Вісник Тернопільського національного технічного університету
Scientific Journal of the Ternopil National Technical University
2018, № 1 (89)
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

MECHANICS AND MATERIALS SCIENCE

МЕХАНІКА ТА МАТЕРІАЛОЗНАВСТВО

UDC 539.388.1:539.389.

DETERMINATION OF THE STRUCTURAL STEELS DAMAGE KINETICS UNDER NON-STATIONARY LOADING

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Summary. *The article presents adapted techniques which make possible to assess the damage of steels at high cyclic fatigue under the amplitudes varying according to the random law. The method for material damage assessment is based on the LM-hardness method. The method for estimation of the fatigue damage kinetics under random asymmetric fatigue loading is based on the use of ultimate exhaustion of cyclic plasticity model (UECP). To confirm the mentioned methods experimental results were obtained testifying the possibility of using them for estimation of steels residual lifetime under non-stationary loading. The article describes : the method, that allows laboratory samples fatigue testing under the amplitudes varying according to the random law; analysis of residual lifetime is using the proposed model and LM-hardness method; creation of the analytical model, that enables to predict fatigue lifetime under the amplitudes changing according to the random law. The presented results can be used for the lifetime estimation of structural elements operating under hard load conditions with the lower error, than those of the stabilized values of inelastic deformations and the known hypotheses of fatigue damage summation.*

Received 20.01.2018

Key words: *random loading, calculation model, inelastic deformation, damage, homogeneity coefficient, measurement methods, microstructure, LM-hardness method, cyclic loading.*

Introduction. The development of methods for the estimation of the structural elements lifetime results in the continuous widening and improvement of the available ideas on the mechanical properties of materials, especially because some problems of safety are arising, natural dizaster risk in particular. Taking into account the fact, that the material fatigue is one of the most sufficient reasons of the structural elements damage, the solving of the problems, which happened to be, is the development of scientific fundamentals of new and improvement of conventional methods for the estimation of the ultimate state of the industrial facilities of Ukraine taking into account the history of their loading, including the development and implementation of means of the scientific monitoring of the engineering health of the hazardous engineering facilities. Because of that the development of investigations on the materials damage under different loading conditions and types of stress state are of special importance.

The analysis of investigations of the structural materials deformation and fracture regularities under cyclic loadings, as well as the developed on its basis methods for the estimation of the structure elements lifetime testify, that the most part of the available investigations contain experimental data obtained under single-axis loading, and the methodic developments as to the calculation of lifetime designed for such conditions are not suitable for those conventional, under which the structure is being operated.

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Unfortunately, most available methods for the estimation of the materials damage being used in the manufacturing operations and being in operation, when different physical and mechanical parameters are treated as the measure correlating the damage, have many disadvantages, which is caused by the fact, that the stable correlation of the measured value possessing the characteristics of the mechanical properties and the structural state of the material is not available.

For many machines and structures the main type of operation loading is that of random. Depending on the product appearance and its purpose such loading can be of hard, medium or light regime of the force action on its elements and can be described by one of the known functions of the probability accumulation of the loading amplitudes. The possible drawbacks while schematization and summation of damages under the random loading at the stage of designing is compensated by the introduction of the reserve factors.

To estimate the metal damage in the investigations the method of LM-hardness was used, which makes possible to estimate the damage basing on the hardness characteristics scattering.

Besides, it is known, that the structural metal materials being under cyclic loading, can demonstrate both cyclic hardening or softening and the stability of the inelastic deformation kinetics at different stages of lifetime, which depends on the material nature and the level of loading. It is caused by the processes of hardening and softening of the material and testifies the fatigue degradation of materials (fatigue damage), that is, when the current cyclic ultimate yield is changed, the initial material plasticity is exhausted. That is, inelastic deformation is one of the characteristics of the multi-cyclic fatigue. According to the inelastic deformation rate the element lifetime can be estimated till the ultimate state is reached as the result of the plasticity exhaustion. This fact is the base of the developed earlier calculation model of the ultimate exhaustion of cyclic plasticity (UECP). The model takes advantage of the experimental data obtained at the symmetric tension-stress of the smooth specimens under the soft loading regime. Taking into account the mentioned above, it is worth the UECP model equation being applied for the method of the fatigue damages summation to predict the lifetime under the irregular regimes of the cyclic loading.

The UECP model itself is based on the calculation determination of the cycle-by-cycle change of the material ultimate cyclic yield and the damage kinetics till they reach the definite value, which is assumed to be the material ultimate state, here the material damage being treated as the continuous hardening/softening of some material volumes, which results in the exhaustion of the material plasticity lifetime and approaching the ultimate state.

The Objective and task of the work is to improve the methods for estimation of the materials damage at the fatigue under the amplitude varying according to the random law, the application of the developed earlier the LM-hardness method and the model of the ultimate exhaustions of the cyclic plasticity in particular, for the estimation of the material lifetime under random asymmetric loading. The damages must be determined step-by-step at every semi-cycle of the loading taking advantage of the UECP model.

Methods for carrying out fatigue tests under the amplitudes varying according to the random law.

The loading was created taking advantage of the electromagnetic testing machine YPC-2/30000[1]. The plane specimens were tested. The steel 45 was chosen to be the testing material. The choice is caused by the fact, that the steel 45 has already been studied for the case under the stable amplitude from the point of view of both the theoretic model being used and the methods of the damage estimation in the fatigue damages accumulation process.

The following scheme was used to describe and analyse the loading affecting the specimen. Variable loading, the frequency of which is specified by the specimen rigidity and some added loads, is transferred to the dynamometer, on which tensor-resistors are sticked connected according to the bridge network. The signal from the tensor-resistors passes to the tensor amplifier. The tensor amplifier creates the alternative voltage in the output proportional to the measured loading. The mentioned loading value passes to the linear output of the computer sound map and is controlled and recorded, if necessary, by the developed software.

