

Fatigue crack initiation and propagation at different stress ratio values of uniaxial pulsating loading

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ABSTRACT The results of investigations of the fatigue macrocrack initiation and growth at the stress ratio $R = 0.1$ and 0.5 in notched specimens (a strip with a U-notch and a strip with a central hole of various tip radius) made of B95T1 (type 7075-T6) aluminium alloy are presented. Two operational parameters, i.e. the relative maximum local stress, $\sigma_{y \max}^*|_{x=d^*(R)}/d^*(R)$, and the relative maximum stress intensity factor, $K_{\max}/d^*(R)$, where d^* is the fatigue process zone size, for description of material resistance to the fatigue crack initiation and propagation are proposed. It is shown that these parameters are able to determine the crack initiation periods and crack propagation rates invariant to the stress ratio R . This approach is compared with the known methods of Kujawski, Tanaka-Taylor, Susmel and Lazzarin.

Keywords fatigue macrocrack; initiation and growth; notched specimens; stress ratio.

NOMENCLATURE

a = crack length
 a_0 = El Haddad length parameter
 a_i = initial macrocrack length
 d^* = fatigue process zone size
 da/dN = fatigue crack growth rate
 b = notch depth
 $f(x/\rho)$ = stress distribution function along the notch axis
 K^* = Kujawski parameter
 $K_{\max}$ = maximum stress intensity factor
 K_t = theoretical stress concentration factor
 K_W = Walker parameter
 L = critical distance
 N_i = number of cycles to macrocrack of length a_i initiation
 $P_{\min}, P_{\max}$ = minimum and maximum load in a loading cycle
 R = stress ratio
 W = specimen width
 x = distance from the notch tip
 ΔK = stress intensity factor range
 ΔK^+ = positive part of the stress intensity factor range
 ΔK_{th} = threshold stress intensity factor range
 $\Delta K(\lambda)$ = stress intensity factor range of the crack of equivalent length ($a = b$)
 ΔP = load range
 $\Delta \sigma_0$ = endurance limit of smooth specimen
 $\Delta \sigma_{eff}$ = effective stress range

$$\begin{aligned}
\Delta\sigma_{\text{nom}} &= \text{nominal stress range} \\
\Delta\sigma_y, \Delta\sigma_y(0) &= \text{stress range at the notch tip} \\
\Delta\sigma_y(x) &= \text{stress range at the distance } x \text{ from the notch tip} \\
\Delta\sigma_y^* &= \text{local stress range} \\
\delta &= \text{elongation} \\
\rho &= \text{notch root radius} \\
\sigma_{\text{eff}}^{\text{max}} &= \text{maximum effective stress} \\
\sigma_{y \text{ max}} &= \text{maximum stress at the notch tip} \\
\sigma_{y \text{ max}}^* &= \text{maximum local stress} \\
\sigma_Y &= \text{yield strength} \\
\sigma_U &= \text{ultimate strength}
\end{aligned}$$

INTRODUCTION

To introduce in the best way the laboratory specimens testing results into structural component life-time assessment we need some regularities which are invariant to structural component geometry (width, thickness, structural stress concentrator shape, etc.). For cyclically loaded components loading cycle parameters (maximum or range of the stress in loading cycle, stress ratio, frequency, etc.) must also be taken into account.

At present there are a number of approaches in the fracture mechanics which take into account the effect of the stress ratio $R = P_{\text{min}}/P_{\text{max}}$ on fatigue crack resistance of materials, but for the crack growth stage only. In this case the stress intensity factor (SIF) is a main parameter of the process. Many researchers are looking for specific expressions for the SIF to obtain a parameter which allows the invariant determination of fatigue crack rates for any stress ratio R . One of the first such parameters was proposed by Walker¹

$$K_W = K_{\text{max}}^{(1-m)} \Delta K^m, \quad (1)$$

where K_{max} and ΔK is the maximum value and range of SIF in a loading cycle, respectively, m is correlation parameter. Another parameter based on a combination of the positive part ΔK^+ of SIF range and the maximum SIF was proposed by Kujawski²

$$K^* = (K_{\text{max}} \Delta K^+)^{0.5}. \quad (2)$$

Later this parameter was modified³

$$K^* = (K_{\text{max}})^\alpha (\Delta K^+)^{1-\alpha} = (1-R)^{-\alpha} \Delta K = M \Delta K, \quad (3)$$

and methods for parameter α determining were suggested.⁴ The research conducted on aluminium alloys, steel and cast iron have proved the correctness of this approach. However, other researchers have shown⁵ that this approach is not quite true in the case of high stress ratio

