

EVALUATION OF CYCLIC ELASTOPLASTIC STRAINS NEAR NOTCHES

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On the basis of direct measurements of the opening displacements of notch contours, we develop an experimental-numerical procedure for the evaluation of the range of local elastoplastic strains $\Delta \varepsilon_r$. The experimental values of $\Delta \varepsilon_r$ are compared with the data of numerical calculations performed by using formulas known from the literature ($\Delta \varepsilon$). It is shown that, for $\Delta \varepsilon_r(\Delta \varepsilon) < 2\%$, the experimental and theoretical values are in good agreement but only in the case where the gradients of strains near the tips of the notches are taken into account. For $\Delta \varepsilon_r > 2\%$, the theoretical values of $\Delta \varepsilon$ are higher than experimental $\Delta \varepsilon_r$ and the smaller the radius of the notch ρ , the greater the difference between these values. Therefore, it is reasonable to use the experimentally evaluated and approved values of the parameter $\Delta \varepsilon_r$.

Difficulties encountered in the analysis of the stress-strain state near concentrators in various structures, especially in the presence of elastoplastic strains, force the researchers to seek new simpler approaches and criteria aimed at the evaluation of the service life of structural members. For this purpose, strain parameters and criteria prove to be the best possible choice because strains can be not only computed but also experimentally measured. The aim of the present work is to perform the comparative analysis of the values of local strains near the notch tips obtained by numerical calculations performed according to the well-known formulas and the data obtained by using the experimental-numerical approach developed by the authors.

As the most popular and widespread numerical method, one can mention the approach suggested by Neuber [1] who derived the following relationship between local elastoplastic strains ε and stresses σ at the notch tip and nominal stresses S_n and strains e_n :

$$K_t^2 = K_\sigma K_\varepsilon = \frac{\sigma}{S_n} \frac{\varepsilon}{e_n}, \quad (1)$$

where K_t is the theoretical value of the stress concentration factor, K_σ is effective stress concentration factor, and K_ε is the effective strain concentration factor.

To determine local cyclic strains and stresses in elastoplastic materials, one must take into account both the nonlinear character of the stress-strain diagram and the cyclic character of loading. This is why dependences of this sort are established [2] on the basis of experimental curves of cyclic deformation of smooth specimens described by the Ramberg-Osgood equation

$$\Delta \varepsilon = \Delta \varepsilon_e + \Delta \varepsilon_p = \frac{\Delta \sigma}{E} + \left(\frac{\Delta \sigma}{K} \right)^{1/n}, \quad (2)$$

where $\Delta \sigma$ is the range of stresses, $\Delta \varepsilon_e$ is the range of the elastic component of the total strain $\Delta \varepsilon$, $\Delta \varepsilon_p$ is the range of the plastic component of the total strain, n is the index of cyclic strain hardening, and K is the plastic modulus. Then, in the case of plasticity localized in the vicinity of a notch, the Neuber equation takes the form [3]

$$\frac{K_t^2 \Delta S_n^2}{2E} = \frac{\Delta \sigma \Delta \varepsilon}{2} = \frac{\Delta \sigma}{2} \left[\frac{\Delta \sigma}{E} + \left(\frac{\Delta \sigma}{K} \right)^{1/n} \right]. \quad (3)$$

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At the same time, it was experimentally established [3] that the application of the system of equations (2) and (3) leads to overestimated values of local strains. In [4], Molski and Glinka proposed an alternative approach based on the application of the criterion of density of elastoplastic strain energy. By using the stabilized curve of cyclic deformation of smooth specimens described by Eq. (2), one can determine local elastoplastic stresses $\Delta\sigma$ and strains $\Delta\varepsilon$ at the tip of the concentrator for nominal stresses ΔS_n and the theoretical value of the stress concentration factor K_t by using the system of equations (2) and (4)

$$\frac{K_t^2 \Delta S_n^2}{2E} = \frac{\Delta\sigma^2}{2E} + \frac{\Delta\sigma}{(n+1)} \left(\frac{\Delta\sigma}{K} \right)^{1/n}. \quad (4)$$

By comparing the experimental data with the data of numerical calculations, it was shown [3] that the energy method of Glinka gives fairly accurate results in determining the levels of strains at the tips of the notches in specimens of different shapes with K_t varying within the range 1.97–4.6 if the levels of strains do not exceed 1.5–2.0%. However, in each special case, one must construct a new computational scheme for the evaluation of the parameters ΔS_n and K_t , which makes numerical analysis extremely laborious if the configuration of investigated objects is complicated. Moreover, this model is characterized by limited applicability to plastic materials ($n \rightarrow 0$) with sharp notches, i.e., for high values of K_t . It is also not clear whether it is possible to simulate fracture processes near notches on the basis of the curves of cyclic deformation of smooth specimens. The experimental results [5] demonstrate that near notches (especially sharp) local stresses are higher than the yield limit and ultimate strength measured for smooth specimens by a factor of 2–3.

Stadnyk and Riznychuk [6] proposed to estimate the range of plastic strains $\Delta\varepsilon_p$ at the tip of the concentrator ($x=0$) by the formula derived from the equation for the density of strain energy

$$\Delta\varepsilon_p(0) = \frac{4(K_{I\max}^2(h) - K_{I\min}^2(h))}{\pi\rho E\sigma_y(1 + (\rho_0\rho^{-1})^2)^{1/2}}, \quad (5)$$

where $K_I(h)$ is the stress intensity factor for the equivalent crack whose length is equal to the depth of the notch h ,

$$\rho_0 = \frac{4K_{Ic}^2}{\pi E\sigma_y\varepsilon_c}$$

is a material constant, ε_c is the tensile fracture strain under static loading, σ_y is the plastic limit, E is the elastic modulus, K_{Ic} is fracture toughness, and ρ is the radius of the notch.