The sound map of the computer was used as the generator of the random signal. The signal created by the software passed to the previous amplifier and then to YPC -2/30000 external generator input.

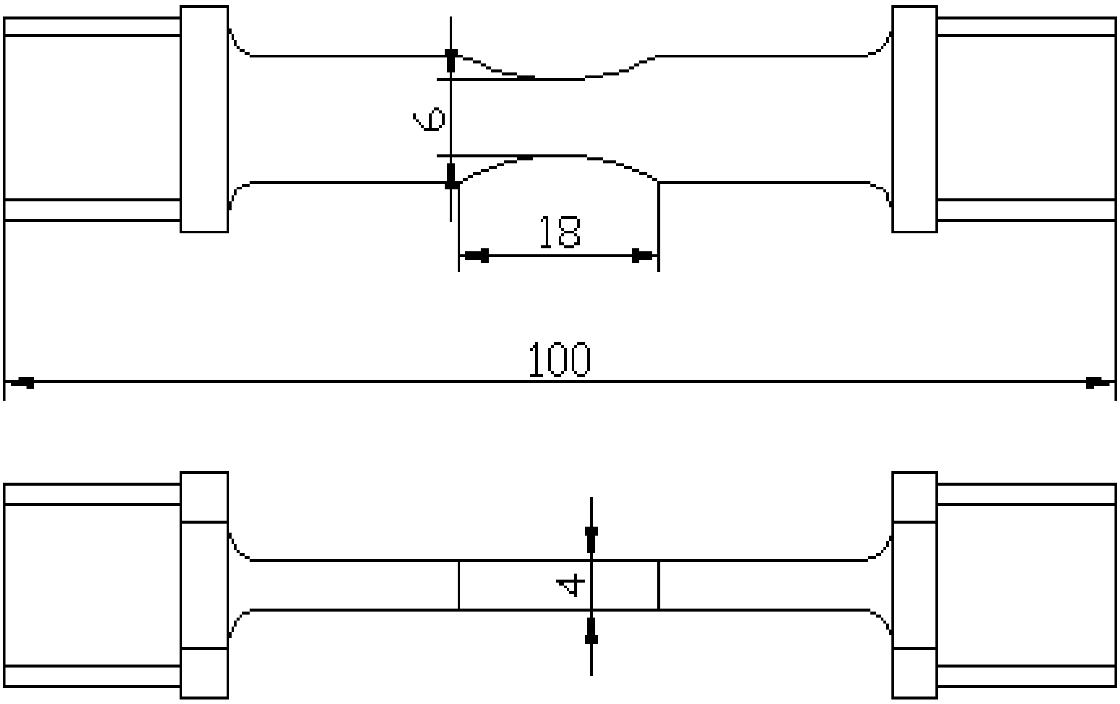


Figure 1. Specimen of steel 45 material for fatigue test

Using one software for the signal analysis and creation makes possible while testing to correct rapidly the output signal basing on the input data on the loading affecting the specimen.

In Figure 2 the fragment of the tensor amplifier signal specifying the random loading on the specimen is presented, as well as the tensor amplifier signal sample corresponding to 60 seconds of the random loading duration.

The library Mathnet. Numerics was used for the creation of the random signal. It makes possible to apply some generators of random numbers, such as the Mercen Twister 19937 generator, Whichman-Hill 1982 generator, parallel additive generator by Fibonacci, etc. Taking advantage of one of the generators the library enables to form the sequence of the random numbers, being the characteristics of the random distribution, β-distribution, the Laplace distribution, etc. The analysis of the obtained signal was carried out taking advantage of the WAFO Matlab toolbox. [2]. This library is the functions set for the analysis of the fatigue resistance under random loading.

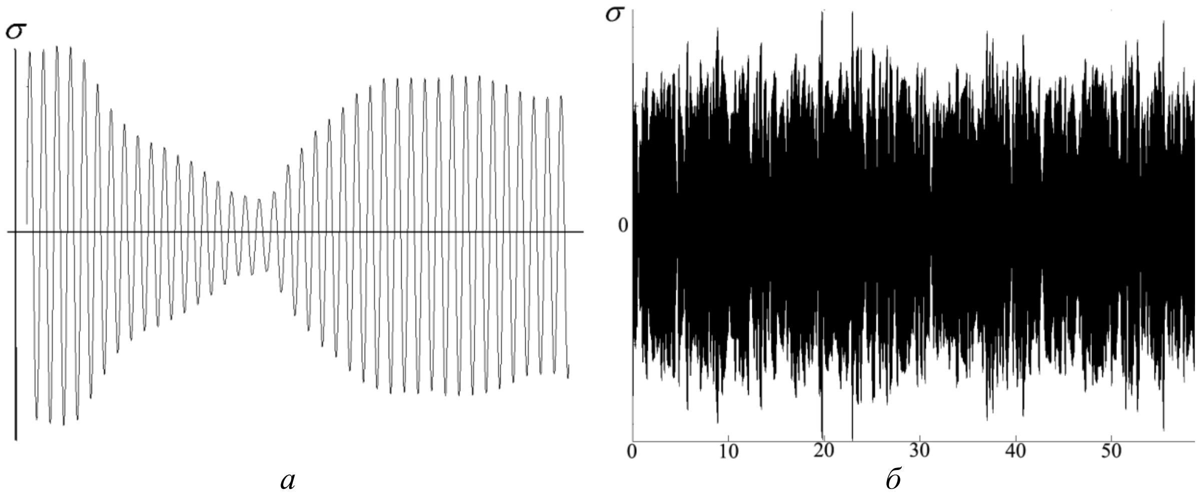


Figure 2. A fragment of the random loading (a) and a sample of the amplifier signal corresponding to 60 seconds of the random loading duration (b)

