Research of the metals elasticplastic cyclic deformation process at reduced temperature

Y G Kabaldin¹, A A Khlybov¹, M S Anosov¹ and D A Shatagin¹

¹NNSTU, 603950 Minin St., 24, Nizhny Novgorod, Russia
Email: dmitsanych@gmail.com

Abstract. In the present work the test results of steel samples 20 and 45 at a temperature 20°C and -30°C when exposed to variable loads are shown. Fractographic studies of breaks were carried out using optical and electron microscopy. A comprehensive analysis of the materials destruction process, based on the analysis of acoustic emission signals, was also conducted. To estimate the damage of metals the algorithm that uses indicators of fractal dimension and informational entropy of the acoustic emission signal is proposed. The research results showed that the characteristics of fractal dimension and information entropy expand and supplement the capabilities of acoustic methods in the problems of evaluating the performance of materials with low-cycle fatigue at low temperatures.

1. Introduction

The accelerated development of the Far North and the Arctic, including the coast and shelf of the Arctic seas, is an important condition for increasing economic potential for Russia [1-4]. First of all, it means the development of basic industries (mining, oil and gas) with the creation of appropriate infrastructure, transport and communications. In this regard, the task of ensuring the safety of technical facilities in cold regions opens new opportunities of research.

Many structural elements and mechanisms operating at low temperatures function in conditions of low-cycle fatigue. During operation, cases of nucleation and development of cracks are often observed. At the stage before the initiation and development of macrocracks, the period associated with a change in the structure is identified: nucleation and accumulation of scattered microdamages, nucleation and growth of micropores that do not interact with each other [5, 6]. The process of damage accumulation begins almost immediately after the application of a variable load; it proceeds covertly, with virtually no visible external signs. The second stage is the development of damage. The resulting micropores (as well as newly born) interact with each other, forming microscopic cracks. A change in the physical-mechanical characteristics of materials is observed. The duration of the damage accumulation period reaches up to 80% of the total destruction of the sample. Hidden processes of material degradation lead to a change in physical and mechanical characteristics: modulus of elasticity, strength and other characteristics. The period of accumulation of damage ends with the formation of macrocracks and the destruction of the structure. By a macrocrack it is meant a crack capable of localizing the stress field and developing independently under the influence of external loads. Such a crack can be detected visually or using flaw detection tools. Moreover, the task is to assess the degree of degradation of the material during its operation.

Therefore, the problem of material damage controlling, the quick assess ability the current state without disrupting the performance of structures in modern industry is quite relevant.
To determine the materials damage and to predict the time of the initiation of macrocracks, the methodology that use various physical methods based on various physical phenomena, for example, changes in electromagnetic properties (eddy current, coercive force [7-10], Barkhausen noise, electrical noise, etc.) are developed and improve.

One of the most promising, in our opinion, is the method of acoustic emission, as it is the most sensitive method that allows continuous monitoring of the technical objects state in real time. There are various views on the mechanisms of microcrack formation under fatigue loading [11-15]. Changes in the fatigue properties of a number of metals with decreasing temperature were studied previously [16]. As studies have shown, despite the fact that the fatigue limit of most metals increases with decreasing temperature, the danger of a transition from fatigue to brittle failure increases with the appearance of the first even small cracks.

In this way, on the basis of the literature review in the studied area, it can be concluded that the study of the behavior and properties of technical materials at low temperatures is a poorly developed field of materials science, in particular, the physical foundations of both brittle and fatigue failure. As it is indicated above, despite the fact that in some cases fatigue strength is increasing, the risks of premature failure remain. In this regard, there is an acute problem of studying the features of the metals destruction mechanisms and structures at low temperatures under conditions of elastoplastic cyclic deformation.

2. Materials, equipment and research methods.

As materials for research, steels 20 and 45 were selected. The microstructures of the materials are shown in Picture 1.

![Microstructures of steel 20 (a) and steel 45 (b).](image)

The study of the microstructure and surface of the samples was carried out with a KYENCE-VHX 1000 optical microscope. The fractographic analysis of the fractures was conducted with a JSM-3U scanning electron microscope. Electron microscopic studies of thin foil samples were performed on a JEM-7A transmission electron microscope.