$R = 0.8-0.9$ and a different representation of the parameter M was proposed

$$M = \begin{cases} (1-R)^{-\beta} & \text{at } 0 \leq R < 0.5; \\ (1.05 - 1.4R + 0.6R^2)^{-\beta} & \text{at } 0.5 \leq R < 1, \end{cases} \quad (4)$$

as well as the methods for determining the index β were proposed. There are also many other approaches based on various combinations of the maximum SIF and its range, using the threshold and critical values of SIF, etc.^{6,7}

Parameters of the stress-strain state, which describe the fatigue cracks initiation in notched specimens invariant to stress ratio R are not available. Therefore, in this paper the emphasis is made on two stages of fatigue fracture, i.e. fatigue crack initiation and propagation at different stress ratio in notched specimens of various shape.

THEORETICAL BACKGROUND

Analysis of the stress-strain state at the notch by the linear fracture mechanics methods shows that the stress value, which reaches its maximum at the notch tip, decreases with increasing of the distance from the tip and this change depends on the concentrator radius. It was suggested^{8,9} to use not the maximum stress, but the stress determined at some distance from the tip [so-called point method (PM)⁸] or the stress averaged over a certain area [line method (LM)⁹]. To evaluate these local (effective) stresses it is necessary to know the law of changes (distribution) of the stresses from the notch tip along the concentrator axis as well as a distance (or area) in which these stress are determined.

The distribution functions proposed by Usami¹⁰ and Lucaš-Klesnil^{11,12} are the most common. In this paper the Lucaš-Klesnil distribution is used:

$$f\left(\frac{x}{\rho}\right) = \left(1 + 4.5 \frac{x}{\rho}\right)^{-1/2}, \quad (5)$$

where ρ is notch radius, x is distance from the notch tip. Ciavarella and Meneghetti have discussed¹³ the similarities between formulations of Peterson, Neuber, Heywood, Lucaş and Klesnil, Atzori and Lazzarin when dealing with stress distributions at notches of different acuity. By using the keyhole notch model, it was shown the applicability of Eq. (5) for effective stress concentration factor K_f and discussed previous formulations where a coefficient 4.0 derived from Creager-Paris' solution substituted the coefficient 4.5.¹⁴ The difference between values of the function $f(x/\rho)$ in these cases is about 1–3% only, depending on notch radius.

Regarding the distance from the notch tip, different concepts are known, such as Neuber's microstructural support length,^{15,16} Peterson's distance,⁸ Novozhilov's parameter,^{17,18} Ostash's process zone size,^{19,20} Pluvina's effective distance,^{21,22} Taylor's critical distance,²³ etc. The critical distance approach based on elastic solutions is one of the most perspective because the influence of various loading parameters and the stress-strain state at the notch or at the macrocrack tip can be determined analytically and also experimentally.²⁴

On the basis of the model used in,²⁵ Taylor's critical distance L ²³ can be calculated by El Haddad formula^{26,27}

$$L = a_0 = \frac{1}{\pi} \left(\frac{\Delta K_{th}}{\Delta \sigma_0} \right)^2, \quad (6)$$

where ΔK_{th} is fatigue threshold of a specimen with a macrocrack; $\Delta \sigma_0$ is endurance limit of a smooth specimen.

