DOI: https://doi.org/10.15407/pmach2024.02.018

UDC 539.3

CALCULATED ASSESSMENT OF CRACK DEVELOPMENT UNDER CYCLIC LOADING OF THE PLATE USING THE PARAMETERS OF DISPERSED DAMAGE OF THE MATERIAL

Pavlo P. Hontarovskyi
gontarpp@gmail.com
ORCID: 0000-0002-8503-0959

Nataliia H. Garmash
garm.nataly@gmail.com
ORCID: 0000-0002-4890-8152

Iryna I. Melezhyk
melezhyk81@gmail.com
ORCID: 0000-0002-8968-5581

Tetiana V. Protasova
tatyprotasova@gmail.com
ORCID: 0000-0003-1489-2081

Anatolii Pidhornyi Institute
of Mechanical Engineering Problems
of NAS of Ukraine,
2/10, Komunalnykiv str., Kharkiv,
61046, Ukraine

The reliable operation of structures and energy machines is related to ensuring thermal strength and durability of their elements and assemblies. Currently, a difficult situation has developed in the modern energy market; the equipment works in difficult conditions and, as a result, it is operated in variable modes, which causes accelerated wear of the resource. Ensuring the reliable use of power machines and structures of various complexity requires a calculated assessment of the thermal strength and durability of their elements, which is based on the application of new methods and calculation models taking into account a number of important factors, including damage, heterogeneity of material properties, the influence of non-stationary temperature fields and the presence of cracks. This paper is devoted to the development of the methodology for crack growth calculations in plate elements of structures under cyclic loading in an elastic-plastic setting using the concept of the accumulation of dispersed damage in the material. At the top of the crack, the processes of sign-changing elastic-plastic deformation and crack resistance of the material are simulated using data from fatigue tests of smooth samples. The thermal stress state of the structure at different loading modes is determined using finite element software for several fixed crack depths. The kinetics of a surface crack in a plate, from both edges of which cracks grow symmetrically under non-zero cyclic loading by tensile stresses, is considered in the paper. Elastic-plastic problems were solved for the cases of plane deformation and plane stress state, the amplitudes of deformation intensities and the number of loading cycles were obtained depending on the depth of crack growth. It was established that the type of stress state significantly affects the destruction of the material. Evaluation of crack development using the concept of accumulation of dispersed damage in the material has advantages for flat and axisymmetric problems, since it has no limitations for the size of the plastic zone and small crack depth. After some improvements, the calculation method can be used for three-dimensional problems of thermoplasticity.

Keywords: *crack kinetics, cyclic loading, finite element method, short-cycle fatigue curves.*

Introduction

The assessment of the reliability of structures operating under conditions of intense thermal force loadings is related to ensuring the thermal strength and durability of their elements [1–4]. When evaluating the calculated resource of elements of power machines, it is important to take into account their durability in the presence of a crack in them, which can make up a significant part of the service life [5]. The kinetics of a crack under cyclic loading can be estimated using the principles of brittle fracture mechanics using various modifications of Paris-type equations [5–8], taking into account the asymmetry of the loading cycle and the crack closure effect [9–12]. When applying techniques that use the range of the stress intensity factor to determine the parameters included in the Paris-type equation, long-term complex experiments on special samples with a crack are required.

First of all, it should be pointed out that the procedure for experimental studies of ductile fracture during plane deformation is standardized and does not require special samples with a crack. In order for the fatigue crack to remain sharp and its top not to become blunt, the cyclic load should not be intense. The thickness of the sample must be much larger than the size of the plastic zone, so that the plane stress zone is relatively small compared to the plane strain zone, otherwise we will get the properties of the sample, not the

---

material. In addition, it is necessary that the size of the crack is larger than the plasticity zone. If the required criteria are not met, the resulting viscosity values will not be a constant for the material.

Another approach for calculating the kinetics of a crack is based on the use of parameters of dispersed material damage at its top [13–16]. Thus, in [15–16], material destruction at the top of a crack under cyclic loading is determined through the amplitudes of elastic-plastic deformations and short-cycle fatigue curves for ordinary cylindrical samples. It should be noted that in this case it is advisable to take into account the scale factor, since the destruction of the material at the top of the crack occurs in a small volume, where, compared to smooth samples, defects are unlikely. Considering this, the crack kinetics will occur somewhat faster when using the parameters of dispersed damage for ordinary samples, which can give a margin for crack resistance.