In zero-to-tension cycles, we have $K_{I\min}(h) = 0$ and $\Delta K(h) = K_{I\max}(h)$. Moreover, for thin-sheet materials under cyclic loading, it seems reasonable to use the characteristic of cyclic fracture toughness ΔK_{fc} instead of static fracture toughness K_{Ic} . Since it is impossible to determine the parameter ΔK_{fc} for thin-sheet plastic materials with sufficiently high accuracy, we can take the value of ΔK for very high fatigue crack growth rates ($v > 10^{-5}$ m/cycle) as ΔK_{fc} . As a result, relation (5) takes the form

$$\Delta\varepsilon_p(0) = \frac{4\Delta K^2(h)}{\pi\rho E\sigma_y(1 + (\rho_0\rho^{-1})^2)^{1/2}}, \quad (6)$$

where

$$\rho_0 = \frac{4\Delta K_{fc}^2}{\pi E\sigma_y\varepsilon_c}.$$

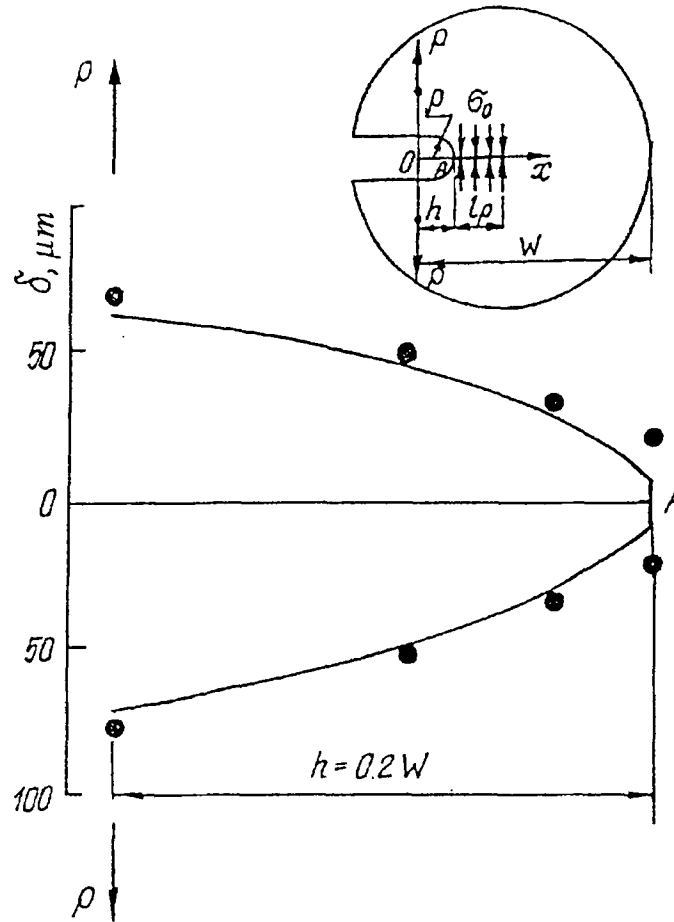


Fig. 1. Notch tip opening displacement (for a notch with root radius $\rho = 4$ mm) in disk specimens under the action of the load $P \approx 3$ kN. The numerical and experimental data are displayed by the solid line and dark symbols, respectively.

Expression (5) is used to describe low-cycle fracture ($N < 10^3$) caused by the plastic component of strains. However, as the number of cycles to fracture increases, plastic strains become comparable with elastic. Therefore, for $N > 10^3$, one must also take into account the elastic component of strains, e.g., in the form [7]

$$\Delta \epsilon_e = \frac{\Delta \sigma_R}{E},$$

where $\Delta \sigma_R$ is the fatigue limit for smooth specimens. As a result, we arrive at the following relation:

$$\Delta \epsilon(0) = \frac{4 \Delta K^2(h)}{\pi \rho E \sigma_y (1 + (\rho_0 \rho^{-1})^2)^{1/2}} + \frac{\Delta \sigma_R}{E}. \quad (7)$$

Distributions of elastoplastic strains near the tips of cracks or notches are analyzed by using both experimental and numerical methods. For their experimental determination, it is customary to use small strain gauges [3, 8], the methods of marks and small-base nets [8], photosensitive coatings [11], etc. In view of the fact that the fracture processes in notched bodies are actually governed not by the entire plastic zone but by the prefracture zone localized in the subsurface layers along the contour of the notch tips [12], these methods are characterized by significant shortcomings. For sharp notches, strain gauges fail to measure local strains because their base is greater than the prefrac-

ture zone by an order of magnitude. In this case, the method of marks is preferable but it requires the application of sophisticated optic equipment. In the case of blunt notches, this method sometimes fails to determine the integral level of strains in the prefracture zone. The indicated methods are based on the results of observation of the surface. Therefore, they do not take into account the strain gradient across the specimen thickness.

Table 1

Object	Notch tip opening displacement δ_A , μm		
	Experiment	Computation according to the model of plastic strips (PS)	
		without oblique PS	with oblique PS
Notch $\rho = 0.75$ mm	10	3	9
Notch $\rho = 4.00$ mm	22	5	23
Notch $\rho = 6.50$ mm	33	7	33

Comment: Material: D16T aluminum alloy (4 mm in thickness).

