \infty$.

Test results and their analysis. The fatigue crack growth tests under bending in 2017A-T4 aluminium alloy were performed under controlled loading. During tests, a number of cycles to the crack initiation N_i (i.e. to the moment of occurrence of a visible crack) were determined, and the fatigue crack lengths were measured [13]. From Fig. 5 it appears that after changing the notch radius root ρ from 0.2 to 22.5 mm, fatigue life of the tested specimen increases. It is evident that with the highest radii, the initiation phase, which depends on the stress conditions at the notch tip, prevails. It follows from the graphs in Fig. 5*a* that for the stress ratio $R = -1$, changed of the notch root radius from $\rho = 0.2$ mm to $\rho = 22.5$ mm causes an increase in the fatigue life of the tested specimens by over 79 times, and Fig. 5*b* presents an increase of the fatigue life by over 13 times for $R = 0$ and which is smaller than for $R = -1$.

Fig. 6 presents the fatigue crack growth rate calculated on the basis of Eqs. (1) and (4) for the stress ratio $R = -1$. Including Y_{2FR} coefficient in Eq. (4) has an influence on the change (an increase) of the value of the SIF ΔK_I range for different rounding radii of the notch root. Fig. 6*a* presents the results da/dN versus the SIF range for $\rho = 0.2$

and 5 mm, whereas Fig. 6*b* for ρ = 10 and 22.5 mm. It follows from Fig. 6 that the smaller the rounding radius of the notch root, the bigger the difference between the values of the SIF range calculated from Eqs. (1) and (4), which agrees with literature data and the actual influence of notches.

The largest influence of the Y_{2FR} coefficient was observed for the radius of the notch root ρ = 0.2 mm and the crack length up to approximately a = 3.00 mm. Where as the smallest influence of the Y_{2FR} coefficient was observed for ρ = 22.5 mm and the crack length up to approximately a = 0.60 mm.

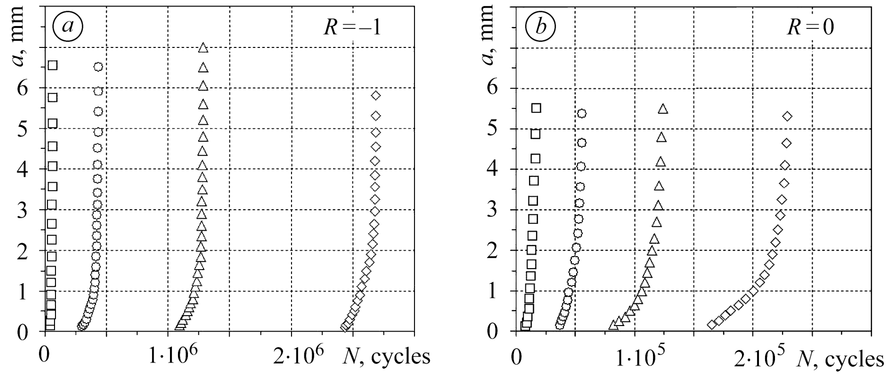

Fig. 5. Fatigue crack length versus number of cycles for different radii of the notch root for R = –1 (*a*) and R = 0 (*b*): □ – ρ = 0.2 mm; ○ – ρ = 5 mm; △ – ρ = 10 mm; ◇ – ρ = 22.5 mm.