From the point of view of damage the maximum values of the amplitude cycle are of the special importance. Because of that the obtained sample was transformed into the mass of the local extremums. To avoid the noise effect the boundary was chosen, below of which the amplitude variation was not taken into account. As the result the matrix was obtained, one column of which corresponds to the time of the extremum appearance, the second one specified the extremum value. To obtain information on the cycle number with the definite loading amplitude the histogram of the random signal amplitude distribution was calculated. To build the histogram some approaches are widely used: the minimum-maximum method, the method of the level intersection, the range method, the method of "falling rain" [3]. In the paper in question the "falling rain" method was used. In Figure 3 the histogram for the random signal amplitudes distribution is presented.

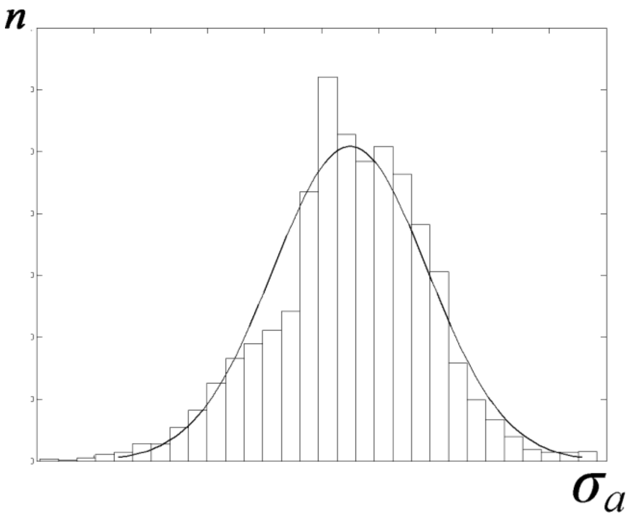
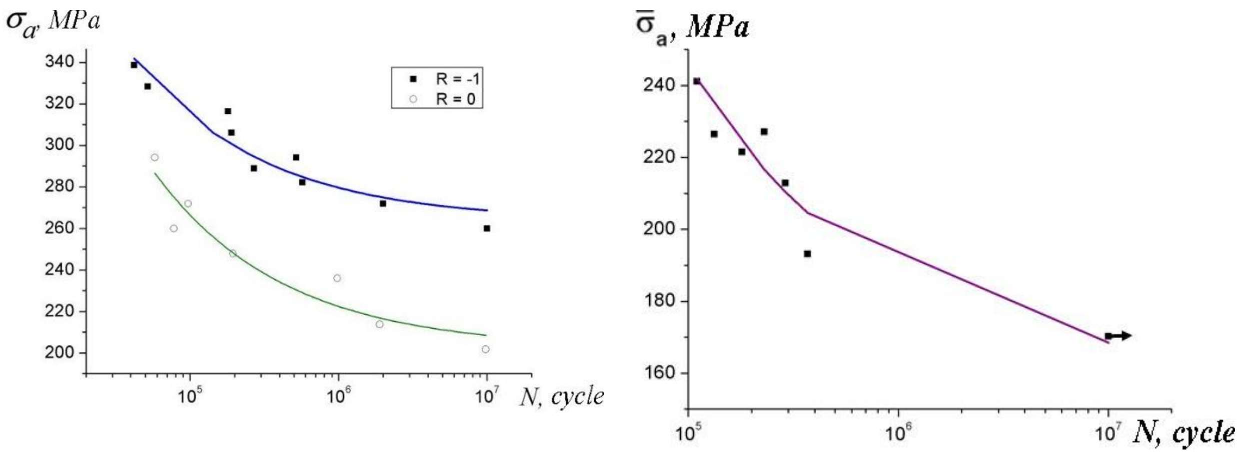


Figure 3. Histogram of the random signal amplitudes distribution with approximation by the normal distribution curve

The results of the fatigue tests under the random amplitude change.

To compare the dependence of the fatigue resistance under the constant amplitude and the amplitude varying according to the random law, the dependence of the fatigue resistance of the same lot specimens used for the investigation of the resistance under the random loading, is presented. (Fig. 4) Using the same lot specimens, investigated in the paper, the fatigue curves at the constant amplitude under different cycle asymmetry have been obtained earlier (Fig. 4, a). As the result of the carried out tests with amplitude varying according to the random law, the dependence of the average amplitude value on the cycles number prior to the microcrack initiation, was obtained (Fig. 4, b).

The results of tests are presented on Table 1. As it is seen the average value of loading is lower, than that of the under the constant amplitude. Thus, to predict the lifetime under the random loading the experimental tests are not enough. The analytical experimental methods are needed, which will make possible to determine the lifetime of such complicated type of loading.



а *б*

Figure 4. Fatigue curves under constant stress amplitude loading at the symmetric and pulsating cycle (a) and dependence of the stress amplitude mean value on the cycles number before the macrocrack initiation (b)

Table 1

Statistical parameters of a given stochastic process and the results of fatigue tests at the random amplitude

Specimen	$\mu(\sigma_a)$, MPa	$\sigma(\sigma_a)$, MPa	Confidence interval bound $\mu(\sigma_a)$, MPa		Confidence interval bound $\sigma(\sigma_a)$, MPa		N, cycle
			bottom	top	bottom	top	
1	221,5	42,2	220,9	222,1	41,8	42,6	1,8e5
2	239,5	26,2	238,9	240,0	25,8	26,6	1,4e5
3	241,1	25,2	240,7	241,6	24,9	25,5	1,1e5
4	227,1	25,1	226,8	227,4	24,9	25,3	2,3e5
5	212,9	41,6	212,3	213,5	41,2	42,0	2,9e5
6	193,1	35,2	192,7	193,4	35,0	35,4	3,7e5
7	170,3	27,2	170,0	170,5	27,0	27,4	1,0e7→
8	274,3	27,1	273,8	274,8	27,4	26,8	2,4e5

where σ_a – cycle stress amplitude; $\mu(\sigma_a)$ – mathematic expectation of the cycle stress amplitude; $\sigma(\sigma_a)$ – standard deviation of the cycle stress amplitude; N – cycles number prior to fracture under the given loading conditions.