It is more efficient to compute local strains in terms of crack (notch) tip opening displacements δ [13–15]. As a common disadvantage of the well-known experimental methods for the evaluation of crack opening displacements [16–18], one can mention the fact that all these methods are designed only for cracks and determine opening displacements δ by the method of similar triangles for measurements carried out at a certain distance from crack tips. This fact substantially restricts their applicability both to elastoplastic and notched bodies because direct experimental measurements and numerical analysis demonstrate [19] that the opening displacement of a notch at a certain distance from its tip δ_x is a nonlinear function of the notch tip opening displacement δ_A (see Fig. 1) and depends on the radius of the notch. The difference between theoretical and experimental values of the opening displacement δ_A is explained by the fact [19] that the plastic zone near the notch tip increases with the radius of the notch and, hence, cannot be simulated by a thin cut according to the model of plastic strips. One must necessarily take into account oblique plastic strips formed around the notch contour in the prefracture zone (Table 1). Therefore, to determine the actual values of notch tip opening displacements, one must either establish nonlinear relationships between the values of δ_A and δ_x or develop analytic and experimental methods for the estimation of opening displacements in the immediate vicinity of the notch tip. The necessity of measuring opening displacements in the immediate vicinity of the tip and the efficiency of their application as parameters of the fracture process is corroborated by the application of the quantity δ_5 in the case of cracks [20]. For analytic methods, it is necessary to improve the model of plastic strips which takes into account the system of oblique strips on the notch contour.

In developing the experimental procedure aimed at measuring opening displacements near the notch tip [21], it was discovered that the dependence of $\Delta\delta$ on x_g is nonlinear (see Fig. 2a). It was also proposed to measure opening displacements $\Delta\delta_p$ along the line of the center of curvature of the notch (Fig. 2b). Then the legs of the gauge are located outside the plastic zone and the opening displacement is the integral characteristic of elastoplastic strains not only on the lateral surfaces but also across the specimen thickness. Strains near the notch tip are computed [21] on the basis of the model of fatigue fracture [12]. It is assumed that these strains are largely caused by the integral deformation of the prefracture zone d^* along the notch contour with the effective radius of curvature $\rho_{\text{eff}} = \rho + d^*$ (see the diagram in Fig. 2). This enables us to suggest the following formula for the evaluation of local elastoplastic strains near the notch tip in terms of its opening displacement [21]:

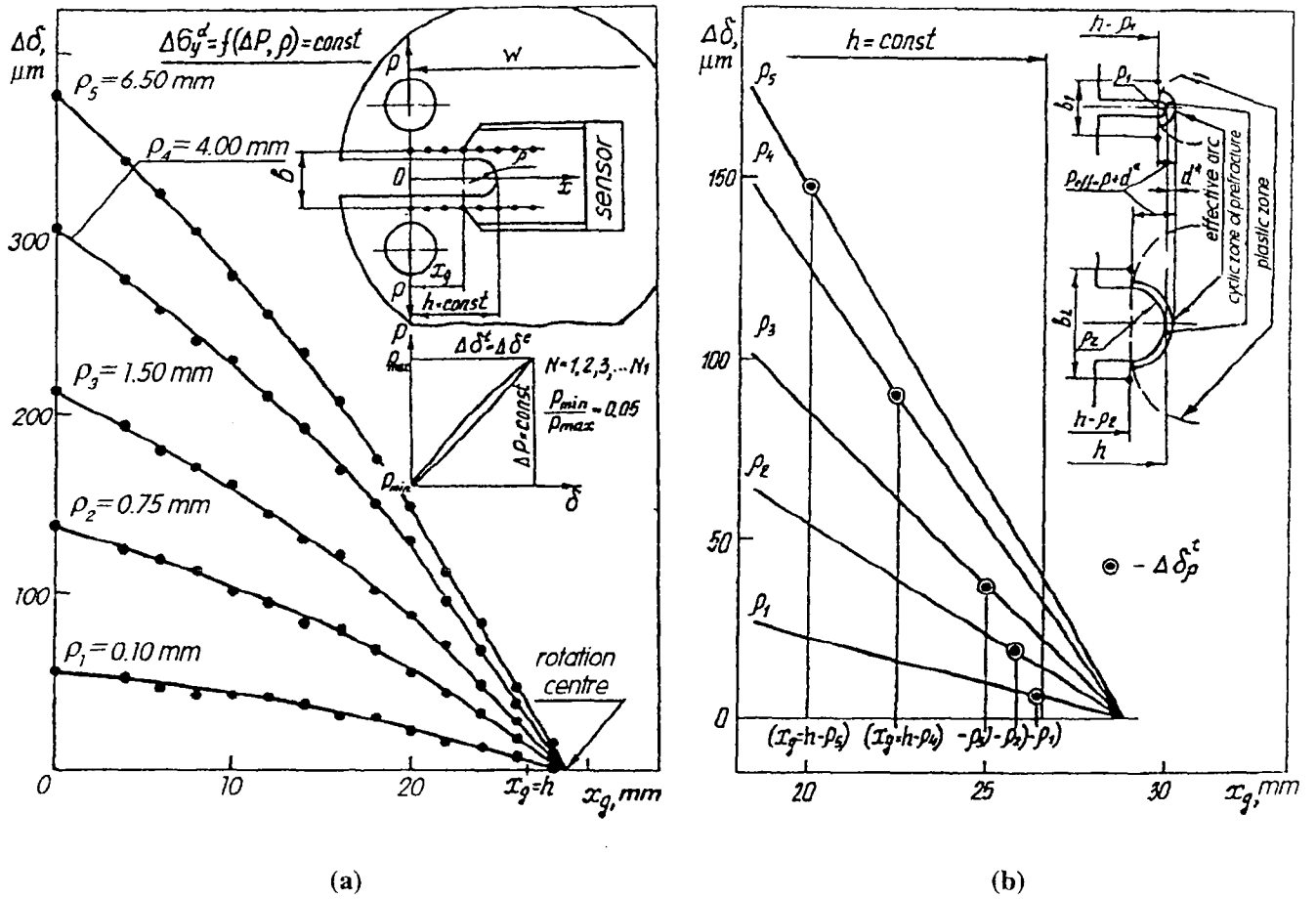


Fig. 2. Measurements of the opening displacements $\Delta\delta$ (displacements of the lips) of a notch in a disk specimen for different radii ρ of the notch (a) and evaluation of the quantity $\Delta\delta'_p$ for 1440T1 aluminum alloy (b).