In paper [15], the crack kinetics was calculated using the solution of the elastic problem by the finite element method. The distribution of the range of elastic-plastic deformations at the top of the crack was approximately determined based on Neiber's method [17]. In paper [16], the distribution of the range of elastic-plastic deformations along the path of crack development was obtained by the finite element method from solving the problem of the theory of plasticity.

The finite element discretization thickens to the top of the crack, which is modeled by a thin cut [18]. As shown by R. B. Heywood's experimental research, the radius of rounding at the top of the crack less than 0.1 mm does not affect the fatigue strength under cyclic loading.

In paper [19], crack development in lamellar and axisymmetric structures under multimode cyclic loading, taking into account the contact of the crack edges, was determined based on the concept of accumulation of dispersed damage in the material.

Statement of the crack development research problem

The problem of thermoplasticity is solved using software developed on the basis of the finite element method for several fixed crack depths l_k with an interval of 0.5–1.0 cm. At the same time, the finite elements thicken to the top of the crack with the same regularity according to the law of geometric progression. The amplitude ranges of the intensity of elastic-plastic deformations in the centers of finite elements x_m on the path of crack development are given in the form of tables $\Delta\varepsilon_m(x_m, l_{k,j})$ for all crack depths l_k for each j-th loading mode. The relative share of N_j cycles of each j-th loading mode $d_{Nj} = \frac{N_j}{N}$ is taken into account in a total number of N cycles. The path of crack development is divided into segments d_{li} with a length of about 0.1 mm, on which the crack grows in jump-like manner during the destruction of the material at its top. Diagrams of the amplitude $\Delta\varepsilon_m(x_m, l_k)$ of intensities of elastic-plastic deformations in the centers of elements $d_{li}(x_i)$ on the path of crack growth are calculated with quadratic interpolation using a table $\Delta\varepsilon_m(x_m, l_{k,j})$. This operation makes it possible to reduce computational costs by almost 100 times compared to solving the problem by the finite element method for each cycle of crack growth. The number of cycles to failure N_{pj} from the j-th loading mode is determined from the short-cycle fatigue curves for the corresponding temperature, which are given in the form of tables.

For each subsequent segment d_{li} of crack growth, the number of cycles to failure decreases both due to the increase in the amplitude of the intensity of deformations when the crack grows, and due to the accumulated damage $\Pi(x_{i+1})$ on the path of crack growth.

Diagrams of the maximum amplitudes of strain intensities for each current crack depth $\Delta\varepsilon^a_i(x_i)$ are found using quadratic interpolation for three neighboring diagrams $\Delta\varepsilon^a_i(x_i, l_{k,j})$ for fixed crack depths l_k. This is appropriate because they grow smoothly with the depth of the crack.

The increase in damage in the element $d_l(x_i)$ for one generalized loading cycle from all k_N modes is determined as

$$\Delta\Pi(x_i) = \sum_{j=1}^{k_N} \frac{d_{Nj}}{N_{pj}(x_i)}. \tag{1}$$

The number of cycles until the destruction of the closest element $d_l(x_i)$ to the top of the crack, which has a depth of l_i, is

$$N_i = \frac{1 - \Pi(x_i)}{\Delta\Pi(x_i)}, \tag{2}$$

where $\Pi(x_i)$ is the accumulated damage at the top of the crack during its growth to the current depth l_i.

The damage at other points x_i on the path of crack growth after the destruction of the next element $d_l(x_i)$ is calculated by the formula

$$\Pi(x_{i+m}) = \Pi(x_{i+m}) + \Delta\Pi(x_{i+m})N_i; \quad m = 1,2,... \tag{3}$$

The number of cycles for which the crack reaches the depth l is found as the sum of cycles from each jump-like growth of the crack

$$N(l) = \sum_i N_i \, .$$

A 6 cm wide plate, from both edges of which cracks are growing symmetrically, is considered. Their initial depth is 0.4 cm (Fig. 1). Calculations of the kinetics of the crack under non-zero cyclic loading with tensile stresses $\sigma_{z\,\max}$=300 MPa were performed. In the case of plane deformation and plane stress state, the calculation scheme is built for the fourth part of the plate with the fulfillment of symmetry boundary conditions: at y=0 – u_z=τ_{xz}=0, and at z=0 – u_x=τ_{zx}=0.

