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Fatigue Damages Evaluation of the Ni-Based Alloy via AE Monitoring under the High-Cyclic Loading

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Abstract

In the paper, there were presented the studies of the process of Ni-based specimens fatigue fracture by means of registration of the AE parameters in various frequency bandwidths. There were investigated the samples made of the high-temperature strength vacuum-arc-melted Ni-alloy. During the fatigue tests the count rate of AE signals were recorded simultaneously in three frequency bands. The experimental results have shown that the specimens having various processing inheritance, being tested on different load levels of high-cycle fatigue, had identical type of the AE count rate distribution. The specific changes of the AE count rate in various frequency bandwidths determine the certain stages of the fatigue failure.

Keywords: fatigue; acoustic emission; hard facing; damages of the material structure; stage-by-stage fracture.

1. Introduction

The task of obtaining reliable data on fatigue resistance of structural materials is relevant for many market segments, as the vast majority of engineering structures operate under cyclic loads, when the determining type of failure is fatigue. Many direct and indirect methods of fatigue tests of specimens and items have been elaborated and

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discussed in details sufficiently Shkolnick (1978); Collins (1984); Troschenko and Sosnovsky (1987); Pisarenko et al. (2014). Unfortunately, none of the methods ensures the reproducible and exact results when estimating the fatigue characteristics of the materials. Even the same reference-books give various endurance limits of the same materials, which differ by more than 100 per-cent. Things are even worse with durability assessment. The mistake by an order of magnitude during defining the durability is not an unusual thing. The methods of determining the point of losing the work ability of material remain unregulated. Moreover, this point is determined by different authors in different ways. But all of these methods, as a rule, are not connected with the physics of the material fracturing. Therefore, they do not allow for effective control of the physical state of the material.

The problem of low accuracy and reliability of determination of the fatigue properties has theoretical and methodical aspects as well. The task becomes much more complicated if we take into account the effect of strengthening operations, as well as the effect of an aggressive environment Yasniy et al. (2017). Taking into account various operational, constructional and technological factors only by calculation methods does not provide the necessary accuracy of forecasting the mechanical behavior of products in conditions of fatigue McEvily (2010); Tsyban'ov et al. (2020).

At present days the conception of stage-by-stage fatigue fracture process by Ivanova and Terent'yev (1975) is generally accepted. According to this theory the complex fatigue process is separated by different zones, regions, stages and periods of fracture, which are determined on a microscopic level. That is why it is worthwhile to estimate the work ability of the elements of constructions in dependence on stages of their fracture. The determination of these stages has to be ensured by using an effective physics-based method. The latter must be sensitive to the structural changes in the deformed volumes of material, sufficiently accurate and allow easy operation of the pertinent facilities. One of the most promising methods for solving this important and complex task is the acoustic emission (AE) method Skalskiy and Andreykiv (2006); Hudramovich et al. (2017). The AE method has high productivity, can be used under exploitation conditions and is capable of registering the kinetics of structural changes (damage accumulation) in the material loaded. In compliance with Guz and Finkel (1972), as elastic energy before the failure growth, the spectrum of AE signals is widened to high frequency area (up to 1 MHz). At the same time, due to correlation between spectral structure of AE impulses and velocity of strain volume growth Muravin and Lezvinskaya (1982); Muravin et al. (1984), the possibility to differ the deformation periods of Fe-Si alloy by means of frequency analysis of AE data has been shown. It testifies about the high information ability of the AE method when talking about the processes occurring in the material during the fatigue failure. However, information about the investigation of the fatigue via AE method is fragmentary and insufficient for the determination of the criteria for estimating the work ability of the elements of constructions.

The purpose of the work is to study the possibility of evaluating the degree of damage of materials with different technological heredity under conditions of high-cycle fatigue based on the data of acoustic emission monitoring of this process.

2. Methods and materials

The following research methods were used in the work: test for high-cycle fatigue; continuous control by the acoustic-emission method under cyclic loads. The high-cycle fatigue tests were carried out according to the cantilever bending scheme with a symmetrical load cycle in the cycle stress range from the endurance limit σ_{-1} to the critical stress σ_{cr} , which corresponds to the critical number of cycles N_{cr} that restricts the high-cycle fatigue zone. Acoustic emission monitoring was carried out using a wideband transducer with simultaneous analysis in three frequency bands: low (0.2 – 0.5 MHz), middle (0.5 – 1.0 MHz), and high (1.0 – 2.0 MHz). The acoustic emission count rate was taken as the informative parameter of AE signals.