$$\Delta\epsilon_t = \ln \left[1 + \frac{\Delta\delta'_p}{\pi(\rho + d^*)} \right], \quad (8)$$

where $\Delta\delta'_p$ is the total range of opening displacements $\Delta\delta$ for $x = h - \rho$, i.e., along the line which passes through the center of curvature of the notch.

The experimental-numerical determination of elastoplastic strains was carried out for plastic materials of various types (Table 2) under cyclic loading with a frequency of 10–15 Hz and a load ratio R of 0.05. We tested compact specimens with base sizes $W = 64 \text{ mm}$ (AMg6 alloy and 08KP steel) and $W = 40 \text{ mm}$ (VCh50 cast iron) 4–8 mm in thickness. Each specimen had a lateral notch with radius $\rho = 0.1$ –4.0 mm and depth $h = (0.2 - 0.7)W$. In this case, the coefficient K_t varies within the range 1.89–15.77 (Table 3).

For high amplitudes of zero-to-tension (pulsating) loading, the stress-strain diagram (the dependence of the opening displacement on the load; see the diagram in Fig. 3a) is nonlinear in the first cycle. This effect is readily detected for blunt notches but is absent (Fig. 3b) or very weak for sufficiently sharp notches. At the same time, beginning with the second cycle, the range of opening displacements $\Delta\delta'_p$ decreases and does not change up to the initiation of a macrocrack ($N = N_1$). The subsequent growth of $\Delta\delta'_p$ for $N > N_1$ is explained by the propagation of a macrocrack of length l (Fig. 3). The decrement of the range of opening displacements after the first loading

cycle and the stabilized value of the range are regarded, respectively, as the plastic $\Delta\delta_p^p$ and elastic $\Delta\delta_p^e$ components of the total range of opening displacements $\Delta\delta_p'$. Hence, for plastic materials, relation (8) takes the form

$$\Delta\varepsilon_t = \ln \left[1 + \frac{\Delta\delta_p^e + \Delta\delta_p^p}{\pi(\rho + d^*)} \right]. \quad (9)$$

Table 2

Material	$\sigma_{0.2}$, MPa	σ_u , MPa	δ , %	E , GPa	ΔK_{fc} , MPa $\sqrt{m}$	K , MPa	n	d^* , μm
AMg6 alloy	175	340	22	71	33	405	0.08	$\frac{270}{100}$
08kP steel	190	270	48	206	72	285	0.02	$\frac{250}{200}$
VCh50 cast iron	310	510	14	160	62	766	0.18	$\frac{200}{200}$

Comment: The values of d^* for the numbers of cycles to failure $N = 10^5 - 10^6$ and $N = 10^3 - 10^5$ are presented in the numerator and denominator, respectively.

For low loading amplitudes (the number of cycles to failure $N > 10^5$ cycles), the plastic component decreases to zero (Fig. 3). A similar distribution of the elastic and plastic components of the strain range as functions of the number of cycles to failure was obtained for smooth specimens [22]. However, the ratio of the plastic component of strain range to its elastic component $\Delta\varepsilon_p/\Delta\varepsilon_e$ increases with the radius of the notch [21] and is maximum for smooth specimens. Strains in the vicinity of sharp notches (cracks) behave as "elastic" (see the diagram in Fig. 3) even for high loading amplitudes and attain values which are much higher than the levels of elastic strains observed in smooth specimens (which never exceed 0.2%) (Table 3). This is explained by the fact that plastic deformation is observed in small volumes surrounded by large amounts of elastically deformed material. This fact requires additional investigation of the physical nature of deformed metal in the indicated local volumes. It must lead to errors in predicting the service life of bodies with sharp notches (cracks) according to the results of testing of smooth specimens, in particular, in the high-amplitude region and for small radii of the notches.

The ranges of local strains determined by using the experimental-numerical procedure based on the application of formula (9) were compared with the values computed according to relations (3), (4), and (7). As follows from Table 3, the values computed for oblique notches ($K_t = 2-4$) by using formula (4) are in good agreement with the experimental data, except those obtained for high loading amplitudes.

Computations performed according to Neuber give overestimated results in agreement with the literature data [3]. On passing to sharp notches ($K_t = 5-16$), the numerical values (obtained according to Neuber and Glinka) become much higher than experimental; moreover, the sharper notch, the greater the difference between these values. This observation also does not disagree with conclusions made in [3]. Indeed, for $n \rightarrow 0$ and high values of K_t , Eq. (4) may be inapplicable. The analysis performed according to relation (7) suggested by the authors coincides with the experimental data only for very sharp notches ($\rho = 0.1$ mm) and low and medium loading amplitudes. As the radius of the notch increases, the numerical values become much higher than experimentally measured strains.