In the case of a three-dimensional problem, the corresponding calculation scheme includes a $\frac{1}{8}$ part of the plate with symmetry conditions on its middle plane equal to y=0.

The elastic characteristics of the plate material are: Young's modulus E=200,000 MPa, Poisson's ratio ν=0.3. The material deformation diagram is given in Table 1.

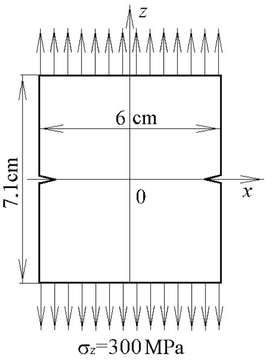

Fig. 1. Scheme of a plate with cracks

Data for low-cycle fatigue of 25Kh1M1FA (P2MA), 20Kh3M3FA (EI-415A), 15Kh1M1FA steels [20] in the form of special tables are placed in the software complex and can be supplemented with new materials. Data for P2MA steel, which depend on the temperature and amplitude of the strain intensity, are given in Table 2.

Table 1. Material deformation diagram

σ_i, MPa	400	500	600
ε_i, %	0.01730	0.04213	0.12600

Table 2. Number of cycles to failure N(T, ε_{ia})

T, °C	Amplitudes of strain intensities ε_{ia}, %								
	0.0675	0.0712	0.081	0.09	0.108	0.135	0.18	0.32	9.0
20	$6\cdot10^8$	$2\cdot10^8$	$2\cdot10^7$	$4\cdot10^6$	$1\cdot10^6$	$9\cdot10^5$	$3\cdot10^4$	8000	1.50
400	$1\cdot10^8$	$2\cdot10^7$	$4\cdot10^6$	$1\cdot10^6$	$3\cdot10^5$	$6.8\cdot10^4$	$1.5\cdot10^4$	4500	1.25
450	$2\cdot10^7$	$6\cdot10^6$	$1\cdot10^6$	$5\cdot10^5$	$1\cdot10^5$	$3\cdot10^4$	6500	2400	1.10
500	$3\cdot10^6$	$1\cdot10^6$	$3\cdot10^5$	$1\cdot10^5$	$2.5\cdot10^4$	8000	3600	1500	0.90
550	$1\cdot10^6$	$2\cdot10^5$	$4\cdot10^4$	$2\cdot10^4$	8500	4500	2000	900	0.80

The results of the calculated assessment of crack development under cyclic loading

Linear interpolation is used to obtain the number of cycles for a specific temperature. After that, quadratic interpolation is carried out for the number of cycles depending on the amplitude of the strain intensity in logarithmic coordinates.

Solutions of elastic-plastic problems using the finite element method for the cases of plane strain and plane stress state [21] are given by amplitudes of strain intensity along the path of crack growth, given in Table 3. In the first column, the arguments x_m (in cm) for the diagrams of the intensity of deformations in the centers of the finite elements, starting from the top of the crack, are given, and in the next three columns – the amplitude of the intensity of deformation (in %) for the three initial depths of the crack for the case of plane deformation, then – similar data for the plane stress state. As can be seen from the table, with the same stresses σ_z at the edges of the plate, the intensity of deformations in the case of a plane stress state is significantly greater than the amplitude of the intensity of deformations in the case of plane deformation.

The number of loading cycles $N(l)$ depending on the depth of crack growth from 4 to 12 mm in the case of plane strain and plane stress state is given in the Table 4, where $\Delta N(l)$ is the number of cycles when the crack moves by 0.1 mm.

Table 3. Amplitudes of strain intensity in the centers of finite elements along the path of crack growth

x_m, cm	Flat deformation			Flat stress state		
	l_k=0.4 cm	l_k=0.8 cm	l_k=1.2 cm	l_k=0.4 cm	l_k=0.8 cm	l_k=1.2 cm
0.0050	0.4717	0.7848	1.1165	1.0750	1.7150	2.3196
0.0155	0.0788	0.1276	0.1930	0.5090	0.8373	1.1339
0.02704	0.0632	0.0648	0.0968	0.3840	0.6543	0.8937
0.03975	0.0643	0.0571	0.0641	0.2920	0.5117	0.7021
0.05264	0.0623	0.0564	0.0573	0.2350	0.4237	0.5833
0.06731	0.0668	0.0569	0.0499	0.1940	0.3561	0.4925
0.08712	0.0707	0.0572	0.0477	0.1530	0.2946	0.4074
0.13860	0.0617	0.0571	0.0460	0.1048	0.2394	0.3272
0.15000	0.0577	0.0595	0.0477	0.0725	0.1868	0.2530
0.19868	0.0530	0.0624	0.0556	0.0644	0.1193	0.1877
0.26470	0.0510	0.0551	0.0657	0.0594	0.0684	0.1236
0.35530	0.0516	0.0534	0.0641	0.0551	0.0686	0.0714
0.45700	0.0531	0.0504	0.0576	0.0548	0.0746	0.0619