The custom-designed model samples of heat-resistant Ni-based alloy were investigated. The chemical composition of the alloy is: Ni – base, Cr – 20.89 %, Ti – 2.6 %, Al – 0.6 %, Fe – 0.46%, Cu – 0.37%, Si – 0.31 %, Mn – 0.29 %, P – 0.08 %, C – 0.04 %, S – 0.04 %, B – 0.01 %. The samples with different technical condition of the surface were investigated. The investigation included, first of all, examination of the samples after various standard technological processing (**S**) such as: fine turning (cutting speed 40 m/min, cutting depth 0.25 mm, feed 0.15 mm per rotation) – **S_T**; plunge grinding (wheel grit 25, wheel hardness CM1, cutting speed 25 m/sec, feed 0.005 m per double stroke) – **S_G**; electro-chemical polishing (current density 30 A/dm^2, time of processing 5 min) – **S_ECP**.

Secondly, the samples subjected to superficial ultrasonic hardening (**H**) for the first two types of standard treatment have been studied. The ultrasonic hardening mode was as follows: ball diameter 2.5 mm, vibration frequency 20 kHz, time of processing 2 min (**S_...+H**).

3. Results and Discussion

The results of fatigue tests are presented in Fig. 1 in accordance with hypothesis Bezhenov (2008) about the existence of a pole of HCF curves for materials of the same class with different technological heredity. Here N_P and σ_P are the pole coordinates of the HCF curves, which are invariants for a material of a certain class; (for nickel-based alloys N_P = 1025 cycles, σ_P = 1000 MPa). The critical number of cycles N_{cr} according to Ivanova and Terent'yev (1975) is equal to $189 \cdot 10^3$ cycles. The values of the endurance limit (test base $N_{base} = 10^7$ cycles) and the indicator of the slope of the fatigue curve (parameter m) as well as the values of the critical stress for the samples having various processing inheritance are presented in Table 1. The strengthening effect is clearly manifested in the increase in the endurance limit σ_{-1} and the parameter m.

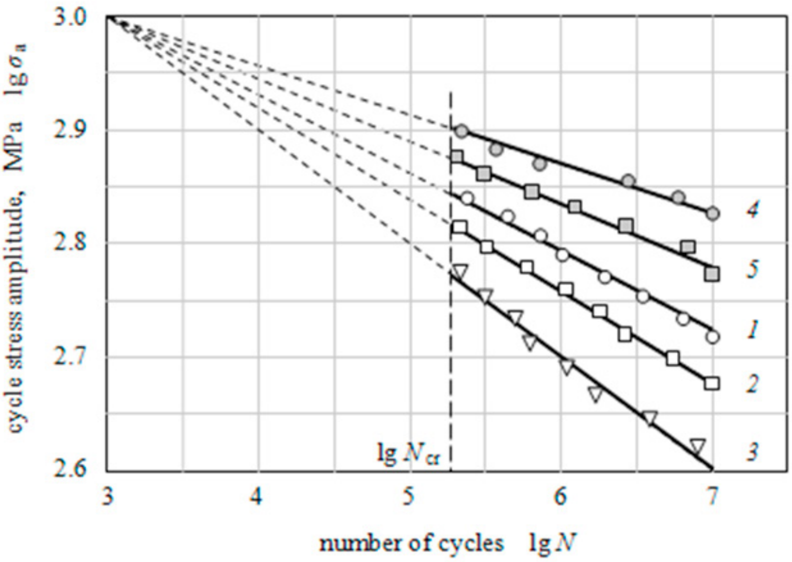

Fig. 1. Fatigue test results: (1) S_T; (2) S_G; (3) S_ECP; (4) S_T+H; (5) S_G+H.

Table 1. Fatigue characteristics of the samples investigated.