The maximum of local stresses [23] and strains [24] is attained at a certain distance from the tip of the notch. This fact was used as a basis of the model of fatigue fracture of materials suggested by the authors in [12, 21]. According to this model, the indicated maximum is attained at the point $x = d^*$.

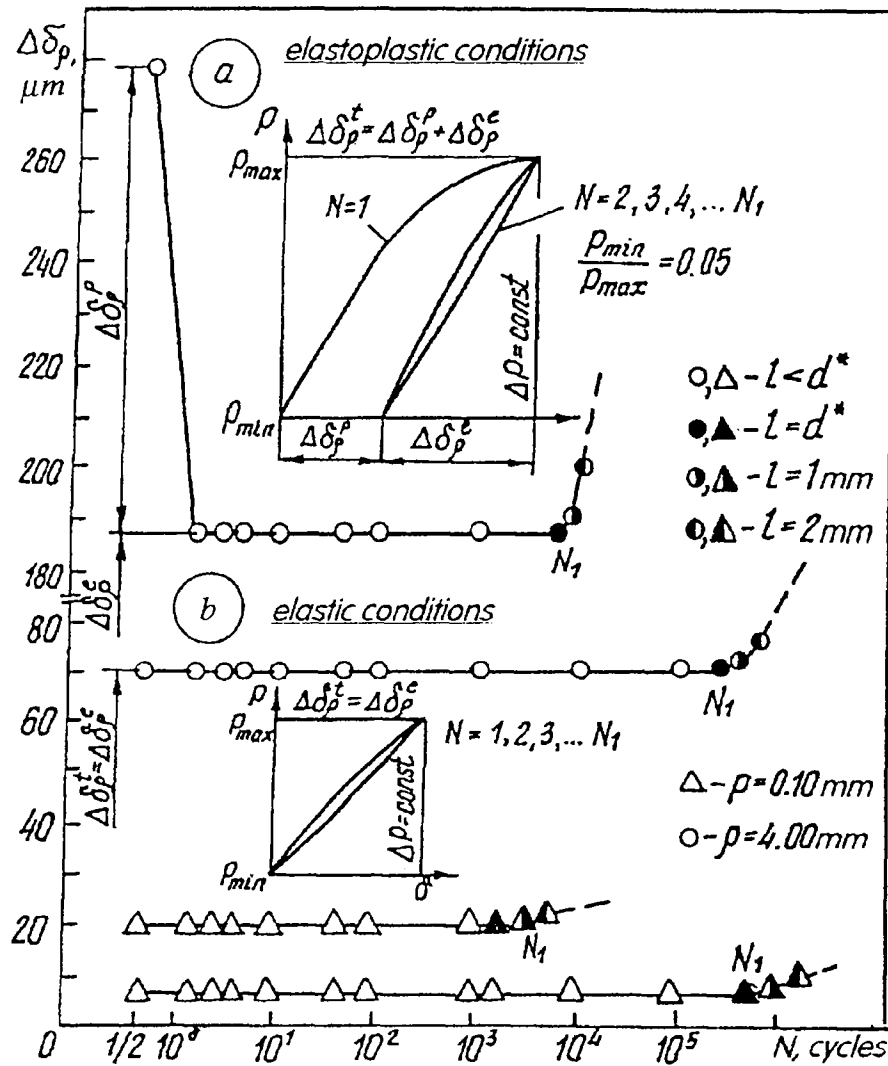


Fig. 3. Notch opening displacement $\Delta\delta_p$ as a function of the number of loading cycles of a given amplitude for AMg6 aluminum alloy.

Table 3

Material	ρ , mm	h/W	K_t	$K_t \Delta S_n$, MPa	Computation according to different formulas							Experiment	
					$\Delta \varepsilon$ for $x = 0$, %			$\Delta \varepsilon$ for $x = d^*$, %				$\Delta \varepsilon_{\text{ex}}$, % $\Delta \varepsilon_f$, %	
					(3)	(4)	(7)	(3) and (11)	(4) and (10)	(3) and (11)	(7) and (11)		
AMG6	0.10	0.21	15.77	416	1.34	0.95	0.35	0.71	0.39	0.50	0.19	0.50	0.50
		0.24	15.76	620	3.09	1.95	0.83	1.64	0.79	1.03	0.44	1.05	1.05
	0.20	15.77	1100	9.80	5.71	2.09	5.19	2.32	3.03	1.12	2.04	2.04	2.04
	0.21	15.77	1428	16.06	9.13	3.36	8.51	3.71	4.84	1.78	2.63	2.63	2.63