In the case of plane deformation at the top of the crack, the stress-strain state is close to all-round stretching (a significant layered stress tensor occurs). Therefore, the stress intensity is significantly lower than the tensile stress, and the crack kinetics, along with the shear deformations, are significantly affected by the separation deformations. Thus, the type of stress state significantly affects the destruction of the material.

In a plate of a given thickness, the amplitudes of the strain intensity near the crack top reach their maximum values at a short distance from the surface, but they are much smaller than the values under plane stress state and somewhat smaller than under plane strain.

The number of loading cycles $N(l)$ depending on crack growth from 4 to 12 mm for plates with a thickness of h=2.8 mm and h=10 mm is given in the Table 5.

Table 4. The number of loading cycles ΔN(l) when the crack is displaced by 0.1 mm and the number of cycles N(l) depending on the depth of crack growth

l, mm	Flat deformation		Flat stress state	
	$\Delta N(l)$	$N(l)$	$\Delta N(l)$	$N(l)$
4	418.9	418.9	78.50	78.50
4.5	355.1	2312	41.30	318
5	305.5	3935	33.60	501
5.5	265.2	5338	28.90	654
6	232.0	6562	25.10	786
6.5	204.5	7638	22.10	903
7	181.5	8589	19.60	1006
7.5	162.0	9437	17.50	1097
8	145.3	10196	15.80	1179
8.5	130.9	10878	14.30	1254
9	118.5	11495	13.10	1322
9.5	107.6	12054	12.00	1384
10	98.1	12563	11.10	1441
10.5	89.7	13028	10.30	1494
11	82.3	13454	9.57	1543
11.5	75.8	13920	8.93	1589
12	69.9	14206	8.37	1632

Table 5. Number of loading cycles N(l) depending on crack growth

l, mm	h=2.8 mm			h=10 mm		
	y=0.1 mm	y=0.5 mm	y=1.4 mm	y=0.1 mm	y=0.7 mm	y=5 mm
4	369	220	179	439	265	289
4.5	1827	1015	900	2219	1267	1571
5	3073	1672	1491	3776	2106	2675
5.5	4126	2231	1981	5151	2833	3629
6	5048	2709	2381	6381	3468	4457
6.5	5852	3119	2706	7487	4029	5180
7	6552	3472	2974	8490	4529	5812
7.5	7166	3778	3198	9403	4977	6369
8	7706	4045	3390	10238	5382	6860
8.5	8184	4281	3557	11007	5750	7295
9	8608	4489	3703	11717	6087	7682
9.5	8987	4674	3833	12375	6396	8027
10	9327	4840	3949	12988	6683	8335
10.5	9632	4988	4054	13560	6949	8611
11	9906	5122	4148	14095	7197	8857
11.5	10151	5241	4234	14597	7428	9077
12	10371	5349	4312	15070	7646	9274

Conclusions

Using the concept of the accumulation of dispersed damage in the material, a calculated assessment of crack kinetics under non-zero cyclic loading by tensile stresses was performed for a plate with cracks growing symmetrically from both edges. Amplitudes of strain intensities were obtained as a result of solving elastic-plastic problems for cases of plane strain and plane stress state using software developed on the basis of the finite element method. Depending on the depth of crack growth, the number of loading cycles is determined. The obtained results showed that the type of stress state has a significant effect on the destruction of the material.

The uneven distribution of the intensity of the deformation amplitude along the thickness of the plate near the top of the crack in the case of a three-dimensional problem [22] does not allow us to correctly consider the kinetics of the crack, since its front near the middle plane precedes the exit to the surface of the plate. At the same time, a crack in a thick plate grows more slowly than in a thin one.

The assessment of crack development using the parameters of dispersed material damage has significant advantages in the case of planar and axisymmetric problems, as it does not impose restrictions on the size of the plastic zone and small crack depth. In addition, after some improvements, it can be used to solve three-dimensional problems of thermoplasticity.