Parameter a_0 can be estimated also using another methods, for example^{28,29}

$$a_0 = \frac{1}{\pi} \left(\frac{\Delta K_{th}}{C E \Delta \varepsilon_e} \right)^2, \quad (7)$$

where $\Delta \varepsilon_e$ is the fatigue limit range and C is the crack shape factor equal to 0.71. It is shown that a_0 -values calculated by Eq. (7) differ from the values of the process zone size^{19,20} estimated experimentally.²⁴

Our researches are based on the unified model of fatigue fracture,^{19,20} where the structural-mechanical parameter d^* (fatigue process zone size) is introduced, which determines the local stress at the notch tip of radius ρ

$$\Delta \sigma_y^* = \Delta \sigma_y(x) = \Delta \sigma_y(0) f\left(\frac{x}{\rho}\right) \Big|_{x=d^*}, \quad (8)$$

where $\Delta \sigma_y$ and $f(x/\rho)$ are the stress range at the notch tip and stress distribution function along the concentrator axis, respectively, determined by the elastic formulation scheme. Parameter d^* determines also the initial macrocrack of length $a_i = d^*$.^{19,20}

For a strip with a U-notch we have³⁰

$$\Delta \sigma_y = \frac{\Delta K(\lambda)}{\sqrt{\rho}} (1,128 + 6,595\xi - 116,5\xi^2 + 705\xi^3), \quad (9)$$

where $\Delta K(\lambda)$ is the SIF range of the crack of equivalent length $\lambda = b/W$; b is notch depth; W is specimen width and $\xi = \rho/W$.

For a strip with a central hole we have

$$\Delta \sigma_y = K_t \Delta \sigma_{nom}, \quad (10)$$

where K_t is the theoretical stress concentration factor⁸ and $\Delta \sigma_{nom}$ is the nominal stress range.

For comparison were calculated also values of the effective stress range $\Delta \sigma_{eff}$ by means of the point method (PM) as proposed by Tanaka³¹ and Taylor³²

$$\Delta \sigma_{eff} = \Delta \sigma_y(x) \Big|_{x=L/2} \quad (11)$$

and Lazzarin³³

$$\Delta \sigma_{eff} = \Delta \sigma_y(x) \cdot \left(1 + \sqrt{2} \frac{x}{\rho} \right) \Big/ \left(1 + \frac{x}{\rho} \right) \Big|_{x=L}. \quad (12)$$

Besides, values of the effective stress ranges were estimated also by the line method (LM)^{23,25,33,34}

$$\Delta \sigma_{eff} = \frac{1}{2L} \int_0^{2L} \Delta \sigma_y(x) dx. \quad (13)$$

MATERIAL AND TEST PROCEDURE

B95T1 aluminium alloy (type 7075-T6 alloy) after conventional heat-treatment ($\sigma_Y = 465$ MPa; $\sigma_U = 538$ MPa; $\delta = 11\%$; $\Delta K_{th} = 3.2$ MPa $\sqrt{m}$ and $\Delta \sigma_0 = 119$ MPa for $R = 0.1$; $\Delta K_{th} = 2.5$ MPa $\sqrt{m}$ and $\Delta \sigma_0 = 115$ MPa for $R = 0.5$) was investigated. The value of parameter d^* was determined by various methods²⁴, including a thermoelectric one.³⁵ For investigated material we have $d^* = 0.15$ mm for stress ratio $R = 0.1$ and $d^* = 0.18$ mm for $R = 0.5$. From Eq. (6) we get $L = 0.23$ mm for $R = 0.1$ and $L = 0.15$ for $R = 0.5$.

Crack initiation tests were performed on strip specimens of 30 mm width and 3.7 mm thickness with a central hole or a U-notch ($b = 8$ –11 mm). There were three values of the notch root radius ($\rho = 0.75$; 1.5; 2.5 mm). Crack propagation tests were performed on CT-specimens (base size $W = 40$ mm and thickness $t = 3.7$ mm). Servohydraulic test machine of type 'BiSS' (India) with capacity of 50 kN was used. Fatigue process was studied in laboratory air at stress ratio $R = 0.1$ and 0.5 at a cycle frequency of 10–15 Hz.

Period N_i up to the initiation of macrocrack of length $a_i = d^*$ versus stress range or its maximum value in a loading cycle were determined as well as fatigue macrocrack growth rates da/dN versus SIF-values.