Material	ρ , mm	h/W	K_t	$K_t \Delta S_n$ MPa	Computation according to different formulas							Experiment		
					$\Delta \varepsilon$ for $x = 0$, %			$\Delta \varepsilon$ for $x = d^*$, %						
					(3)	(4)	(7)	(3) and (11)	(4) and (10)	(3) and (11)	(7) and (11)	$\Delta \varepsilon_0$ %	$\Delta \varepsilon_f$ %	
AMG6	0.75	0.19	5.99	344	0.90	0.67	0.95	0.73	0.51	0.54	0.77	0.55	0.55	
		0.25	5.79	550	2.49	1.58	2.05	2.02	1.21	1.28	1.66	1.20	1.20	
		0.36	5.71	733	4.43	2.67	3.46	3.59	2.05	2.16	2.80	1.71	1.85	
		0.48	5.14	1387	14.97	8.81	11.76	12.13	6.75	7.14	9.76	2.54	2.90	
	1.50	0.28	4.37	352	0.82	0.70	1.04	0.72	0.61	0.62	0.91	0.57	0.60	
		0.45	3.86	490	1.95	1.30	1.79	1.72	1.13	1.14	1.57	1.05	1.23	
		0.60	3.20	685	3.83	2.40	3.36	3.37	2.08	2.11	2.96	1.56	1.90	
		0.67	2.88	1041	9.13	4.94	7.22	8.03	4.28	4.35	6.35	1.98	2.60	
	4.00	0.29	2.72	207	0.31	0.31	0.52	0.29	0.29	0.29	0.49	0.39	0.39	
		0.36	2.51	570	2.52	1.64	2.33	2.39	1.55	1.56	2.20	0.96	1.60	
		0.56	2.13	702	3.34	2.49	3.41	3.17	2.35	2.36	3.22	1.43	2.17	
		0.43	2.48	997	8.20	4.76	6.63	7.79	4.50	4.52	6.27	1.72	3.26	
	08KP	0.15	0.26	13.80	780	2.11	1.14	0.76	1.05	0.43	0.57	0.38	0.51	0.51
			0.25	13.84	1318	6.12	3.19	1.87	3.06	1.21	1.55	0.94	1.35	1.35
			0.28	13.78	1820	11.77	6.01	3.42	5.88	2.28	3.01	1.71	1.62	1.98
			0.31	13.65	3115	33.43	17.53	9.73	16.72	6.66	8.66	4.86	2.07	2.68
	0.75	0.23	6.53	500	0.71	0.41	0.68	0.50	0.26	0.29	0.48	0.30	0.30	
		0.23	6.53	1000	3.55	1.30	2.34	2.52	0.82	0.92	1.66	0.73	0.90	
		0.26	6.42	1090	4.11	2.22	2.63	2.92	1.40	1.57	1.87	0.94	1.34	
		0.27	6.28	1500	7.89	4.10	4.84	5.60	2.59	2.91	3.44	1.46	2.25	
	4.00	0.58	2.08	427	0.56	0.33	0.53	0.50	0.30	0.30	0.48	0.30	0.30	
		0.50	2.29	597	1.18	0.66	0.89	1.07	0.59	0.60	0.81	0.50	0.60	
		0.60	1.89	750	1.95	1.05	1.31	1.77	0.95	0.95	1.19	0.68	0.85	
		0.59	1.90	1100	4.13	2.25	2.64	3.76	2.06	2.05	2.38	0.94	1.83	

Material	ρ , mm	h/W	K_t	$K_t \Delta S_n$ MPa	Computation according to different formulas							Experiment	
					$\Delta \varepsilon$ for $x = 0$, %			$\Delta \varepsilon$ for $x = d^*$, %					
					(3)	(4)	(7)	(3) and (11)	(4) and (10)	(3) and (11)	(7) and (11)	$\Delta \varepsilon_s$, %	$\Delta \varepsilon_f$, %
VCh50	0.10	0.24	12.46	781	1.91	1.14	0.58	0.96	0.41	0.57	0.16	0.53	0.53
		0.25	12.40	1041	3.24	1.85	0.81	1.62	0.66	0.92	0.22	0.85	0.85
		0.40	12.10	1386	5.17	3.00	1.33	2.59	1.07	1.50	0.36	1.06	1.30
		0.62	8.83	2073	10.42	5.90	2.18	5.21	2.11	2.95	0.58	1.26	1.68
	0.75	0.26	5.38	610	1.18	0.75	0.72	0.84	0.47	0.52	0.48	0.46	0.46
		0.29	4.89	935	2.88	1.55	1.49	2.04	0.98	1.10	0.99	0.82	0.98
		0.31	4.12	1080	3.27	1.92	1.73	2.32	1.82	1.37	1.15	0.90	1.20
		0.63	3.38	1644	6.99	3.90	3.67	4.96	2.46	2.78	2.44	1.23	1.69
	3.00	0.30	2.50	500	0.82	0.55	0.38	0.72	0.48	0.48	0.33	0.50	0.52
		0.46	2.20	773	1.82	1.11	0.56	1.59	0.96	0.97	0.49	0.75	0.93
		0.47	2.18	1110	3.39	1.98	0.89	2.96	1.71	1.73	0.78	0.97	1.50
		0.52	1.92	1498	5.81	3.35	1.42	5.08	2.90	2.93	1.24	1.35	1.97

Note that Glinka [3] made an attempt to analyze fracture processes near sharp notches (cracks) by using not the maximum values of strains at the tip but their levels at a certain distance from the tip. Therefore, the levels of strains computed according to relations (3), (4), and (7) were corrected by taking into account their gradient, i.e., they were determined at a distance $x = d^*$ from the tip of the notch. For this purpose, one may use either the following formula for the distributions of stresses and strains near the notch suggested by Usami [25]:

$$\Delta \varepsilon_x = \frac{\Delta \varepsilon(0)}{3} \left[1 + \frac{1}{2} \left(1 + \frac{x}{\rho} \right)^{-2} + \frac{3}{2} \left(1 + \frac{x}{\rho} \right)^{-4} \right], \quad (10)$$

or the formula deduced by Ostash, which takes into account the effective radius of curvature of the notch ρ_{eff} [12, 21]:

$$\Delta \varepsilon_x = \Delta \varepsilon(0) \frac{(1 + x\rho_{\text{eff}}^{-1})(1 - 30\alpha\beta)}{(1 + 2x\rho_{\text{eff}}^{-1})^{1.5}}, \quad (11)$$

where

$$\rho_{\text{eff}} = \rho + d^*, \quad \alpha = \frac{\rho}{W}, \quad \beta = \frac{d^*}{W},$$