	Material's condition	σ_{-1}, (MPa)	Parameter m	σ_{cr}, (MPa)
1	Fine turning (S_T)	530	14.47	697.2
2	Plunge grinding (S_G)	475	12.32	654.7
3	Electro-chemical polishing (S_ECP)	415	9.846	588.6
4	Turning + ultrasonic hardening (S_T+H)	670	22.93	796.5
5	Grinding + ultrasonic hardening (S_G+H)	600	18.08	749.3

The results of AE monitoring of fatigue tests showed that samples with different technological heredity, tested at different levels of loading in the region of high-cycle fatigue, had identical type of the AE count rate distribution. The typical view of AE monitoring results of fatigue tests is schematically shown in Fig. 2.

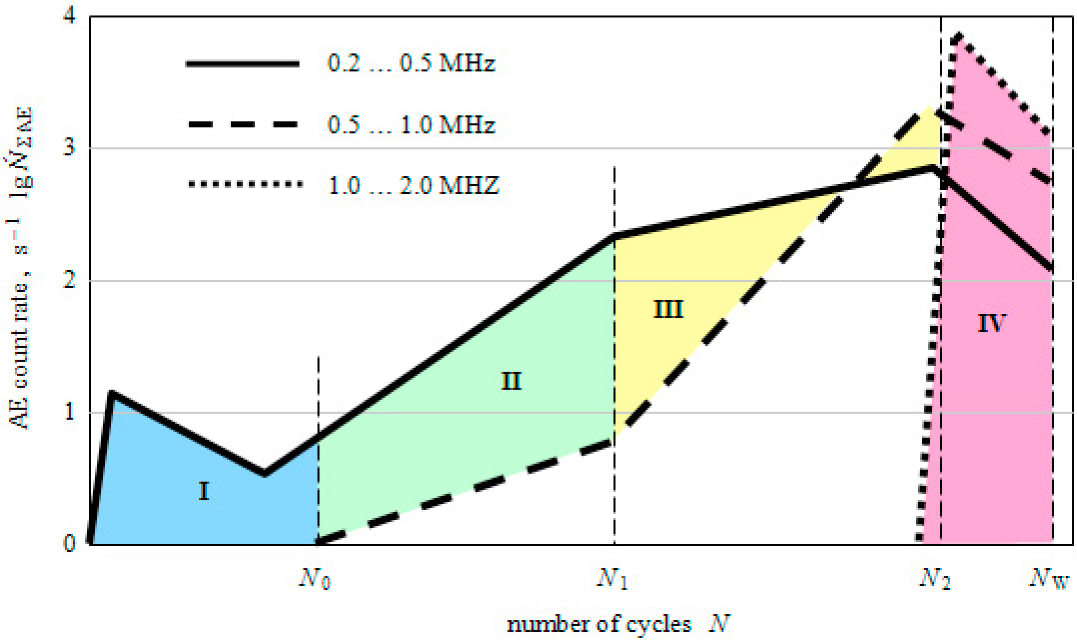

Fig. 2. Typical results of AE-monitoring of high-cycle fatigue test (scheme).

This nature of the distribution of the AE count rate from the beginning of cyclic loading of the sample to the point of its destruction was observed for samples with different technological heredity at different levels of average cycle stresses. In this diagram, in accordance to Bezhenov (2022), four areas with fundamentally different characteristics of the acoustic emission activity in three frequency bands can be distinguished. The first stage, from the beginning of cyclic loading to number of cycles N_0 (when low AE count rate occur), evidently, characterizes the stage of the incubation-period when the passive accumulation of damages occurs at the level of crystal lattice of the material. The second stage is characterized by the same high increase of AE count rate simultaneously in low and middle frequency bandwidths. This fact testifies that active structure changes in the material occur because of nucleation and propagation of the crack. The third stage, being corresponded to the cycle loading period from the value N_1 to N_2, is characterized by changing the correlation of AE count rate increasing in low and middle frequency bandwidths. The flow of middle frequency signals is intensified, but the low frequency one grows weak. It can be conditioned by the nucleation and stable growth of the macroscopic crack. Lastly, the fourth stage of catastrophic failure is characterized by fast increasing of the AE count rate of high frequency signals followed by fast decreasing of the AE count rate of signals in general bandwidth analyzed.