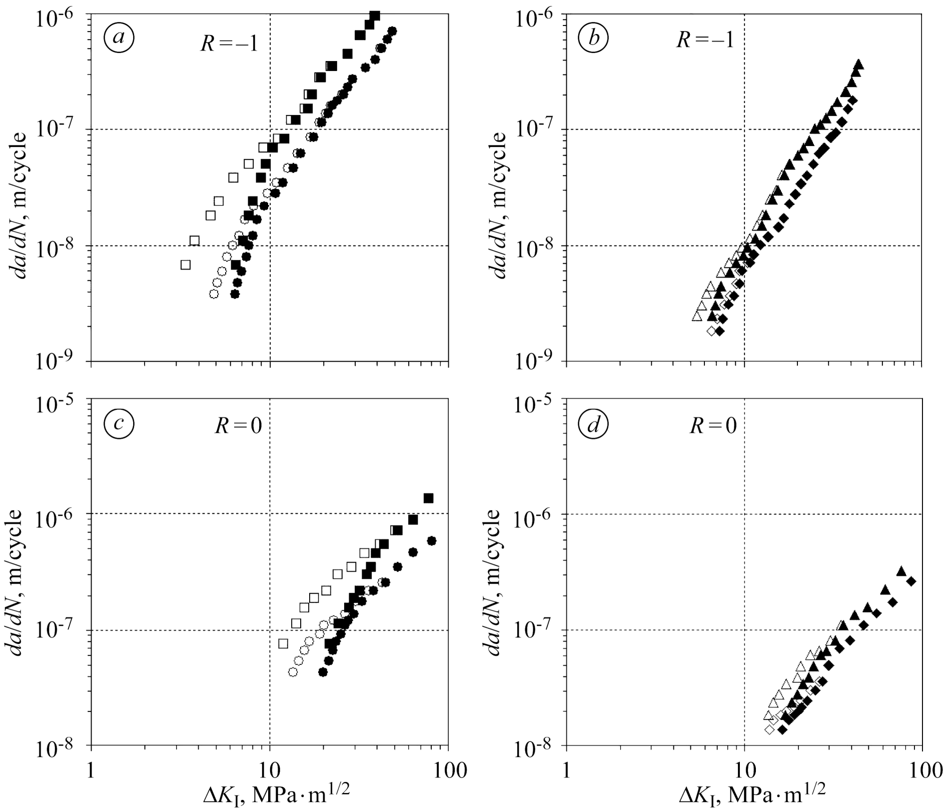

Fig. 6. Fatigue crack growth rate da/dN versus ΔK_I with and without the correction factor Y_{2FR} for ρ = 0.2; 5 mm (*a*, *c*) and ρ = 10; 22.5 mm (*b*, *d*).
□, ■ – ρ = 0.2 mm, Eqs. (1) and (4), ○, ● – ρ = 5 mm, Eqs. (1) and (4) (*a*, *c*);
△, ▲ – ρ = 10 mm, Eqs. (1) and (4), ◇, ◆ – ρ = 22.5 mm, Eqs. (1) and (4) (*b*, *d*).

Fig. 6*c*, *d* presents the fatigue crack growth rate calculated on the basis of Eqs. (1) and (4) for the stress ratio $R = 0$. Fig. 6*c* presents the results da/dN vs. the SIF range for the notch ρ = 0.2 and 5 mm, whereas Fig. 6*d* for ρ = 10 and 22.5 mm. It follows from Fig. 6*c*, *d*, as from Fig. 6*a*, *b* that the smaller the rounding radius of the notch root, the bigger the difference between the values of the SIF range calculated from Eqs. (1) and (4). The largest influence of the Y_{2FR} coefficient was observed for the radius of the notch root ρ = 0.2 mm and the crack length up to approximately $a = 2.40$ mm. Whereas the smallest influence of the Y_{2FR} coefficient was observed for ρ = 22.5 mm and the crack length up to approximately $a = 0.80$ mm. Above these crack lengths (for $R = –1$ and 0) the difference (the influence of the notch impact) between the results obtained from the Eqs. (1) and (4) disappears.

CONCLUSIONS

The presented results of the fatigue crack growth in the plane notched specimens made of 2017A-T4 alloy tested under bending allow us formulate the following conclusions:

– Eq. (4) well describes the results including additional influence of the notch during fatigue crack growth and it can be applied for determination of duration and quality of the notch influence;

– it has been confirmed that the change of the stress ratio from $R = –1$ to $R = 0$ causes an increase of the fatigue crack growth rate and decrease of the aluminium alloy life;

– the smaller was the radius of a notch root, the greater was fatigue crack growth rate.

РЕЗЮМЕ. Подано результати випробувань на згин зразків з прямокутним поперечним перерізом із алюмінієвого сплаву 2017A-T4. Зразки послаблені гострими і тупими односторонніми вирізами (радіус вирізу 0,2; 5; 10 і 22,5 mm). Для випробувань на втому використано стенд MZGS-100 у режимі низьких і високих циклів. Введено сталі значення номінального коефіцієнта навантаження $R = –1$; 0 і моменту амплітуди $M_a = 15{,}84$ N·m. Проаналізовано значення параметра ΔK з урахуванням впливу вирізу.

РЕЗЮМЕ. Представлены результаты испытаний на изгиб образцов с прямоугольным поперечным сечением из алюминиевого сплава 2017A-T4. Образцы ослаблены острыми и тупыми односторонними вырезами (радиус выреза 0,2; 5; 10 и 22,5 mm). Для испытаний на усталость использован стенд MZGS-100 в режиме низких и высоких циклов. Введены постоянные значения номинального коэффициента нагрузки $R = –1$; 0 и момента амплитуды $M_a = 15{,}84$ N·m. Проанализированы значения параметра ΔK с учетом влияния надреза.

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