Kinetics of the fatigue damages accumulation of the steel 45 at the cyclic loading under the amplitude varying according to the random law.

To estimate the metal fracture the method of the LM-hardness was used, which makes possible to estimate damage basing on the hardness characteristics scattering.

The level of the metal degradation in the initial state or after running is similar to that the level of its structural non-homogeneity, which can be estimated by the statistic characteristics of the hardness numbers scattering at multiple measurements. That is why the material homogeneity coefficient *m* before the Weibull distribution was chosen to be the characteristics of the mechanical properties scattering [4-6].

According to the Gumball formula [7] the homogeneity coefficient is found according to the formula

$$m = \frac{d(n)}{2{,}30259}\left[\frac{1}{n-1}\sum_{i=1}^{n}\left(\lg H_i - \overline{\lg H}\right)^2\right]^{-\frac{1}{2}}, \qquad (1)$$

where $d(n)$ – the function of the measurements number n ($n \geq 15$); H_i - the material hardness at the i- th measurement; at the hardness measurements by the Brinnel and Wickers methods, MPa; by the Rockwell method – in the hardness dimensionless units; $lg\ H$ – average value of the hardness numerical values logarithms.

The lower level of the hardness characteristics scattering corresponds to the greater values of the coefficient *m,* and as the result, the better organization of the material structure, low level of damage; more higher level of damage corresponds to the lower values.

The steel hardness is measured by the portable hardness-meter COMPUTEST SC produced by the company "ERNST" (Switzerland), equipped with the automatic system of the testing data processing with the hardness values being on the screen. The hardness-meter COMPUTEST SC makes possible to measure the depth of the unrecoverable print automatically and with high accuracy, which meets the requirements of the hardness measurement standards and makes possible to exclude the contacting materials plasticity effect on the recorded data, and the indenter flat in the top (0,06 mm diameter) will contribute to the introduction to the process zone (from the very beginning) a great number of the structure elements, including the mosaic blocks and the slipping packages, which result in the obtaining of the integral characteristics of the microhardness of the polycrystalline or even heterogeneous material. The indenter penetration depth is 100 mkm, the absolute error for measurement of the depth being till 1mkm.

The tests were carried out on the material specimens, the surface of which was treated in some stages in the variable directions to eliminate the notches of the previous treatment. The number of the stages of the surface trimming is determined according to the roughness requirements of ГОСТ 2789. The final preparation of the surface is performed by the thin grinding cloth.

The Smirnov criterion was used to describe the results obtained as the sharp emissions. This criterion can be applied, when the average quadratic error of the measured value is not known in advance.

The hardness measurement was performed for the every loading block in some definite number of the loading cycles after the total unloading of the specimen. Not less than 30 measurements of hardness were performed in one block.

For the investigation results processing the relative values of the homogeneity coefficient were used calculated according to [8];

$$m_{rel} = m_i / m_{in}\,, \qquad (2)$$

where m_i – the current value of the homogeneity coefficient, calculated according to the results of the specimen metal hardness measurements after the current block of the cyclic loading at the given level of loading; m_{in} – the homogeneity coefficient value obtained according to the results of processing of the specimen metal hardness measurement in the initial state.

The analysis of the obtained results showed, that the obtained earlier regularities of the homogeneity coefficient variations m_{rel} – for the other materials [9] during the material deformation depending on the running time are confirmed. It is shown, that the coefficient m_{rel} is the parameter, which is more sensitive to the value of the accumulated creep deformation, the level of the cycle maximum stress and the number of running cycles, than the hardness of the investigated steel. The data presented in Figure 5 are the confirmation of the mentioned above.

