Investigation of Energy Balance in Metals under Cyclic Loading

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Abstract. The peculiarities of energy balance in metals under cyclic loading were investigated using IR express-techniques for determination of material endurance limit (EL). According to the main idea of this technique the transition through the EL is accompanied by the sharp change of damage kinetics and as consequence changing of specimen temperature. The combination of two different registration techniques (acoustic emission and infrared thermography) allows us to estimate the number of defects, their size distribution and spatial and time evolution of heat sources induced by defects. As a result, we determine the difference between thresholds of defect accumulation and heat dissipation. We also link the dissipation activity of metals with acoustic emission (AE) rate. The special experiment was carried out to investigate the effect of grain size on dissipation ability of metals. The fine grain titanium specimens were prepared by the method of intensive plastic deformation. It was shown that high initial defect density has great influence on dissipation ability of metals and leads to linear temperature kinetics versus stress amplitude up to specimen failure.

Introduction

The process of material structural evolution under plastic deformation leads to conversion of the expended energy into dissipated and stored parts. The classical assumption about full dissipation of deformation energy into heat [1] is valid only in the limited number of cases. Modern experimental data [2-4] show that the considerable part of the deformation energy can be stored into material. The energy accumulation process in metal is closely connected with mesostructure material evolution and influences on its mechanical behavior. The investigation of this process can create both new opportunities in the development of new nondestructive damage monitoring techniques and verification of theoretical model of defect evolution in solids.

This work is devoted to the investigation of energy balance in metals (armko-iron, titanium Grade 2) under cyclic loading. The main ideas of this work are to study the effect of initial heterogeneity on material dissipation ability and determine the link between defect initiation rate and specimen temperature difference. The experimental conditions correspond to the express method for determination of material EL [5]. This method allows us to investigate the peculiarities of damage evolution and heat dissipation under different values of applied stress. Each experiment contains several loading steps. The stress amplitude was increased step by step on 10 MPa. We used two registration techniques to receive real time information about dissipation energy rate and number of initiating defects. In the experiments with armko-iron we used IR camera CEDIP Silver 450M and system Vallen AMSY5 for infrared monitoring and AE data analysis, respectively. In the experiments with titanium we used IR camera CEDIP Silver 450M due to specimen size problems.

It has been shown that the mesodefects initiation and energy dissipation in metals under cyclic loading are threshold processes. At stress amplitude less than 60 MPa (iron yield stress is 130±10 MPa, the stress value corresponds to plastic plateau is 180±10МПа) the AE system does not register mesodefects initiation (the amplitude of signals was comparable to level of system noise). The specimen temperature does not change during step of loading. At high stress amplitude the AE impulses start to be generated by jumps. This process is not accompanying by change of specimen

temperature up to impulses generation rate 100 hits/sec. The first remarkable temperature difference was registered at stress amplitude comparative with EL (90 MPa). The AE rate jumps in the beginning of test and then monotonously decreases. At the moment of fatigue crack initiation the process qualitatively changes. The energy dissipation is localized in crack tip that leads to drop of the specimen temperature and growth of number and amplitude of generated AE signals.

A special part of the paper is devoted to the investigation of energy dissipation in fine grain (nanocrystalline) titanium. It has been shown that increasing of initial defect density leads to the specific dissipation ability of materials and increases its EL.

Material and experimental conditions

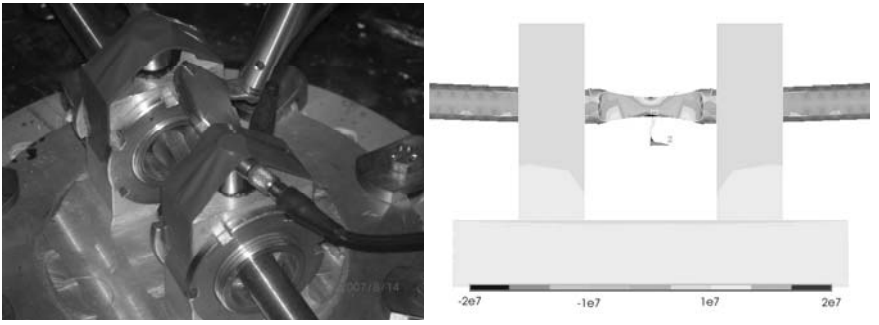
The iron specimens were tested on modified vibration setup ВЭДС-400 А. The moving part of experimental machine was refined with a goal to bend a specimen but avoid its translation motion. Captures represent four elastic rings put on the sample and fixed by four washers in pairs towards each other. The resonant frequency of the system and the maximum pressure in the centre of the sample can be estimated as follow

$$\nu = \frac{(1.875)^2}{2\pi l^2}\sqrt{\frac{EJ}{\rho S}},$$

$$\sigma = \frac{P\,l\,r}{J},$$

where l is half of specimen length, E is Young's modulus, $J = \frac{\pi r^4}{4}$, ρ is density, $S = \pi r^2$, $P = \frac{3EJz}{l^3}$, z is displacement of the end of specimen.