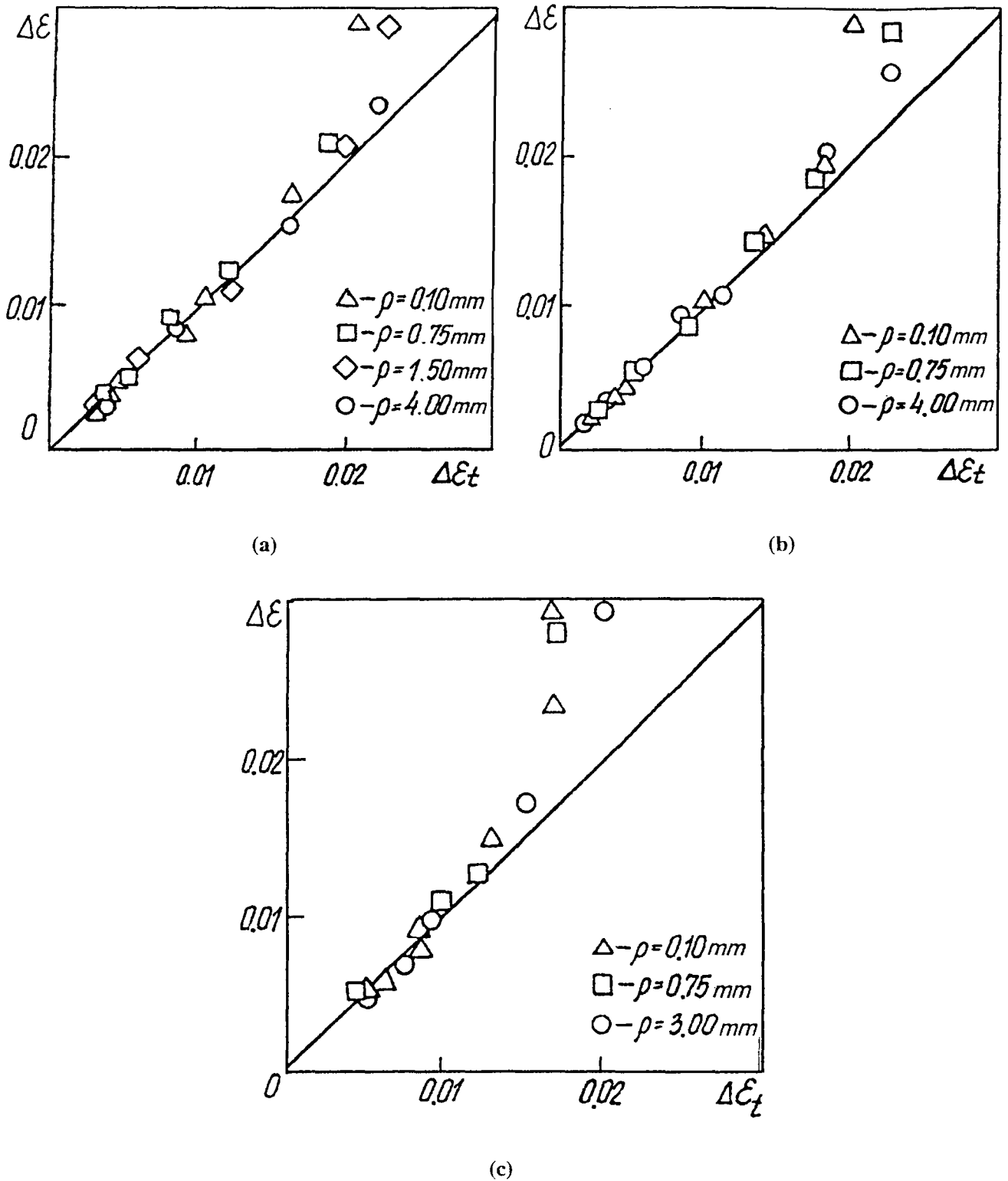


Fig. 4. Comparison of the values of local strains $\Delta\epsilon$ obtained numerically according to formulas (4) and (11) and by using the experimental-numerical procedure $\Delta\epsilon_t$ for AMg6 aluminum alloy (a), 08KP steel (b), and VCh50 cast iron (c).

and W is the characteristic size of a compact specimen. This approach corresponds to the concept of the experimental-numerical procedure for the determination of local strains examined in the present work. In relations (10) and (11), the values of $\Delta\epsilon(0)$ at the notch tip were computed by using relations (3), (4), and (7).

Relations (4) and (11) guarantee the best possible agreement of numerical and experimental data for any radius ρ when the level of strains does not exceed 1.5–2.0% (Table 3 and Fig. 4). This enables us to conclude that the values of $\Delta\epsilon_t$ and $\Delta\epsilon$ are reliable. If the level of strains is higher than 2%, the numerical results are overestimated for all investigated materials and radii ρ . In this case, the proposed experimental procedure proves to be more adequate because its applicability to the evaluation of invariant characteristics of resistance of the material to the initiation of fatigue macrocracks [21] was checked in a broad range of strain amplitudes (0.2–5.0%). Due to its relative simplicity, this procedure can be efficiently applied in engineering practice.

CONCLUSIONS

It was proved that local strains in the vicinities of notches (cracks) are determined by the total level of strains in the characteristic prefracture zone.

We experimentally demonstrated that, under cyclic loading, stresses in local volumes of the material near sharp notches are linear functions of strains even for large absolute values of the latter ($\sim 2\%$) which are higher than the values of elastic strains in smooth specimens by an order of magnitude. Therefore, the application of the data obtained for smooth specimens inevitably lead to errors in the numerical analysis of the stress-strain states of bodies with sharp notches and cracks.