Verification of such an assumption was carried out by constructing (according to Ivanova's method Ivanova and Terent'yev (1975)) the lines of the beginning of the nucleation of the submicroscopic cracks and the macroscopic ones. Such fragments of generalized fatigue failure diagrams for nickel alloy samples after various processing are shown in Fig. 3. The fatigue curves (lines 3) were drawn in virtue of the fatigue test results (the dark points). The lines 1 and 2 are theoretical lines. The results of AE-monitoring of the fatigue tests are also presented in Fig. 3 as the light points, being corresponded to the point N_0 when one starts to register AE signals in middle frequency bandwidth (0.5 … 1.0 MHz). It is evident from Fig. 3 that the experimental points are situated very closely to the theoretical lines. This fact testifies that the appearance of AE signals in the bandwidth over 0.5 MHz is connected with the beginning of propagation of the microscopic crack in the material of the investigated samples. This point can be used as the criterion for definition of crack resistance of the material on the prescribed level of stresses.

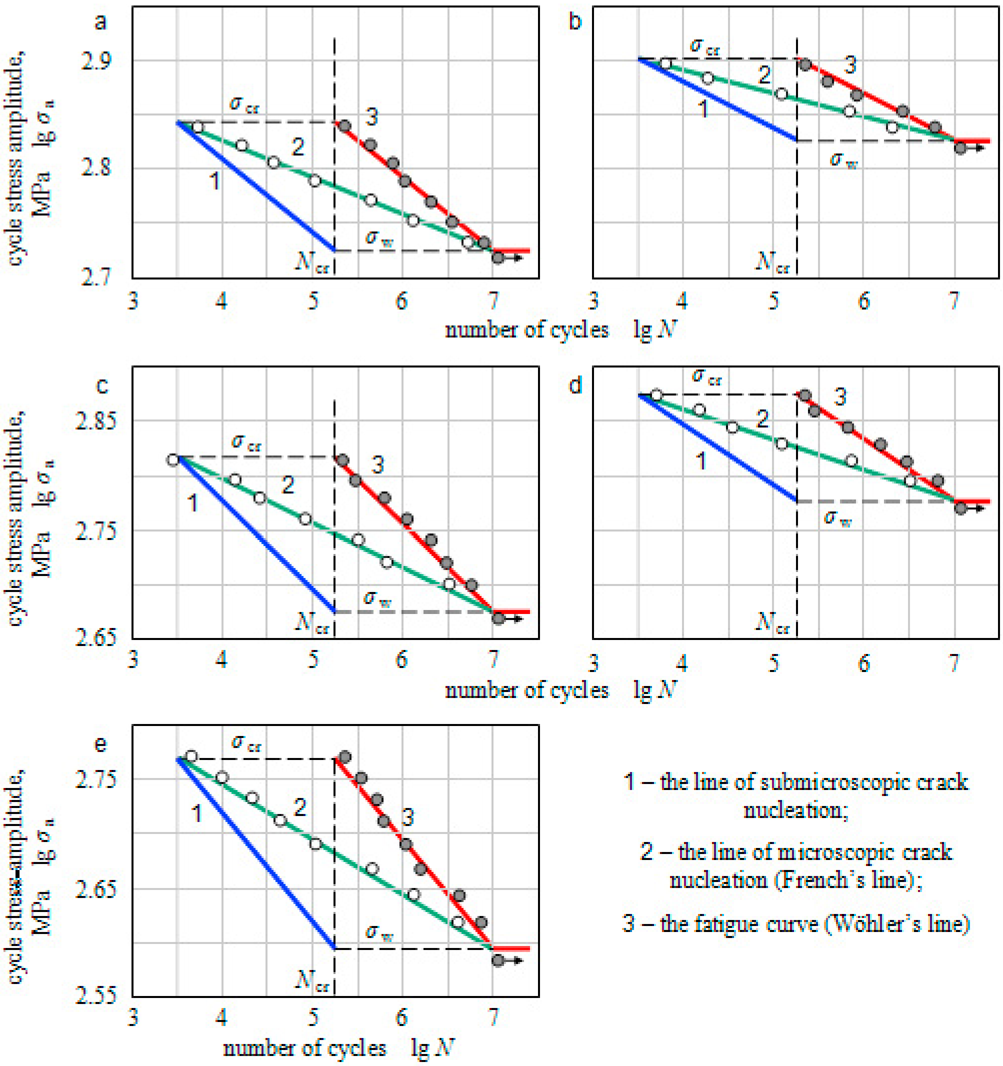

Fig. 3. Fragments of generalized fatigue failure diagrams for nickel alloy samples (a) fine turning; (b) fine turning with ultrasonic hardening; (c) plunge grinding; (d) plunge grinding with ultrasonic hardening; (e) electro-chemical polishing.