The optimum geometry of the sample and clutches was designed by a mathematical modeling. Numerical simulation of the experiment was carried out in ANSYS 8.0 software. The final-element solution and photo of experimental setup are presented in fig 1.



a) b)

Fig. 1 Clutches with AE gages and specimen (a), numerical simulation of stress distribution in a specimen (b).

The geometry of samples and a special screw connected pen-cease for AE gages are presented in figure 2. The resonant frequency of system is 78 Hz.

To register the AE signals the system Vallen Amsy 5 has been used. The system was completed with high-frequency gages VS2MP (frequency range is 350-2000 kHz) and low-frequency gages AE104A (frequency range is 50-400 kHz). The system allows to record, sort, analyze and store AE signals on eight channels with frequency more than 3 10^5 impulses per second and to record the form of arriving signals with rate 2.5 Mb/sec. In our experiments a discrimination threshold was 35, 55 decibel for high and low frequencies, respectively. Discrimination times had values: 180 μc (the parameter defining a minimum length of the cascade of impulses), 50 μc (the parameter defining a minimum distance between impulses). The amplitude of a signal was measured and analyzed in volts.

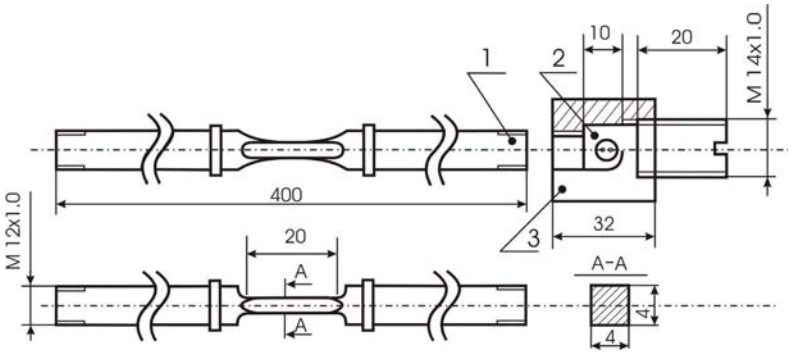


Fig. 2 The geometry of the sample and a pen-case for AE gage (1 is a sample, 2 is AE gage, 3 is pen-case).

To study the temperatures field evolution the infra-red camera CEDIP Silver 450M was used. A spectral range of the camera is 3-5 microns. The maximum frame size is 320x240 points. A temperature sensitivity of the camera is less than 25 мK at 300°K.

To calculate the stress amplitude a displacement of the centre and the end of the specimen were measured by laser gages. The gauges provided accuracy of measurement of position of object up to 1 micron with speed 1 kHz.

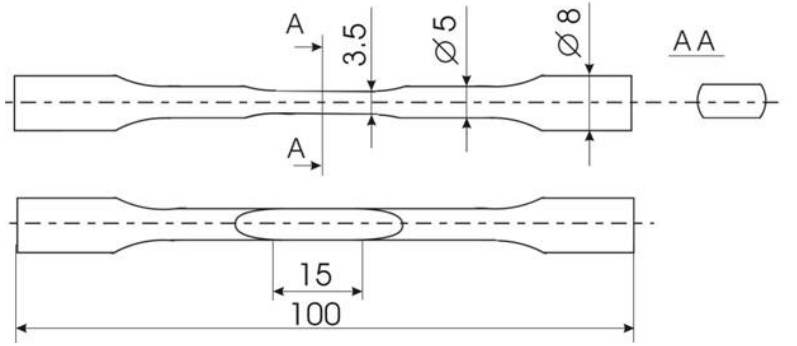


Fig. 3 Geometry of titanium specimens The sizes of a gage part of a sample 15x5x3,5 mm.

Each sample was loaded with blocks on 50000 cycles. On each subsequent step stress amplitude increased on 10 MPa. At each step of loading a temperature rise and AE activity of the specimen were measured. Between loading steps the samples were unloaded and relaxed until they reached thermal equilibrium with the environment.