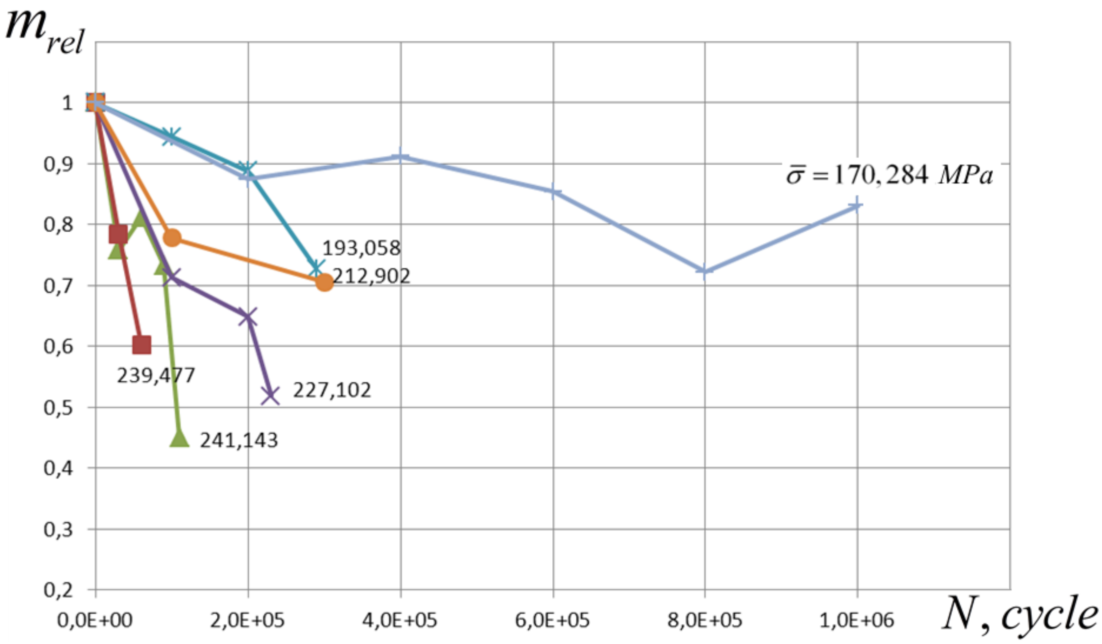


Figure 5. Dependence of steel 45 damage on the running time under the conditions of fatigue loading with the amplitudes, varying according to the random law

For the implemented loading type it is shown, that the change of the cycle average stresses value $\bar{\sigma}$ influences sufficiently the process of the damage accumulation. Thus, the cycle stress amplitude being increased, the intensive changes of the homogeneity coefficient is revealed, which testifies the metal damage kinetics.

The analysis of the obtained experimental data on the damages accumulation while running time showed, that for the cyclic loading under the amplitudes varying according to the random law the homogeneity coefficient m_{rel} change nature during the material deformation is similar to that of the strain under the small-cyclic fatigue [8].

Basing on the experimental data it is shown, that when the ultimate state is reached with the further fracture development, the value of the homogeneity coefficient m_{rel} of the investigated steel during the running time decreases, especially sufficiently in the loading cycles range approaching the failure, that is, when the metal ultimate state is reached. It should be noted, that for the fatigue failure under the non-stationary loading the dependence of the damage parameter caused by stress is almost of the linear nature (Fig. 6). Such conclusions can be noticed for the other type of loading in the papers by A. A. Lebedev [10].

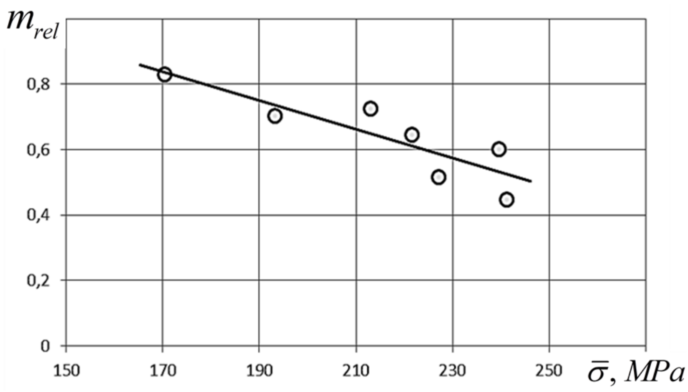


Figure 6. Correlation between steel 45 relative homogeneity coefficient m_{rel} and the level of average stresses $\bar{\sigma}$ under conditions of fatigue failure

Calculation determination of the damage kinetics and material lifetime under the random asymmetric loading.

To determine the fatigue lifetime under the random asymmetric loading the model UECP was used. The main ideas of the model UECP are presented in the previous papers. There is no need to introduce the hypothesis of the fatigue fracture summation in the UECP model, because the material damage is treated as the continuous hardening/softening up till the material plasticity exhaustion, which causes its ultimate state – failure. The description of the material hardening/softening process, which results in the change of the cyclic creep boundary, is performed due to the function of the plasticity exhaustion. It is the dependence, which describes the cycle-by-cycle change of the cyclic creep boundary since the original value $\sigma_{T,0}$ till the critical one $\sigma_{T,cr,}$ under which the ultimate state is reached.

To determine the lifetime under the random asymmetric loading taking advantage of the UECP model it is necessary to analise the obtained before dependence of the gained damage from the cyclic creep boundary [11, 12]. The calculation damage of such appearance accompanies the process of boundary change of the material cyclic creep from its initial value till the critical one in the relative values. In the general case of the random loading to find the total lifetime it is necessary to use the system compiled from the found earlier equations for the calculation of the inelastic deformation and the cyclic creep boundary in every semi-cycle [13, 15] taking into account the ultimate state conditions.

As the model is expected to be used under the asymmetric loading cycle, that is, under which some static component is in action, it is necessary to have the criterion of the static component effect on the gained fatigue damage in order the UECP model is used. For this purpose it is necessary to determine the family of the fatigue curves under different cycle asymmetries through the initial fatigue curve. Thus, for the same lifetime the interrelation between the stresses amplitude and the average stress in the cycle can be expressed as some functional dependence:

$$\sigma_a^r = f\left(\sigma_a^{-1}, \sigma_m\right), \quad (3)$$

where r – the cycle asymmetry coefficient; $\sigma^{-1}{}_a$ – the stress amplitude along the fatigue curve for the symmetric cycle; $\sigma^r{}_a$ – the stress amplitude at the asymmetry coefficient r, which corresponds to the lifetime for the stress $\sigma^{-1}{}_a$.

The most conventional dependence is the linear dependence. That is, it can be written, that the interrelation between the amplitude and average stress in the cycle can be expressed as follows:

$$\sigma_a^r = \sigma_a^{-1}\left(1 - \frac{\sigma_m}{\sigma_e}\right), \tag{4}$$

where σ_e – ultimate plasticity (or the creep boundary) of the material under static tests for the given temperature.

