

PREDICTION OF THE PERIOD OF INITIATION OF MACROCRACKS IN NOTCHED SPECIMENS

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We propose an experimental–numerical procedure for the prediction the number of cycles N_i to the initiation of a fatigue crack near stress concentrators in specimens of complex shape. This procedure is based on direct measurements of the opening displacements of the concentrator and the numerical evaluation of the total range of local strains $\Delta\epsilon^*$ or its elastic component $\Delta\epsilon_e^*$ near the tip of the notch. The applicability of this procedure to the prediction of N_i is experimentally checked for specimens in the form of strips cut out from rolled sheets of V95pchT2 alloy with stress concentrators of different geometries.

Under cyclic loading, structural elements fail, as a rule, in the vicinity of stress concentrators, i.e., near notches, fillets, welds, etc. Their service life is often determined by the number of cycles N_i to the initiation of a fatigue macrocrack. As the main factor determining the period of crack initiation, one can mention the stress–strain state in the vicinity of stress concentrators [1, 2]. In the traditional force approach [1], it is often very difficult to determine local stresses near stress concentrators in structural elements of complex geometry, especially in the case where these elements contain several concentrators and in the presence of elastoplastic strains. Therefore, it is better to use deformation parameters because the levels of strains can be not only computed but also directly measured [2].

There are numerous methods used for the evaluation of local stresses and strains in the vicinity of stress concentrators [3]. However, they give satisfactory results only for strains lower than 2%. Moreover, they are based on the investigation of smooth specimens and, to apply these methods, it is necessary to know the distribution of stresses in the vicinity of a stress concentrator [4].

The well-known experimental methods for the determination of strains also have serious disadvantages. Thus, small-size strain gauges fail to record local strains in the vicinity of very sharp notches [5]. On the contrary, the method of grids with small base [6] is inapplicable in the case of large radii of stress concentrators, requires advanced optical equipment, and is hardly applicable to actual structures.

In what follows, we use our experimental–numerical method (approved for different materials) for the determination of the ranges of local elastic ($\Delta\epsilon_e^*$) and elastoplastic strains ($\Delta\epsilon^*$) caused by the deformation of the characteristic process zone d^* at the tip of a stress concentrator (notch or crack) (Fig. 1). This method is based on direct measurements of the opening displacements of the concentrator δ along a line passing through the center of radius of its tip with the help of a displacement transducer [7]. Note that, for $N_i = \text{const}$, the quantity $\Delta\epsilon^*$ is independent of the radius of the stress concentrator and the geometry of the specimen [7].

Material and Experimental Procedure

We tested specimens of V95pchT2 aluminum alloy ($\sigma_{0.2} = 456$ MPa, $\sigma_u = 510$ MPa, $\delta = 12\%$, and $d^* = 0.1$ mm for $N_i = 10^3$ – 10^6 cycles [8]) in the form of strips with thickness $t = 4.4$ mm and lengths $L_1 = 190$ mm

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and $L = 160$ mm (Fig. 2). The specimens contained side notches and holes of various types whose sizes can be found in Table 1. The basic curve of resistance to the initiation of a fatigue macrocrack was obtained in laboratory air on standard compact specimens with a gauge length W of 64 mm [7] for a constant loading amplitude at a frequency of 10 Hz with a load ratio $R = 0.05$. The time of initiation of a crack and its length were recorded by using a KM-6 cathetometer with an $\times 25$ magnification. As the number of cycles to the initiation of an initial crack N_i , we take the number of cycles for which the crack length a_i becomes equal to $d^* = 0.1$ mm [1]. The elastic component $\Delta\delta^e$ and the total range of opening displacements of the concentrator $\Delta\delta^t$ were measured according to the well-known procedure from [7]. Then we determined the elastic component $\Delta\epsilon_e^*$ and the total range $\Delta\epsilon^*$ of local strains [7]:

$$\Delta\epsilon_e^* = \ln \left[1 + \frac{\Delta\delta^e}{\pi(\rho + d^*)} \right], \quad (1)$$

$$\Delta\epsilon^* = \ln \left[1 + \frac{\Delta\delta^t}{\pi(\rho + d^*)} \right]. \quad (2)$$

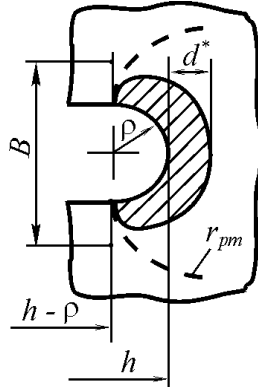


Fig. 1. Schematic diagram of measuring opening displacements of the notch: B gauge length.