Financing

The results of this article were partially obtained as part of the research work on the Target Scientific and Technical Program of Defense Research of the National Academy of Sciences of Ukraine for 2020–2024, program expenditure classification code 6541230 (applied research).

References

1. Gontarovskyi, P., Garmash, N., & Melezhyk, I. (2023). Numerical modeling of dynamic processes of elastic-plastic deformation of axisymmetric structures. In: Altenbach H., et al. *Advances in Mechanical and Power Engineering. CAMPE 2021. Lecture Notes in Mechanical Engineering*. Cham: Springer, pp. 334–342. https://doi.org/10.1007/978-3-031-18487-1_34.
2. Hontarovskyi, P. P., Smetankina, N. V., Garmash, N. H., & Melezhyk, I. I. (2020). Analysis of crack growth in the wall of an electrolyser compartment. *Journal of Mechanical Engineering – Problemy Mashynobuduvannia,* vol. 23, no. 4, pp. 38–44. https://doi.org/10.15407/pmach2020.04.038.
3. Hontarovsky, P. P., Smetankina, N. V., Ugrimov, S. V., Harmash, N. H., & Melezhyk, I. I. (2022). Simulation of the crack resistance of ion-exchange strengthened silicate glass subject to bending strain. *International Applied Mechanics*, vol. 58, iss. 6, pp. 715–724. https://doi.org/10.1007/s10778-023-01195-0.
4. Alyokhina, S., Kostikov, A., Smetankina, N., Gontarovskyi, P., Garmash, N., & Melezhyk, I. (2021). Methodology for determining the thermal and thermal-stress states of a concrete storage container for spent nuclear fuel for assessment of its service life. *Nuclear and Radiation Safety*, no. 4 (92), pp. 33–39. https://doi.org/10.32918/nrs.2021.4(92).05.
5. Shulzhenko, M. H., Hontarovskyi, P. P., Matiukhin, Yu. I., Melezhyk, I. I., & Pozhydaiev, O. V. (2011). *Vyznachennia rozrakhunkovoho resursu ta otsinka zhyvuchosti rotoriv i korpusnykh detalei turbin* [Determination of estimated resource and evaluation of rotor life and body parts of turbines]: Methodological guidelines. Regulatory document SOU-N MEV 0.1–21677681–52:2011. Approved by the Ministry of Energy and Coal Mining of Ukraine. Effective as of 07.07.11. Kyiv: Ministry of Energy and Coal Mining of Ukraine (in Ukrainian).
6. Cherepanov, G. P. (1979). Mechanics of Brittle Fracture. New York: McGraw-Hill.
7. Kumar, P. (2009). Elements of Fracture Mechanics. New Delhi: Tata McGraw Hill Publication.
8. ASME Boiler and Pressure Vessel Code, Section XI, Appendix A, The American Society of Mechanical Engineers, New York, Addenda, 1990.
9. Bloom, J. M. (1994). An approach to account for negative R-ratio effects in fatigue crack growth calculations for pressure vessels based on crack closure concepts. *Journal of Pressure Vessel Technology*, vol. 116, iss. 1, pp. 30–35. https://doi.org/10.1115/1.2929555.
10. Alshoaibi, A. M. & Fageehi, Y. A. (2023). Numerical analysis on fatigue crack growth at negative and positive stress ratios. *Materials*, vol. 16, article 3669, 14 p. https://doi.org/10.3390/ma16103669.
11. Wu, X. R., Newman, J. C., Zhao, W., Swain, M. H., Ding, C. F., & Phillips, E. P. (1998). Small crack growth and fatigue life predictions for high-strength aluminium alloys: Part I: experimental and fracture mechanics analysis. *Fatique & Fracture of Engineering Materials & Structures,* vol. 21, iss. 11, pp. 1289–1306. https://doi.org/10.1046/j.1460-2695.1998.00080.x.
12. Newman, J. C., Wu, X. R., Swain, M. H., Zhao, W., Phillips, E. P., & Ding, C. T. (2000). Small-crack growth and fatigue life predictions for high-strength aluminium alloys. Part II: crack closure and fatigue analyses. *Fatique & Fracture of Engineering Materials & Structures*, vol. 23, iss. 1, pp. 59–72. https://doi.org/10.1046/j.1460-2695.2000.00242.x.