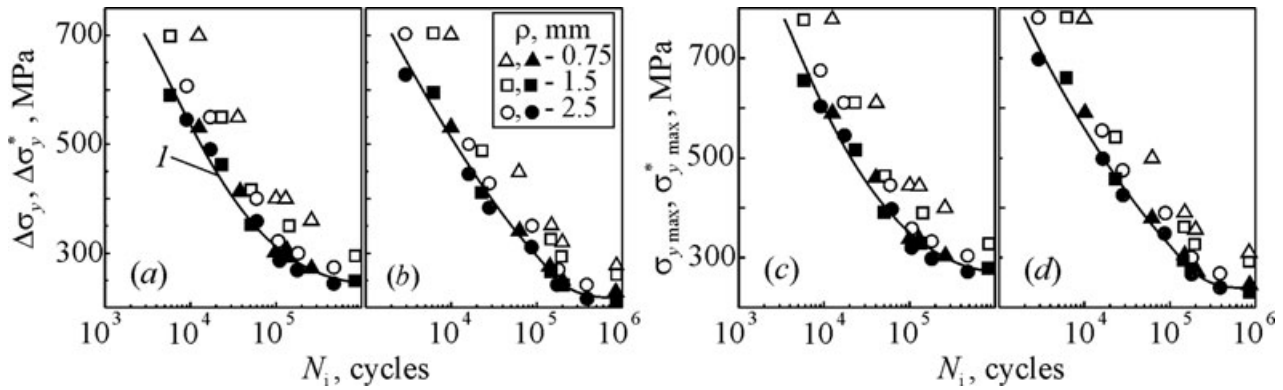


Fig. 1 Relationships of periods N_i to fatigue macrocrack initiation versus stress σ_y at the notch tip (light symbols) or local stress σ_y^* (dark symbols) for $R = 0.1$: (a) and (b) for stress ranges; (c) and (d) for maximum stress in a loading cycle; (a) and (c) for a strip with an edge notch; (b) and (d) for a strip with a central hole.

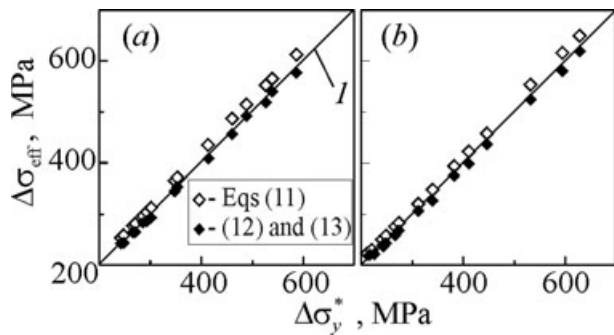


Fig. 2 Comparison of the local $\Delta\sigma_y^*$ (line 1) and effective $\Delta\sigma_{\text{eff}}$ (symbols) stress ranges for $R = 0.1$: (a) for a strip with an edge notch; (b) for a strip with a central hole.

RESULTS AND DISCUSSION

Crack initiation

The obtained data at $R = 0.1$ show (Fig. 1, Tables S1 & S3) that contrary to the relationships $(\Delta\sigma_y - N_i)$ and $(\sigma_{y \max} - N_i)$ indicated by light symbols, the relationships $(\Delta\sigma_y^* - N_i)$ and $(\sigma_{y \max}^* - N_i)$ indicated by dark symbols and lines 1 are invariant with respect to the notch radius

for both specimen shapes. Values of $\sigma_{y \max}$ and $\sigma_{y \max}^*$ are calculated by Eqs (8), (9) and (10) taking $P_{\max}$ in a loading cycle instead of ΔP .

Similar results are obtained when the process parameter is the effective stress range $\Delta\sigma_{\text{eff}}$ because of equality of values $\Delta\sigma_y^*$ and $\Delta\sigma_{\text{eff}}$ (Fig. 2). As it can be seen (Fig. 2), the calculation by Eq. (11) gives a small overcharge (4–5%) of $\Delta\sigma_{\text{eff}}$ -values when compared to $\Delta\sigma_y^*$ -values, because at the stress ratio $R = 0.1$ we have $d^* > L/2$. At the same time, the values $\Delta\sigma_{\text{eff}}$ calculated by Eqs (12) and (13) practically agree well though they are smaller (1–3%) than $\Delta\sigma_y^*$. So, we have proved here that each of the presented approaches has the right to exist.