Availability of an effective nondestructive method of determination of the fatigue fracture stages gives the opportunity to make strict and grounded estimation of work ability of the machine parts. Evidently, stressed machine parts neither can be allowed to operate in the period of accelerative catastrophic fracture of materials, nor can this period be considered as a reserve of their work ability. The beginning of this stage can be considered as the point of fracture of material. The period of the macroscopic crack propagation, evidently, also can not be realized in the machine parts. But it can be taken in consideration as the reserve of work ability of the material characterizing its life ability. The crack resistance of material of the items on prescribed stress level in dependence on the purpose and work conditions can be characterized either by the beginning of the second stage for the crucial elements, or by the beginning of the third stage for the machine parts of general importance.

4. Conclusions

It is shown that ultrasonic hardening of the surface of products has a positive effect on the fatigue resistance characteristics of the nickel alloy for all investigated technological operations.

It is revealed that the specimens having various processing inheritance, being tested on different load levels of high-cycle fatigue, have identical type of the AE count rate distribution.

It is suggested that the specific changes of the AE count rate in various frequency bands determine the different stages of the fatigue fracture.

The possibility to determine more correctly the point of the items' fracture via AE monitoring is established. This fact allows evaluating the degree of damage to the material of items, establish its life ability and set the work ability reserve.

References

Bezhenov, S.A., 2008. About some methodological problems of the theory of the fatigue fracture of structural materials, Reliability and Durability of Machines and Structures 30, pp. 6 – 14 (in Russian).

Bezhenov, S., 2022. Damage evaluation of the power plants materials based on the AE model of material degradation under high-cyclic fatigue, Procedia Structural Integrity 36, 356-361.

Collins, J., 1984. Damages of materials in structures: analysis, prediction, prevention. Mir, Moscow (in Russian).

Guz, I.S., Finkel, V.M., 1972. Dependence of spectrum of waves radiated by growing crack on elastic energy potential at the crack tip. Solid-State Physics 7, 1865-1869.

Hudramovich, V.S., Skalskiy, V.R., Selivanov, Yu.M., 2017. Holographic and acoustic emission diagnostics of inhomogeneous structures and materials. Prostir-M, Lviv (in Ukrainian).

Ivanova, V.S., Terent'yev, V.F., 1975. The nature of the fatigue of metals. Metallurgy, Moscow (in Russian).

McEvily, A.J., 2010. The analysis of the emergency failures. Technosfera, Moscow (in Russian).

Muravin, G.B., Finkel, V.M., Lezvinskaya, L.M., 1984. Investigation of the deformation of the Si-iron by means of AE method, Defectoskopiya 10, 88-91.

Muravin, G.B., Lezvinskaya, L.M., 1982. Investigation of spectral density of signals of acoustic emission, Defectoskopiya 7, 10-15.

Pisarenko, G.G., Matokhnyuk, L.E., Voinalovych, O.V., Kofto, D.G., 2014. Prediction of Fatigue Resistance Characteristics of Structural Materials at Large Numbers of Loading Cycles. Strength Mater 46, 619–624.

Shkolnick, L.M., 1978. Methodic of fatigue testing. Hand-book. Metallurgiya, Moscow. (in Russian)

Skalskiy, V.R., Andreykiv, O.E., 2006. Evaluation of the volume damage of materials by means of the acoustic emission method. Ivan Franko Publishing Center, Lviv. (in Ukrainian)

Troschenko, V.T., Sosnovsky, L.A., 1987. Fatigue resistance of metal and alloys. Hand-book. Naukova dumka, Kiev. (in Russian)

Tsyban'ov, G.V., Novikov, A.I., Kurash, Yu.P., 2020. Analysis of fatigue crack growth rate in steels due to plastic deformation and fracture at its top. Message 2. Establishing the relationship between the parameters of fatigue crack growth and plastic deformation, Strength of Materials 6, 100–112.

Yasniy, O., Pyndus, Yu., Iasnii, V., Lapusta, Y., 2017. Residual lifetime assessment of thermal power plant superheater header, Engineering Failure Analysis 82, 390–403.