The value of the average cycle stress due to the asymmetry coefficient and the amplitude value of the stress is expressed as follows:

$$\sigma_m = \frac{1+r}{1-r}\sigma_a^r . \tag{5}$$

Having substituted the expressions (5) in (4), after transformations we will obtain:

$$\sigma_a^r = \sigma_a^{-1} - \frac{\sigma_a^{-1}}{\sigma_e}\frac{1+r}{1-r}\sigma_a^r . \tag{6}$$

From here the value of stress of the symmetric cycle $\sigma^{-1}{}_a$, equal in lifetime to the stress of the asymmetric cycle of loading $\sigma^r{}_a$, will be found as follows:

$$\sigma_a^{-1} = \frac{\sigma_a^r}{1 - \frac{\sigma_a^r}{\sigma_e}\frac{1+r}{1-r}} . \tag{7}$$

To model the random asymmetric process we will use the normal distribution law. Then to describe the change of the maximum stress in the cycle during some loading fragment the normal distribution law is used:

$$f\left(\sigma_a, \mu(\sigma_a), \sigma(\sigma_a)\right) = \frac{C}{\sqrt{2\pi \cdot \sigma(\sigma_a)}} \cdot e^{-\frac{(\sigma_a - \mu(\sigma_a))}{2\cdot\sigma(\sigma_a)}}, \tag{8}$$

where C – the coefficient of the probable distribution interval, which depends on the chosen loading range.

Having used the probability densities presented on the Table 1 due to the equation(8) the modeling of the random process of the loading amplitude value changes depending on the number of cycles have been carried out. In Figure 7 the example of the modeled random process of the loading amplitude change for the specimen 1 from the Table 1 is presented.

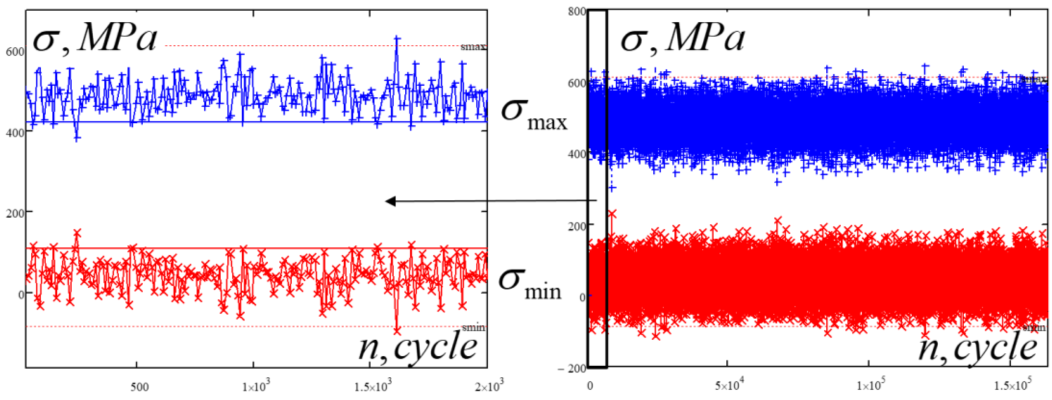


Figure 7. Modeling of the random process of changing the loading amplitude, depending on the number of load cycles for specimen 1 from Table.2. ($\mu(\sigma_a)$ = 221.53 MPa, $\sigma(\sigma_a)$ = 42.189 MPa). The boundary domain for stress amplitudes definition is marked by horizontal lines: the entire loading interval (b) and the enlarged zone (a)

Calculated lifetime forecast under random asymmetric fatigue loading taking advantage of the UECP model is presented on Table 2. As the loading process is stochastic, the numerical experiment was performed 10 times at every loading level to find the average calculation result. As it is seen from the Table, every of the numerical experiments on one level of loading corresponds to different lifetime, but they are almost equal. Thus, the maximum difference between the lifetime found in one of ten numerical experiments is not less than 5%. The parameters and the ultimate characteristics of the random asymmetric fatigue loading, calculated due to them the asymmetry coefficient values and the comparison of the obtained results, are presented on Table 3.

Table 2

Calculated lifetime forecast under random loading

Specimen	Lifetime of the numerical experiment *N*, cycle									
	1	2	3	4	5	6	7	8	9	10
1	1.71E5	1.66E5	1.63E5	1.57E5	1.70E5	1.60E5	1.64E5	1.69E5	1.63E5	1.59E5
2	1.27E5	1.30E5	1.27E5	1.28E5	1.27E5	1.27E5	1.31E5	1.30E5	1.26E5	1.29E5
3	1.27E5	1.29E5	1.27E5	1.29E5	1.29E5	1.31E5	1.27E5	1.27E5	1.29E5	1.28E5
4	2.59E5	2.52E5	2.56E5	2.61E5	2.54E5	2.52E5	2.55E5	2.55E5	2.60E5	2.58E5
5	2.75E5	2.62E5	2.48E5	2.72E5	2.74E5	2.73E5	2.75E5	2.58E5	2.51E5	2.60E5
6	4.04E5	4.04E5	4.11E5	4.16E5	4.14E5	4.28E5	4.10E5	3.99E5	4.30E5	4.14E5
7	1.42E7	1.42E7	1.42E7	1.42E7	1.42E7	1.42E7	1.42E7	1.41E7	1.42E7	1.42E7
8	2.41E5	2.46E5	2.49E5	2.43E5	2.50E5	2.45E5	2.49E5	2.45E5	2.42E5	2.46E5

Table 3

Parameters and ultimate characteristics of random asymmetric fatigue loading and calculated lifetime forecast under the random loading