13. Ellyin, F. (1997) Fatigue damage, crack growth and life prediction. Dordrecht: Springer, 470 p. https://doi.org/10.1007/978-94-009-1509-1.
14. Ferreira, S. E., Pinho de Castro, J. T., & Meggiolaro, M. A. (2018). Fatigue crack growth predictions based on damage accumulation ahead of the crack tip calculated by strip-yield procedures. *International Journal of Fatigue*, vol. 115, pp. 89–106. https://doi.org/10.1016/j.ijfatigue.2018.03.001.
15. Shulzhenko, M. H., Hontarovskyi, P. P., Harmash, N. H., & Melezhyk, I. I. (2013). *Rozrakhunkove doslidzhennia rozvytku trishchyny pry tsyklichnomu navantazhenni z vykorystanniam parametriv rozsiianykh poshkodzhen* [Computational study of crack development under cyclic loading using diffuse damage parameters]. *Visnyk Ternopilskoho natsionalnoho tekhnichnoho universytetu – Scientific Journal of the Ternopil National Technical University*, vol. 71, no. 3, pp. 197–204 (in Ukrainian).
16. Shulzhenko, M. H., Hontarovskyi, P. P., Harmash, N. H., & Melezhyk, I. I. (2017). *Otsinka rozvytku trishchyny pry tsyklichnomu navantazhenni plastynchatykh elementiv iz vykorystanniam parametriv rozsiianykh poshkodzhen materialu* [Assessment of crack development during cyclic loading of lamellar elements using parameters of diffuse material damage]. *Visnyk NTU «KhPI». Seriia: Enerhetychni ta teplotekhnichni protsesy y ustatkuvannia – NTU "KhPI" Bulletin. Series: Power and Heat Engineering Processes and Equipment*, no. 9, pp. 41–44 (in Ukrainian). https://doi.org/10.20998/2078-774X.2017.09.06.
17. Pospishil, B., Kvitka, A. L., Tretyachenko, G. N., Kravchuk, L. V., Kuriat, R. I., Semenov, G. R., & Voroshko, P. P. (1987). *Prochnost i dolgovechnost elementov energeticheskogo oborudovaniya* [Strength and durability of elements of power equipment]. Kyiv: Naukova Dumka, 216 p. (in Russian).
18. Melezhyk, I. I. (2008). *Rozvytok ta vykorystannia metodyky rozrakhunkovoi otsinky zhyvuchosti vysokotemperaturnykh elementiv enerhomashyn z trishchynamy* [Development and application of a technique for a crack resistance estimation calculation of high-temperature power machines elements with cracks]: Extended abstract of Cand. Sci. (Eng.) thesis. Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the NAS of Ukraine, Kharkiv, Ukraine, 20 p. (in Ukrainian).
19. Shulzhenko, M. H., Hontarovskyi, P. P., Harmash, N. H., & Melezhyk, I. I. (2017). *Rozrakhunkova otsinka rozvytku trishchyny z kontaktuiuchymy berehamy v ploskykh elementakh konstruktsii* [Calculation assessment of crack development with contacting edges in flat structural elements]. *Visnyk Zaporizkoho natsionalnoho universytetu – Computer Science and Applied Mathematics*, no. 1, pp. 365–374 (in Ukrainian).
20. (1985). *Detali parovykh statsionarnykh turbin. Raschet na malotsiklovuyu ustalost: RTM 108.021.103-85* [Details of stationary steam turbines. Calculation for low-cycle fatigue: RTM 108.021.103-85]. Moscow, 49 p. (in Russian).
21. Podgornyy, A. N., Gontarovskiy, P. P., Kirkach, B. N., Matyukhin, Yu. I., & Khavin, G. Yu. (1989). *Zadachi kontaktnogo vzaimodeystviya elementov konstruktsiy* [Problems of contact interaction of structural elements]. Kyiv: Naukova dumka, 232 p. (in Russian).
22. Shulzhenko, N. G., Gontarovskiy, P. P., & Zaytsev, B. F. (2011). *Zadachi energeticheskikh agregatov* [Problems of energy units]. Kharkiv: Kharkiv National Automobile and Highway University, 444 p. (in Russian).