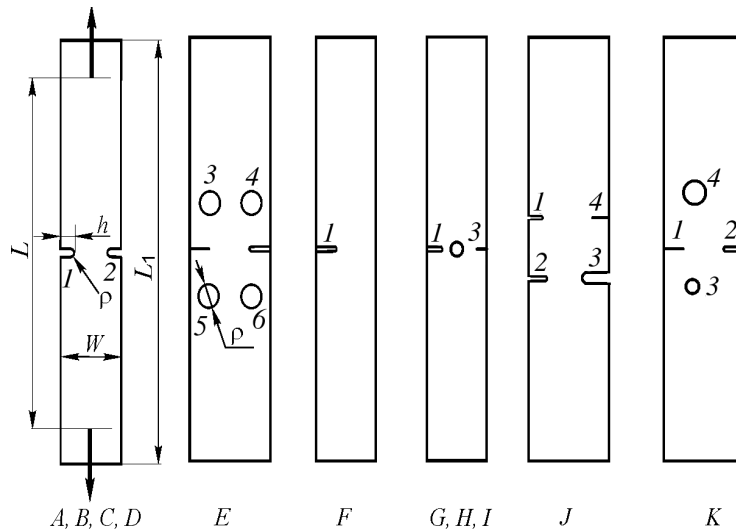


Fig. 2. Schematic diagrams of tested specimens.

Table 1. Geometric Characteristics of Tested Specimens

Specimen type	W , mm	No. of the notch or hole	ρ , mm	h , mm
<i>A</i>	31	1	0.10	3.7
		2	0.10	3.7
<i>B</i>	31	1	0.20	7.2
		2	0.20	7.2
<i>C</i>	31	1	0.75	6.4
		2	0.75	6.6
<i>D</i>	20	1	0.75	9.1
		2	0.10	3.6
<i>E</i>	42	1	0.10	7.0
		2	0.75	10.1
		3	4.0	—
		4	3.0	—
		5	3.0	—
		6	4.0	—
<i>F</i>	22	1	0.75	9.8
<i>G</i>	31	1	0.75	8.3
		2	0.10	4.0
		3	1.50	—
<i>H</i>	31	1	0.1	3.8
		2	0.1	3.7
		3	1.35	—
<i>I</i>	31	1	0.2	5.3
		2	0.2	5.3
		3	3.0	—
<i>J</i>	41	1	0.65	8.1
		2	0.75	10.1
		3	3.00	15.0
		4	0.10	5.7
<i>K</i>	41	1	1.5	18.5
		2	0.1	9.6
		3	2.0	—
		4	5.0	—

Table 2. Comparison of the Numerical and Experimental Data

Specimen type	ρ , mm	$\Delta\epsilon_e^*$, %	$\Delta\epsilon^*$, %	B	k	$N_i^{\text{cal}} \cdot 10^{-3}$, cycles		$N_i^{\text{exp}} \cdot 10^{-3}$, cycles
						relation (4)	relation (7)	
<i>A</i>	0.10	0.82	0.82	1.01	1.06	19.1	19.1	18
	0.10	0.82	0.82	1.01	1.06		19.1	
<i>B</i>	0.20	2.00	2.31	1.05	1.08	1.97	2.2	1.3
	0.20	2.00		1.05	1.08		2.2	
<i>C</i>	0.75	1.27	1.82	1.11	1.16	3.3	5.4	4.2
	0.75	1.28		1.11	1.16		5.3	
<i>D</i>	0.75	2.00	2.30	1.11	1.16	2	1.6	1.1
	0.10	0.56		1.01	1.06		48.3	
<i>E</i>	0.10	1.86	1.86	1.01	1.06	3.1	2.8	2.6
	0.75	0.75		1.11	1.16		20.9	
<i>F</i>	0.75	1.04	1.38	1.11	1.16	6.1	8.8	6.2
<i>G</i>	0.75	1.15	1.41	1.11	1.16	3.9	6.8	4.5
	0.10	1.27		1.01	1.06		7	
	1.50	0.31		1.15	1.25		232	
<i>H</i>	0.10	2.05		1.01	1.06		2.3	3.8
	0.10	2.05		1.01	1.06		2.3	
	1.35	0.30	0.31	1.14	1.24	170	258	
<i>I</i>	0.20	1.16		1.05	1.08		8	9.9
	0.20	1.16	1.27	1.05	1.08	7.4	8	
	3.00	0.31		1.18	1.39		303	
<i>J</i>	3.00	1.29	1.70	1.18	1.39	3.9	4	4.2
	0.10	0.67		1.01	1.06		31	
	0.65	0.89		1.10	1.14		13.6	
	0.75	0.64		1.11	1.16		31	
<i>K</i>	1.50	2.22	3.71	1.15	1.25	0.8	1	1.5
	0.10	2.83		1.01	1.06		1.1	
	2.00	0.51		1.16	1.31		61	
	5.00	0.49		1.21	1.46		80	