The dependences $(\Delta\sigma_y^* - N_i)$ and $(\sigma_{y \max}^* - N_i)$ obtained at stress ratio $R = 0.5$ (Fig. 3, curves 2; Tables S2 & S4) are similar to the above presented for $R = 0.1$ (curves 1) for both specimen geometries with respect to the notch radius influence, but mismatch with regard to the stress ratio influence: if the R -value is higher the dependences $(\Delta\sigma_y^* - N_i)$ shift to the bottom (Fig. 3a & b) and dependences $(\sigma_{y \max}^* - N_i)$ vice versa – shift to the top (Fig. 3c & d).

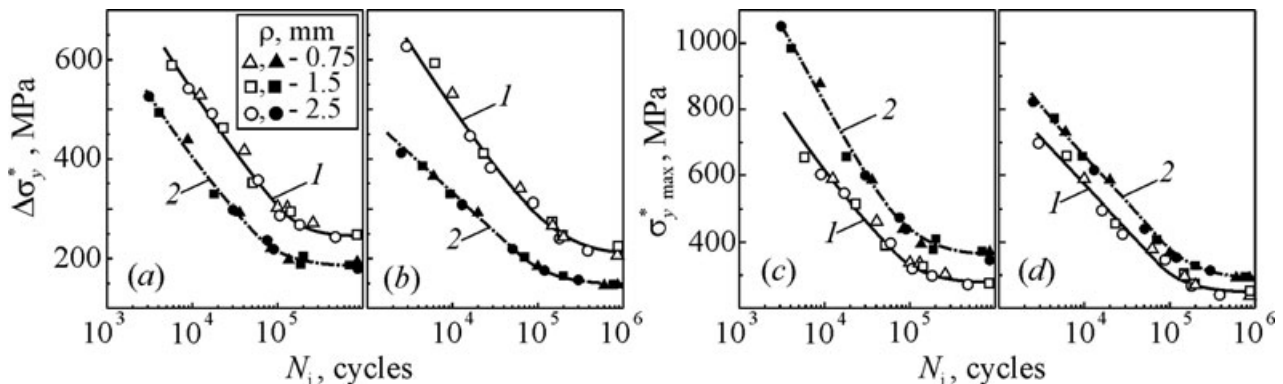


Fig. 3 Periods N_i to the fatigue macrocrack initiation versus (a, b) local stress range $\Delta\sigma_y^*$ and (c, d) maximum local stress $\sigma_{y \max}^*$ for $R = 0.1$ (lines 1) and $R = 0.5$ (lines 2): (a) and (c) for a strip with an edge notch; (b) and (d) for a strip with a central hole.