Received 10 April 2024

Розрахункова оцінка розвитку тріщини при циклічному навантаженні пластини з використанням параметрів розсіяних пошкоджень матеріалу

П. П. Гонтаровський, Н. Г. Гармаш, І. І. Мележик, Т. В. Протасова

Інститут проблем машинобудування ім. А. М. Підгорного НАН України,
61046, Україна, м. Харків, вул. Комунальників, 2/10

Надійна робота конструкцій та енергетичних машин пов'язана із забезпеченням термоміцності й довговічності їх елементів і вузлів. Нині на сучасному енергоринку склалася складна ситуація, обладнання працює у важких умовах, як наслідок, воно експлуатується на змінних режимах, що викликає прискорене спрацювання ресурсу. Забезпечення надійного використання енергетичних машин і конструкцій різної складності вимагає розрахункової оцінки термоміцності й довговічності їх елементів, що ґрунтується на застосуванні нових методик і розрахункових моделей з урахуванням ряду важливих факторів, серед яких пошкоджуваність, неоднорідність властивостей матеріалу, вплив нестаціонарних температурних полів і наявність тріщин. Дана робота присвячена розвитку методики розрахунків росту тріщини в пластинчастих елементах конструкцій при циклічному навантаженні в пружнопластичній постановці з використанням концепції накопичення розсіяних пошкоджень у матеріалі. У вершині тріщини моделюються процеси знакозмінного пружно-пластичного деформування й тріщиностійкості матеріалу з використанням даних випробувань на втому гладких зразків. Термонапружений стан конструкції на різних режимах навантаження визначається за допомогою розробленого на основі методу скінченних елементів програмного забез-

печення для кількох фіксованих глибин тріщини. У роботі розглянута кінетика поверхневої тріщини в пластині, з обох країв якої симетрично підростають тріщини при віднульовому циклічному навантаженні розтягуючими напруженнями. Пружно-пластичні задачі розв'язано для випадків плоскої деформації і плоского напруженого стану, отримано амплітуди інтенсивностей деформацій і кількість циклів навантаження залежно від глибини підростання тріщини. Встановлено, що на руйнування матеріалу суттєво впливає вид напруженого стану. Оцінка розвитку тріщин із використанням концепції накопичення розсіяних пошкоджень у матеріалі має переваги для плоских і осесиметричних задач, оскільки не має обмежень для величини пластичної зони і невеликої глибини тріщини. Після деяких удосконалень розрахункова методика може бути використана і для тривимірних задач термопластичності.