Specimen	Random asymmetric fatigue loading								
	Input parameters						Output data		
	Stress, MPa			Asymmetry coefficient			Average numerical experiment, cycle	Experiment, cycle	Difference, %
	σ_m	σ_a	$\sigma(\sigma_a)$	*min(r)*	*av(r)*	*max(r)*			
1	305.91	221.53	42.189	-0.187	0.095	0.679	1.64E+05	1.80E+05	-9.69
2	291.89	239.47	26.21	-0.061	0.115	0.374	1.28E+05	1.40E+05	-9.29
3	291.51	241.14	25.186	-0.063	0.11	0.37	1.28E+05	1.10E+05	14.33
4	277.26	227.10	25.08	-0.061	0.132	0.421	2.56E+05	2.30E+05	10.23
5	296.05	212.90	41.575	-0.191	0.106	0.716	2.65E+05	2.90E+05	-9.56
6	263.46	193.05	35.201	-0.067	0.237	0.913	4.13E+05	3.70E+05	10.41
7	224.63	170.28	27.174	-0.181	0.113	0.765	1.42E+07	not destroyed	–
8	274.3	220.1	27.1	-0.037	0.172	0.509	2.46E+05	2.15E+05	12.49

As it is seen from the Table 3 the asymmetry coefficient has been changing in the wide range: from – 0,187 till 0,913. The maximum deviation of the lifetime average value between the numerical and real experiment equals 14,33%. The deviations are explained by the fact, that the experimental data have scatterings and the numerical calculations are performed due to the 50% fatigue curve. The specimen №7, which was subjected to the basis tests, in the numerical experiment was damaged under the lifetime of $1{,}42 \cdot 10^7$ cycles. That is, the UECP model makes possible to predict lifetime according to the characteristics of the random process. The peculiarity of it is, that it was possible to come from the constant amplitude to that of being changed according to the random law, and this model makes possible to take into account the available damage.

In Figure 8 the example of the calculation of the damage kinetics under random asymmetric loading for the specimen 1 from the Table 2, taking advantage of the model, is presented. In Figure 8 drastic jumps at damage accumulation are caused by the specimen loading with the loading amplitude, which is almost the same as the small-cyclic values. Non-uniformity of the damage accumulation is caused by the stochastic change of the amplitude under the random loading. It is seen, that the model hypothesis of the damages summation takes into account fatigue damages not linearly and gives more precise estimation as compared with that linear one.

Using the data from the Table 3 the results of calculation under the random loading is presented in Figure 9 in the way suitable for the comparison. Experimental and calculation points at different loading levels do not belong to the same fatigue curve. Besides, taking advantage of the model the fatigue curves for the cases presented on the Table 2. can be built.