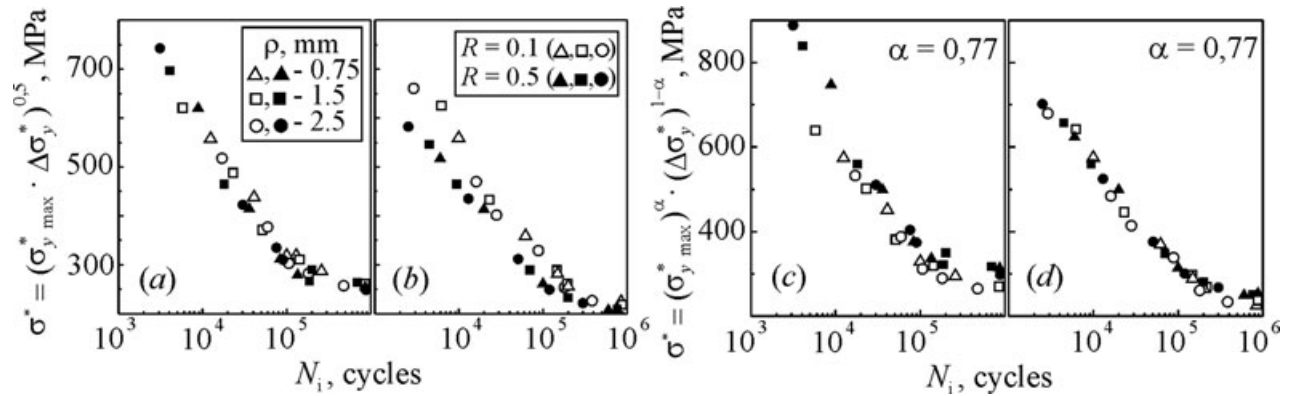


Fig. 4 Periods N_i to the fatigue macrocrack initiation versus mixed local stress σ^* for various R -value: (a) and (c) for a strip with an edge notch; (b) and (d) for a strip with a central hole.

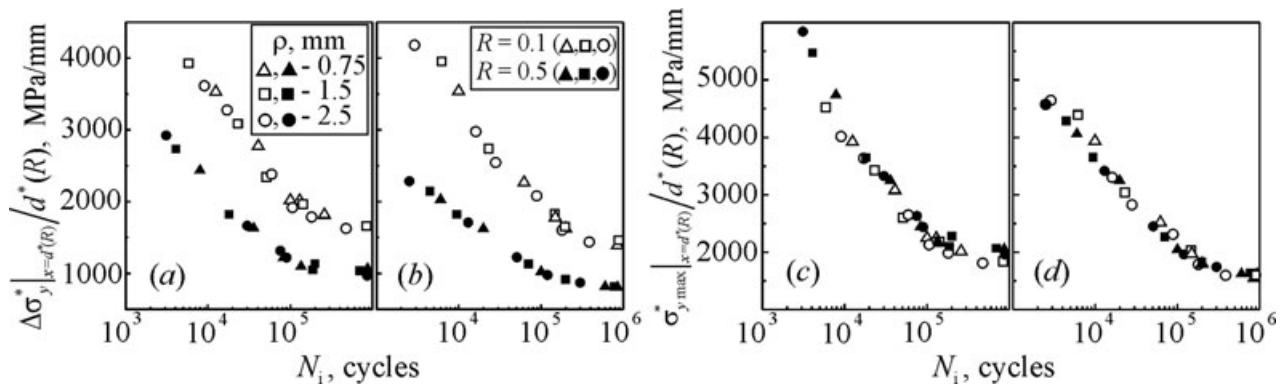


Fig. 5 Periods N_i to the fatigue macrocrack initiation versus (a, b) relative local stress range and (c, d) relative maximum local stress for various R -value: (a) and (c) for a strip with an edge notch; (b) and (d) for a strip with a central hole.

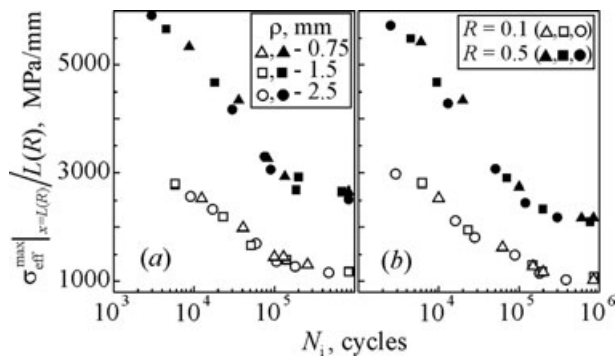


Fig. 6 Periods N_i of the fatigue macrocrack initiation versus relative maximum effective stress for various R -value: (a) for a strip with an edge notch; (b) for a strip with a central hole.