***Ключові слова**: кінетика тріщини, циклічне навантаження, метод скінченних елементів, криві малоциклової втоми.*

Література

1. Gontarovskyi P., Garmash N., Melezhyk I. Numerical modeling of dynamic processes of elastic-plastic deformation of axisymmetric structures. In: Altenbach H., et al. *Advances in Mechanical and Power Engineering. CAMPE 2021. Lecture Notes in Mechanical Engineering*. Cham: Springer, 2023. P. 334–342. https://doi.org/10.1007/978-3-031-18487-1_34.
2. Hontarovskyi P. P., Smetankina N. V., Garmash N. H., Melezhyk I. I. Analysis of crack growth in the wall of an electrolyser compartment. *Journal of Mechanical Engineering – Problemy Mashynobuduvannia.* 2020. Vol. 23. No. 4. P. 38–44. https://doi.org/10.15407/pmach2020.04.038.
3. Hontarovsky P. P., Smetankina N. V., Ugrimov S. V., Harmash N. H., Melezhyk I. I. Simulation of the crack resistance of ion-exchange strengthened silicate glass subject to bending strain. *International Applied Mechanics*. 2022. Vol. 58. Iss. 6. P. 715–724. https://doi.org/10.1007/s10778-023-01195-0.
4. Alyokhina S., Kostikov A., Smetankina N., Gontarovskyi P., Garmash N., Melezhyk I. Methodology for determining the thermal and thermal-stress states of a concrete storage container for spent nuclear fuel for assessment of its service life. *Nuclear and Radiation Safety*. 2021. No. 4 (92). P. 33–39. https://doi.org/10.32918/nrs.2021.4(92).05.
5. Визначення розрахункового ресурсу та оцінка живучості роторів і корпусних деталей турбін. Методичні вказівки: СОУ- Н МЕВ 40.1–21677681– 52:2011 / М. Г. Шульженко, П. П. Гонтаровський, Ю. І. Матюхін, І. І. Мележик, О. В. Пожидаєв. Київ: ОЕП «ГРІФРЕ»: Міністерство енергетики та вугільної промисловості України, 2011. 42 с.
6. Черепанов Г. П. Механика хрупкого разрушения. Москва: Наука, 1974. 640 с.
7. Kumar P. Elements of Fracture Mechanics. New Delhi: Tata McGraw Hill Publication, 2009. 290 p.
8. ASME Boiler and Pressure Vessel Code, Section XI, Appendix A, The American Society of Mechanical Engineers, New York, Addenda, 1990.
9. Bloom J. M. An approach to account for negative R-ratio effects in fatigue crack growth calculations for pressure vessels based on crack closure concepts. *Journal of Pressure Vessel Technology*. 1994. Vol. 116. Iss. 1. P. 30–35. https://doi.org/10.1115/1.2929555.
10. Alshoaibi A. M., Fageehi Y. A. Numerical analysis on fatigue crack growth at negative and positive stress ratios. *Materials*. 2023. Vol. 16. Article 3669, 14 p. https://doi.org/10.3390/ma16103669.
11. Wu X. R., Newman J. C., Zhao W., Swain M. H., Ding C. F., Phillips E. P. Small crack growth and fatigue life predictions for high-strength aluminium alloys: Part I: experimental and fracture mechanics analysis. *Fatique & Fracture of Engineering Materials & Structures*. 1998. Vol. 21. Iss. 11. P. 1289–1306. https://doi.org/10.1046/j.1460-2695.1998.00080.x.
12. Newman J. C., Wu X. R., Swain M. H., Zhao W., Phillips E. P., Ding C. T. Small-crack growth and fatigue life predictions for high-strength aluminium alloys. Part II: crack closure and fatigue analyses. *Fatique & Fracture of Engineering Materials & Structures*. 2000. Vol. 23. Iss. 1. P. 59–72. https://doi.org/10.1046/j.1460-2695.2000.00242.x.
13. Ellyin F. Fatigue damage, crack growth and life prediction. Dordrecht: Springer, 1997. 470 p. https://doi.org/10.1007/978-94-009-1509-1.
14. Ferreira S. E., Pinho de Castro J. T., Meggiolaro M. A. Fatigue crack growth predictions based on damage accumulation ahead of the crack tip calculated by strip-yield procedures. *International Journal of Fatigue*. 2018. Vol. 115. P. 89–106. https://doi.org/10.1016/j.ijfatigue.2018.03.001.
15. Шульженко М. Г., Гонтаровський П. П., Гармаш Н. Г., Мележик І. І. Розрахункове дослідження розвитку тріщини при циклічному навантаженні з використанням параметрів розсіяних пошкоджень. *Вісник Тернопільського національного технічного університету*. 2013. Т. 71. № 3. С. 197–204.
16. Шульженко М. Г., Гонтаровський П. П., Гармаш Н. Г., Мележик І. І. Оцінка розвитку тріщини при циклічному навантаженні пластинчатих елементів із використанням параметрів розсіяних пошкоджень матеріалу. *Вісник НТУ «ХПІ». Серія: Енергетичні та теплотехнічні процеси й устаткування.* 2017. № 9 (1231). С. 41–44. https://doi.org/10.20998/2078-774X.2017.09.06.

17. Поспишил Б., Квитка А. Л., Третьяченко Г. Н., Кравчук Л. В., Куриат Р. И., Семенов Г. Р., Ворошко П. П. Прочность и долговечность элементов энергетического оборудования. Киев: Наук. думка, 1987. 216 с.
18. Мележик І. І. Розвиток та використання методики розрахункової оцінки живучості високотемпературних елементів енергомашин з тріщинами: автореф. дис… канд. техн. наук: 05.02.09. Харків, 2008. 20 с.
19. Шульженко М. Г., Гонтаровський П. П., Гармаш Н. Г., Мележик І. І. Розрахункова оцінка розвитку тріщини з контактуючими берегами в плоских елементах конструкцій. *Вісник Запорізького національного університету*. 2017. № 1. С. 365–374.
20. РТМ 108.021.103–85. Детали паровых стационарных турбин. Расчет на малоцикловую усталость. Москва, 1986. 48 с.
21. Подгорный А. Н., Гонтаровский П. П., Киркач Б. Н., Матюхин Ю. И., Хавин Г.Ю. Задачи контактного взаимодействия элементов конструкций. Киев: Наук. думка, 1989. 232 с.
22. Шульженко Н. Г., Гонтаровский П. П., Зайцев Б. Ф. Задачи энергетических агрегатов. Харьков: ХНАДУ, 2011. 444 с.