As for the energy approach developed by Glinka and extensively used in practice, we can conclude that it guarantees the most accurate prediction of the range of local strains $\Delta\epsilon$ near notches of different radii only in the case where $\Delta\epsilon < 2\%$ and under the condition that the strain gradient is taken into account.

REFERENCES

1. H. Neuber, "Theory of stress concentration for shear-strained prismatic bodies with arbitrary nonlinear stress-strain law," *J. Appl. Mech.*, **28**, 544–551 (1969).
2. ASTM Designation: E 606-77T. *Tentative Recommended Practice for Constant-Amplitude Low-Cycle Fatigue Testing*, ASTM (1977).
3. G. Glinka, "Energy density approach to calculation of inelastic strain-stress near notches and cracks," *Eng. Fract. Mech.*, **22**, No. 3, 485–508 (1985).
4. K. Molski and G. Glinka, "A method of elastic-plastic stress and strain at a notch root," *Mater. Sci. Eng.*, **50**, No. 1, 93–100 (1981).
5. D. M. Tracey, "Finite element solutions for crack-tip behavior in small-scale yielding," *Trans. ASME, J. Eng. Mater. Technol.*, **98**, No. 2, 58–65 (1976).
6. M. M. Stadnik and R. V. Riznichuk, "Computational model for the determination of the fatigue service life of a body weakened by a thin cavity," *Fiz.-Khim. Mekh. Mater.*, **25**, No. 3, 83–88 (1989).
7. V. P. Kogaev, N. A. Makhutov, and A. P. Gusenkov, *Durability and Strength Analysis of Machine Parts and Structures. A Handbook* [in Russian], Mashinostroyeniye, Moscow (1985).
8. E. Czoboly, B. Csizmazia, and I. Havas, "Experimental determination of plastic zones," *Fiz.-Khim. Mekh. Mater.*, **32**, No. 1, 99–110 (1996).
9. Y. Furuya and H. Shimada, "Local crack-tip strain approach to fatigue crack propagation," *Eng. Fract. Mech.*, **26**, No. 3, 349–356 (1987).
10. D. S. Dawicke and M. A. Sutton, "CTOA and crack-tunneling measurements in thin sheet 2024-T3 aluminum alloy," *Exp. Mech.*, **34**, 357–368 (1994).
11. P. S. Theocaris and E. Marketos, "Elastic-plastic analysis of perforated thin strips of a strain-hardening material," *J. Mech. Phys. Solids*, **12**, No. 6, 377–390 (1964).
12. O. P. Ostash and V. V. Panasyuk, "To the theory of initiation and growth of fatigue cracks," *Fiz.-Khim. Mekh. Mater.*, **24**, No. 1, 13–21 (1988).
13. A. E. Andreikiv, "Computational model for the evaluation of the period of initiation of a fatigue macrocrack," *Fiz.-Khim. Mekh. Mater.*, **12**, No. 6, 27–30 (1976).
14. V. V. Panasyuk, "Deformational criteria in fracture mechanics," *Fiz.-Khim. Mekh. Mater.*, **12**, No. 1, 7–17 (1986).
15. G. V. Tsybanev, "Estimation of the cyclic durability of specimens with stress concentrators according to the values of their notch opening displacements," *Probl. Prochn.*, No. 3, 26–30 (1987).

16. BS5762: 1979. *Methods for Crack Opening Displacement (COD) Testing*, The British Standards Institution, London, UK. (1979).
17. O. Kolednic and P. Kutlesa, "On the influence of specimen geometry on the critical crack-tip-opening displacement," *Eng. Fract. Mech.*, **33**, 215–223 (1989).
18. C. R. Pratap and R. K. Pandey, "A composite crack profile model for CTOD determination: II. An experimental application to a small scale yielding situation," *Eng. Fract. Mech.*, **24**, 539–552 (1986).
19. V. V. Panasyuk, H. S. Ivanyts'ka, O. P. Ostash, and E. M. Kostyk, "Theoretical-experimental determination of notch opening displacements in deformed bodies," *Fiz.-Khim. Mekh. Mater.*, **31**, No. 3, 83–90 (1995).
20. K.-H. Schwalbe and B. Neale, "A procedure for determining the fracture behavior of materials—the unified fracture mechanics test method EFAM FTP 94," *Fatigue Fract. Eng. Mater. Struct.*, **18**, No. 4, 413–424 (1995).
21. V. V. Panasyuk, O. P. Ostash, E. M. Kostyk, and R. V. Chepil', "Deformational approach to the evaluation of the periods of initiation and growth of a fatigue macrocrack," *Fiz.-Khim. Mekh. Mater.*, **31**, No. 5, 7–21 (1995).
22. D. F. Socie, I. Morrov, and W.-Ch. Chen, "A procedure for estimating the total fatigue life of notches and cracked members," *Eng. Fract. Mech.*, **11**, 851–859 (1979).
23. R. M. McMeeking, "Finite deformation analysis of crack-tip opening in elastoplastic materials and its application to fracture," *J. Mech. Phys. Solids*, **25**, No. 5, 357–381 (1977).
24. S. Karashima, H. Oikawa, and T. Ogura, "Studies on substructures around a fatigue crack in FCC metals and alloys," *Trans. Jap. Inst. Metals*, No. 3, 205–213 (1968).
25. H. Y. Ahmad, E. R. de los Rios, and J. R. Yates, "The influence of notch plasticity on short fatigue crack behavior," *Fatigue Fract. Eng. Mater. Struct.*, **17**, No. 2, 235–242 (1994).