To test metals for fatigue at low temperatures, a specialized table was used (RF Patent No. 2645162). The samples made in accordance with GOST 25.502-79 (type IV) were used for testing. The dimensions of the working part of the samples are: thickness 3 mm, width 15 mm, length 110 mm, R = 35 mm. The samples were loaded according to the cantilever bending scheme (cycle asymmetry coefficient is R = -1). The frequency of the elastoplastic cyclic loading is 25 Hz.

To record the temperature on the sample, pt100 temperature sensors were used. Temperature accuracy is ± 1 °C. To record the Acoustic Emission (AE) signal, National Instruments three-channel analog-to-digital converters (ADCs), GlobalTest AE sensors (GT350) and a personal computer were used.

For processing AE signals, software that use the LabVIEW development environment, where AE signal processing allows you to establish a relationship between the processes of deformation and
destruction of materials with AE signals was developed. The following parameters were used as informative parameters: energy $E$, fractal dimension of the attractor $D_f$ and information entropy $S_e$ of AE signal.

It should be noted that there are significant achievements in the field of assessing the damage of materials under flood loading using indicators of the fractal dimension $D_f$ and informational entropy of acoustic signals $S_e$ [17-19]. The use of these indicators showed good efficiency for solving the problems of predicting the residual resource.

3. Experimental studies. Analysis of experimental studies.

According to the results of low-cycle fatigue testing of the samples, the dependences of the number of loading cycles before fracture of the sample ($N$) on the stress amplitude ($σ_{\text{max}}$) were obtained. For the convenience of analyzing the obtained data, these dependencies are given in double logarithmic coordinates (Picture 2).

The analysis of the data showed that when the test temperature is lowered from $t = +20 °C$ to $t = -30 °C$, the tangent of the angle $\tan(\alpha)$ of the fatigue curve slope remains almost unchanged, the number of cycles to the destruction of samples for steel 45 increases by an average of 1.6 times, for steel 20 in amount of 1.15 times. As studies of the fracture mechanisms of the materials in a wide temperature range have shown [9], steel 20 exhibits greater resistance to fracture under impact loads and have a lower temperature of the viscous-brittle transition. In this regard, and taking into account the data obtained (picture. 2), the study of the features of deformation and fracture during elastoplastic deformation with the registration of the AE signal was conducted on samples of steel 20.

The results of processing the AE signal when testing steel 20 with the determination of the parameters — the fractal dimension of the attractor $D_f$ and information entropy $S_e$ of the AE signal are presented in Picture 3. The relative axis shows the number of loading cycles $N / N_\Sigma$, where $N$ is the current number of loading cycles, and $N_\Sigma$ is the number of loading cycles during which the destruction of the sample occurred. Fractograms of fractures at the corresponding temperatures are shown below.

![Figure 2](image-url)  
Figure 2. Dependence of the decimal logarithm of the cycles number before the sample destruction $\lg(N)$ and the stress amplitude $\lg(σ_{\text{max}})$ for: a) steel 45; b) steel 20
Figure 3. Dependences of the fractal dimension of the attractor $D_f$ and the information entropy of the AE signal $S_e$, as well as fractograms of fractures (x5000) of steel 20 at: a) $t = +20 \, ^\circ C$ and b) $t = -30 \, ^\circ C$.

As it can be seen in Picture 3, in the general case, the process of accumulation of damage and destruction of the sample material during fatigue tests can be divided into two phases. In the first phase, structural changes in the sample are accompanied by a rearrangement of dislocations from their random distribution to the formation of a strip structure. It is noteworthy that such a sequence of alternation of types of dislocation structures (chaotic, fragmented, strip) also occurs with other types of metal deformation, in particular, with metal forming. The same types of dislocation structures were also revealed under tension. This is probably a kind of ability of the material to structural rearrangements with an increase in the degree of deformation is genetically programmed in the structure of metals, for the efficient dissipation of the stored strain energy.

The AE signal in the first phase does not contain significant bursts of pulses, and the values of the information entropy and fractal dimension of the AE signal are practically unchanged. The second phase of fatigue failure is accompanied by an increase in bursts of AE pulses and upon reaching a certain number of loading cycles, an intensive growth of microcracks occurs, which is accompanied by an increase in the $D_f$ - fractal dimension and $S_e$ - information entropy of the AE signal. These transitions are accompanied by an increase in the fractal dimension of the AE signal and a change in the shape of the signal attractor. The first phase at a test temperature of $t = +20 \, ^\circ C$ is less than at a reduced temperature of $t = -30 \, ^\circ C$ by about 1.35 times.