Taking into account the above discussed usage of mixed SIF for the description of the fatigue crack growth invariant to the stress ratio R (see Eqs 2 & 3), we consider, as parameter for crack initiation, the mixed local stress near a notch $\sigma^* = (\sigma_{y \max}^* \cdot \Delta \sigma_y^*)^{0.5}$ or $\sigma^* = (\sigma_{y \max}^*)^\alpha (\Delta \sigma_y^*)^{1-\alpha}$. But in this case we do not always obtain successful results

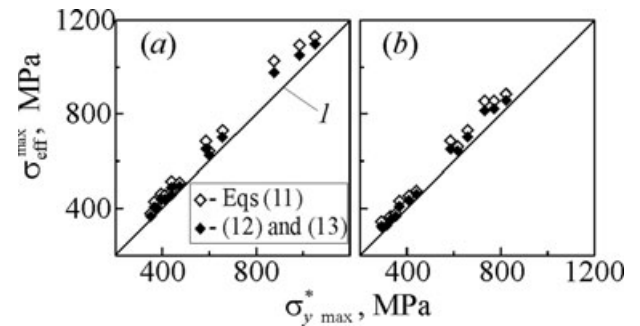


Fig. 7 Comparison of the local $\sigma_{y \max}^*$ (line 1) and effective $\sigma_{\text{eff}}^{\max}$ (symbols) maximum stresses for $R = 0.5$: (a) for a strip with an edge notch; (b) for a strip with a central hole taking $P_{\max}$ instead of ΔP .

(Fig. 4), because index α depends on the specimen geometry: value of $\alpha = 0.5$ is optimal for an edge notched strip (Fig. 4a) and $\alpha = 0.77$ for a strip with a central hole (Fig. 4d).

It is assumed that the stress ratio affects the process zone size d^* and should take into account this change of the value of d^* . Experimental studies by various

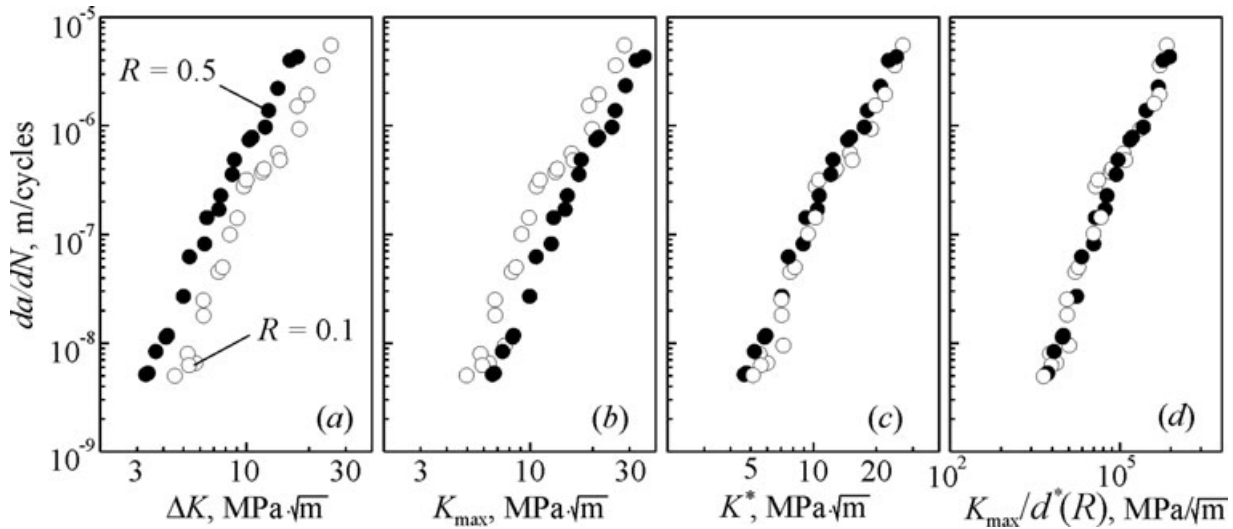


Fig. 8 Fatigue crack growth rates versus different parameters: (a) for range SIF, (b) for maximum SIF, (c) for Kujawski parameter, (d) for our relative maximum SIF.

techniques show that parameter d^* increases from 0.15 to 0.18 mm with increasing R from 0.1 to 0.5. Based on this fact and also on the results presented in Fig. 3c and d, it is proposed to consider the relative maximum local stress $\sigma_{y \max}^*|_{x=d^*(R)}/d^*(R)$ as a parameter of crack initiation process. Data analysis in Fig. 5 shows that contrary to the relative local stress range $\Delta\sigma_y^*|_{x=d^*(R)}/d^*(R)$ (Fig. 5a & b) the relative maximum local stress $\sigma_{y \max}^*|_{x=d^*(R)}/d^*(R)$ enables us to receive the dependences of the fatigue macrocrack of length $a_i = d^*$ initiation period invariant to stress ratio R for both specimen geometries (Fig. 5c & d).