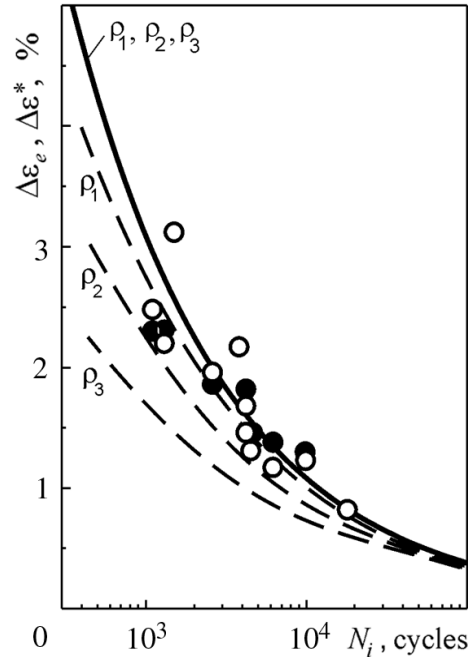


Fig. 3. Basic dependences of the number of cycles N_i to the initiation of a fatigue macrocrack (of length $a_i = d^*$) on the range of the elastic component of local strains $\Delta\epsilon_e^*$ (dashed lines) and the total range of local strains $\Delta\epsilon^*$ (solid line) for a notched compact specimen ($\rho_1 = 0.1$ mm, $\rho_2 = 0.75$ mm, and $\rho_3 = 4.0$ mm) and the comparison of predicted values (solid line) with the experimental data (symbols) for specimens of any shape: (●) and (○) mark the values of $\Delta\epsilon^*$ determined according to relation (2) and the approximate formula (5), respectively.

Experimental Results

The $\Delta\epsilon^*-N_i$ and $\Delta\epsilon_e^*-N_i$ dependences constructed according to the results of testing of standard compact specimens with side notches are used as basic for the prediction of the period N_i in structural elements with stress concentrators (Fig. 3). The $\Delta\epsilon^*-N_i$ dependences can be rather accurately described by the formula [2]

$$\Delta\epsilon^* = \epsilon'_f (N_i)^m, \quad (3)$$

where $\epsilon'_f = 68.55$ and $m = 0.454$. Thus, we get

$$N_i = 10946 (\Delta\epsilon^*)^{-2.2}. \quad (4)$$

Since the quantity $\Delta\epsilon^*$ is independent of the radius of the concentrator and the geometry of the specimen, we can find the periods N_i^{cal} by measuring $\Delta\delta^t$ and finding the range $\Delta\epsilon^*$ according to (2) for specimens of any geometry. Note that the values of N_i^{cal} obtained as indicated above are in good agreement with the experimental data N_i^{exp} (Table 2).

In specimens subjected to sustained loading, it is impossible to record the plastic component $\Delta\delta^p$ of the total range of opening displacements $\Delta\delta^t$ (it is observed only in the first loading cycles [7]), i.e., the quantity

$\Delta\varepsilon^*$ can hardly be found. Therefore, it is reasonable to predict the duration of the period N_i by analyzing the elastic component $\Delta\varepsilon_e^*$ of the total range of local strains with the help of phenomenologically deduced approximate relations. The analysis of the experimental data (Fig. 3) demonstrates that the relationship between the quantities $\Delta\varepsilon_e^*$ and $\Delta\varepsilon^*$ can be described by the formula

$$\Delta\varepsilon^* = B(\Delta\varepsilon_e^*)^k, \quad (5)$$

where B and k are coefficients depending only on the radius of the stress concentrator ρ because the quantity $\Delta\varepsilon_e^*$ is a function of this parameter [7]. Specifically, for V95pchT2 alloy, we can write

$$B = 1.13\rho^{0.046}, \quad k = -0.016\rho^2 + 0.161\rho + 1.046. \quad (6)$$

In this case, relation (4) takes the form

$$N_i = 10,946[B(\Delta\varepsilon_e^*)^k]^{-2.2}. \quad (7)$$

Hence, in the analyzed case, the procedure of evaluation of durability can be described as follows:

- for a standard compact specimen, we plot the dependences $\Delta\varepsilon_e^*(N_i)$ and $\Delta\varepsilon^*(N_i)$ for notches of different radii ρ_j ($j = 1, 2, 3, \dots, n; n \geq 3$) and determine, for a given material, the coefficients of the basic dependences (3) and (5), i.e., ε'_f , m , B , and k ;
- for a specimen (structural element) of any shape, we measure only the ranges of the elastic component of local strains near all notches, compute the values of $(N_i^{\text{cal}})_j$ by using formula (7), and choose the smallest of these values.

This value of N_i^{cal} is in good agreement with the experimentally determined value N_i^{exp} (Table 2).

Thus, the experimental data obtained for specimens of complex geometry demonstrate the applicability of the proposed approach (Fig. 2). If, for a given material, we have dependences similar to (4) and (7), then it is possible to predict, with sufficiently high accuracy, the period of initiation of fatigue macrocracks N_i in structures with stress concentrators according to the measured values of the range of their opening displacements (either the range of the elastic component or the total range).

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