Thus, during fatigue tests at low temperatures, the process of microcrack nucleation is less intense. However, the second phase is much less with decreasing temperature than with $t = +20 \, ^\circ C$, meaning macrocrack extends faster.

Analysis of the results of fractographic studies of the fracture surfaces of steel 20 shows that fatigue grooves alternate with a dimple fracture mechanism. This suggests that fatigue advancement of microcracks is preceded by intense plastic deformation. Analysis of the fractogram of picture 3b shows that at a reduced temperature, numerous secondary microcracks are visible on the fracture surface as the fatigue crack propagates.

The results obtained also correlate with the results of tests for impact bending of metals.

In the work of Gulyaev A.P. [20] it is noted that the upper temperature of the cold brittleness threshold is associated with the beginning of a decrease in the crack development work and the appearance of crystalline areas in the kink, and the lower boundary of the cold brittleness threshold is characterized by a decrease in the crack development work to zero and obtaining almost completely brittle fracture.

This work was carried out under the grant of the Russian Science Foundation No. 19-19-00332 “Development of scientifically based approaches and hardware and software for monitoring damage of structural materials based on artificial intelligence approaches to ensure the safe operation of technical facilities in the Arctic”
References

[1] Larionov V.P., Kovalchuk V.A. Cold resistance and wear of machine parts and welded joints. Novosibirsk: Science, Siberian Branch, 1976.-205 p.

[2] Levin A.I., Bolshakov A.M., Prokhorov V.A. Risk analysis of the operation of gas pipelines at low temperatures // Sat. tr conf. "The strength of materials and structures at low temperatures." St. Petersburg: SPbSU - NiPT, 2000. 14-16 c.

[3] Material science: a textbook for high schools / B.N. Arzamasov, V.I. Makarov, G.G. Mukhin etc; under the general ed. B.N. Arzamasova, G.G. Mukhina. - 5th ed., Stereotype. - M.: Publishing House of MSTU. N.E. Bauman, 2003.-- 648 p.; III.

[4] Y.P. Solntsev, B. S. Ermakov, O. I. Sleptsov. Materials for low and cryogenic temperatures: Encyclopedic guide. - SPb.: HIMIZDAT, 2008. -- 768 p.; III.

[5] Terentyev V.F. Fatigue of metallic materials. - M.: Science, 2003.

[6] Goritsky V. M. Diagnostics of metals. - M.: Metallurgizdat, 2004.

[7] Mitenkov F.M., Kaydalov V.B., Korotkikh Yu.G., Panov V.A., Pichkov S.N. Methods of substantiation of the resource of nuclear power plants. - M.: Engineering, 2007. P.445

[8] Prigorovsky N. I. Methods and means of determining the fields of deformations and stresses: a reference book / N. I. Prigorovsky. M.: Engineering. 1983.- 248 p.

[9] Zakharov V.A., Ulyanov A.I., Gorkunov E.S. Patterns of change in coercive force during biaxial asymmetric deformation of steel St3. - Flaw detection. - 2010. - No. 3. P. 55.

[10] Scherbinin V. E., Gorkunov E. S. Magnetic control of the quality of metals, otv. Ed. G. S. Korzunin. - Yekaterinburg: UrO. RAS, 1996. -- 263 p.

[11] Panin V.E., Likhachev V.A., Grinyaev Yu.V. Structural levels of deformation of solids. Novosibirsk; Nauka, 1985.

[12] Aero E.L., Bulygin F.N. Nonlinear theory of localized waves in complex crystal lattices as in discrete-continuous systems // Computational mechanics of continuous media, vol. 1, no. 1,2008. S.14-30

[13] Kashchenko M.P. Wave model of martensite growth during γ-α transformation in iron-based alloys. Yekaterinburg: UIF "Nauka", 1993. - 224 p.

[14] Koneva N.A., Teplyakova L.A., Sosnin O.V., Celermaer V.V., Kovalenko V.V. Dislocation substructures and their transformation under fatigue loading (review) // News of universities. Physics, No. 3, 2002. p. 87-98.

[15] Ivanova B.C., Terentyev V.F. The nature of metal fatigue. M.; Metallurgy, 1975.-456p.