Our attempt to apply, similarly to the above mentioned, the relative maximum effective stress $\sigma_{\text{eff}}^{\max}|_{x=L(R)}/L(R)$ evaluated in terms of $P_{\max}$ loading parameter and the critical distance L for the given R -value, gives no positive result (Fig. 6), although the effective $\Delta\sigma_{\text{eff}}$ or $\sigma_{\text{eff}}^{\max}$ and local $\Delta\sigma_y^*$ or $\sigma_{y \max}^*$ stresses for both stress ratios are very close (Figs 2 & 7). It is connected with the difference in d^* - and L -values at $R = 0.5$. Basing on Eq. (6) distance L decreases from 0.23 to 0.15 mm with increasing the stress ratio R , but it has been found in our experiments that d^* -parameter exhibits an opposite trend – it increases from 0.15 to 0.18 mm, which confirms our previous data.³⁶

CRACK PROPAGATION

As the next step, the proposed approach was applied to fatigue crack growth stage (see Tables S5 & S6). In Fig 8a and b the traditional dependences ($da/dN - \Delta K$) and ($da/dN - K_{\max}$) are presented. Applying the above mentioned Eq. (2), we have a dependence for the crack growth rates invariant to stress ratio R (Fig. 8c). A similar result was also obtained using our relative maximum SIF,

$K_{\max}/d^*(R)$, which describes the experimental data more precisely than the Kujawski parameter (Fig. 8d), with the correlation index being equal to $R^2 = 0.9644$ and 0.9592 , respectively.

CONCLUSIONS

1. The proposed operation parameters, i.e. the relative maximum local stress, $\sigma_{y \max}^*|_{x=d^*(R)}/d^*(R)$, and the relative maximum SIF, $K_{\max}/d^*(R)$, enable us to receive the fatigue crack initiation and propagation resistance dependences, respectively, which are invariant to the stress ratio R .
2. The application of local stress parameter for description of the life time of a notched component requires experimental techniques or analytical calculation methods in the frame of linear fracture mechanics for accurate and precise determination of the critical size (d^* , L , x_{eff} , etc.) of the fatigue process zone for various test conditions.
3. Additional investigations are needed for application of our parameters in the case of negative R .

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Supporting Information

Additional Supporting Information may be found in the online version of this article, containing the calculations that lead to results 4 and 5, and an extended section on the Supreme Court.

Table S1: Fatigue crack initiation experimental data (strip with U-notch: $W = 30$ mm; $t = 3.7$ mm; $R = 0.1$; $d^* = 0.15$ mm; $L = 0.23$ mm)

Table S2: Fatigue crack initiation experimental data (strip with U-notch: $W = 30$ mm; $t = 3.7$ mm; $R = 0.5$; $d^* = 0.18$ mm; $L = 0.15$ mm)

Table S3: Fatigue crack initiation experimental data (strip with central hole $W = 30$ mm; $t = 3.7$ mm; $R = 0.1$; $d^* = 0.15$ mm; $L = 0.23$ mm)

Table S4: Fatigue crack initiation experimental data (strip with central hole $W = 30$ mm; $t = 3.7$ mm; $R = 0.5$; $d^* = 0.18$ mm; $L = 0.15$ mm)

Table S5: Fatigue crack propagation experimental data (CT-specimen $W = 40$ mm; $t = 3.7$ mm; $R = 0.1$; $d^* = 0.15$ mm)

Table S6: Fatigue crack propagation experimental data (CT-specimen $W = 40$ mm; $t = 3.7$ mm; $R = 0.5$; $d^* = 0.18$ mm)

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