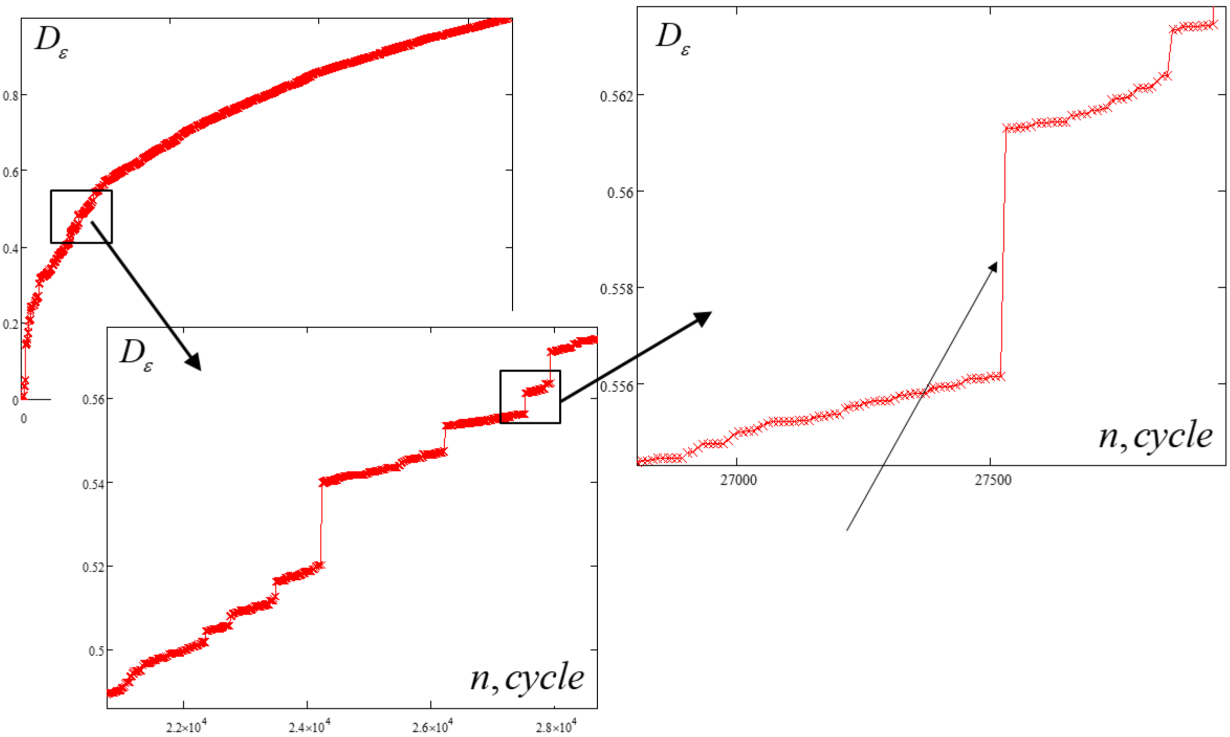


Figure 8. Example of damage calculation for the specimen 1 from Table. 2

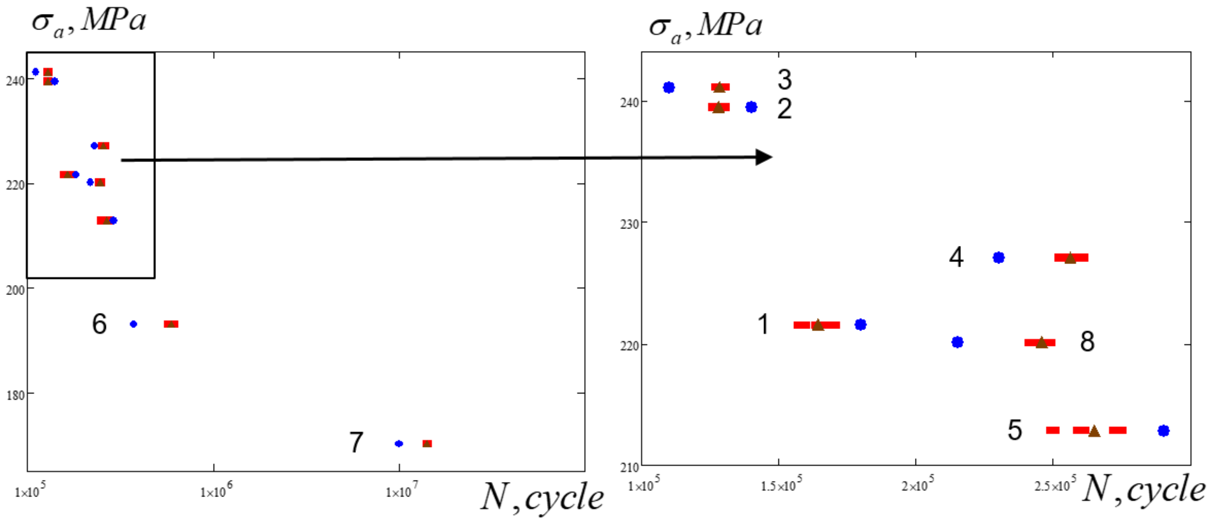


Figure 9. Estimated lifetime forecast for random loading: ■ – calculation by model; ▲ – averaged calculations; ● – experiment. Note: experimental points do not belong to one curve of fatigue

Conclusions. The method of the random asymmetric fatigue loading was developed. Electromagnetic machine YPC – 2/30000, as the system providing the amplitude by PC, was used as the testing machine. The fatigue testing of specimens from steel 45 under the amplitude varying according to the random law was carried out.

It was found, that for the cyclic loading under the amplitude random change, the nature of the homogeneity coefficient change m_{rel} during deformation is similar to that of deformation under the small-cyclic fatigue.

The dependence of the damage parameter on the stresses was found to be of the nature similar to that of linear.

It was shown, that when the ultimate state is reached with the further fracture development, the homogeneity coefficient value m_{rel} of the investigated steel during running time decreases sufficiently enough in the range of the loading cycles close to fracture, that is, when the metal ultimate state is reached.

Taking advantage of the UECP model the approach, which makes possible to forecast the lifetime according to the characteristics of the random process, was developed. The peculiarity of the UECP model, which enabled to come from the constant amplitude to that changing according to the random law, is that the model takes into account the amplitude of every cycle.

The maximum deviation of the average lifetime value between the numerical and real experiments equals 14,33%. The deviation is caused by the fact, that experimental data have scatterings and the numerical calculation are performed due to the 50% fatigue curve.

Application of the UECP model for the summation of the fatigue damages under the random asymmetric fatigue loading makes possible to estimate the lifetime with the less error in comparison with those, stabilized characteristics of inelastic deformations and hypothesis of the fatigue damages summation.

The obtained results of investigations, carried out in the paper, make possible to improve the available approaches and obtain new ones for the estimation of the metal lifetime, taking into account the damage under the cyclic loading basing on the limited amount of simple fundamental experiments.

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UДК 539.388.1:539.389.2

ВИЗНАЧЕННЯ КІНЕТИКИ ПОШКОДЖУВАНОСТІ КОНСТРУКЦІЙНИХ СТАЛЕЙ ЗА НЕСТАЦІОНАРНОГО НАВАНТАЖЕННЯ

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Резюме. *Наведено адоптовані методики, що дозволяють проводити оцінювання пошкоджуваності сталей за багатоциклової втоми з амплітудою, що змінюється за випадковим законом. Методика, яка дозволяє проводити оцінювання пошкоджуваності матеріалу, базується на методі LM-твердості. А методика розрахункового оцінювання кінетики втомного пошкодження при випадковому асиметричному втомному навантаженні базується на використанні моделі граничного вичерпання циклічної пластичності (ГВЦП). Для підтвердження наведених методик отримано експериментальні результати, що свідчать про можливість їх використання для оцінювання залишкової довговічності сталей при нестаціонарному навантаженні. Описано створення методики, що дозволяє випробовувати лабораторні зразки за втоми з амплітудою, що змінюється за випадковим законом; аналіз залишкової довговічності з використанням запропонованої моделі та методу LM-твердості; створення аналітичної моделі, що дає можливість прогнозувати довговічність за втоми з амплітудою, що змінюється за випадковим законом. Наведені результати можуть бути використані для розрахункового оцінювання довговічності елементів конструкцій, які працюють у режимі жорсткого навантаження, з меншою похибкою у порівнянні з застосуванням стабілізованих значень непружних деформацій і відомих гіпотез підсумовування втомних пошкоджень.*

Ключові слова*: випадкове навантаження, розрахункова модель, непружна деформація, пошкоджуваність, коефіцієнт гомогенності, методи вимірювань, мікроструктура, метод LM-твердості, циклічне навантажування.*

Отримано 20.01.2018