The fine grain titanium Grade 2 specimens were manufactured by the method of intensive plastic deformation [6] and had the grain size of about 150 nanometers. The geometry of samples is

represented in figure 3. Due to specimen size problems the cyclic loading was carried out using a resonant electro dynamical testing machine Vibrophore Amsler providing uniaxial tension loading (resonance frequency was 76 Hz) and AE activity of the specimen didn't investigated.

Experimental results (interaction of energy dissipation and AE activity)

Figure 4 presents the results of experiments with iron specimens. The error bars in figure 4 (with probability 0.95) is calculated only for temperature differences. The error bars for average rate of AE generation have the similar tendency: good repeatability of results at low values of stress and a wide scatter at the big one. The analysis of these results allows us to conclude that energy dissipation and rate of AE generation are threshold processes. At stress amplitude less than 60 MPa amplitudes of AE signals don't exceed the usual noise level in system. The temperature of the specimen doesn't change during a step of loading. Generation of AE signals starts by jumps at stress amplitudes about 62 MPa and then gets a constant value depending on loading stress. It is interesting to note that standard procedure of an estimation of material EL by the method of infra-red thermography as a crossing of gradients of the left and right branches of the curve of temperature change versus stress amplitude, gives a value of EL higher than given value. The standard procedure gives the value of EL about 90МПа. It means that the evolution of material structure starts at stress amplitude below EL. That can explain the fatigue failure of materials at small stress and the high number of cycles.

At high stress amplitude the evolution of AE activity of materials changes. Analysis of experimental data allows us to obtain three basic scenarios of structural evolution and energy dissipation in a material. At small stress (60-70 МПа) the generation of AE signals exhibits several jumps during one loading steps and does not leads to an essential heating of specimen (fig. 5).

The first registered temperature rise was observed at stress amplitude 75МПа and rate of AE signals equals 150 hits/sec. At this amplitude the AE rate and their amplitude is approximately constant during all loading step (fig. 6).

At stress amplitude higher than material EL (90МПа and above) there is a strong interaction between AE rates and energy dissipation. The AE rate and amplitude jump at the beginning of the loading step and monotonously decreases during loading. The same behavior was observed under increasing of stress amplitude during one loading step (fig. 7). This process leads to sharp heating of the specimen in the beginning of experiment and its relaxation in thermodynamic equilibrium during cyclic process.

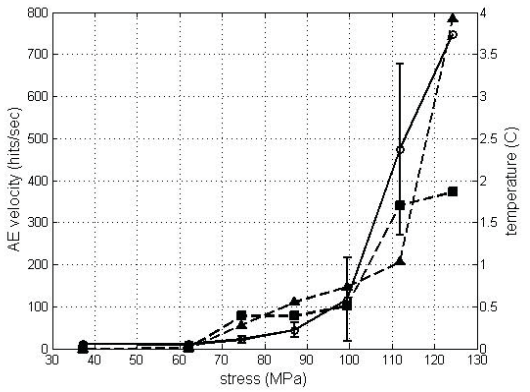
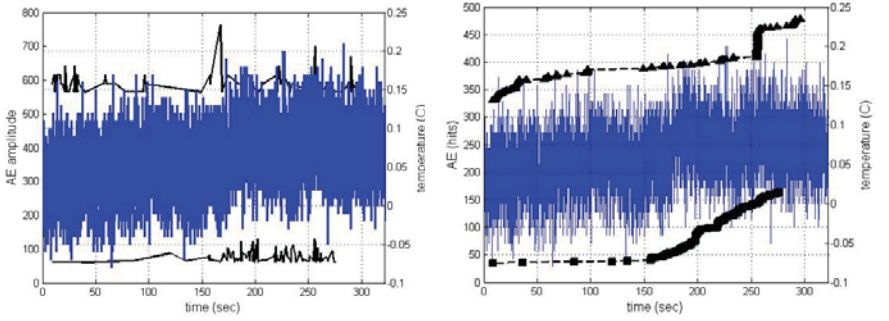


Fig. 4 Specimen temperature increase and average AE rate for one loading step versus stress amplitude (■-average AE rate in a range 50-400 kHz, ▲ - average AE rate in a range 350-2000 kHz, ○ – temperature change).



a) b)

Fig. 5. Specimen temperature increase (a continuous line), AE amplitudes (a) and total number of AE signals (b) versus time at amplitude of pressure 62 MPa. (■ – number of AE signals in a range 50-400 kHz, ▲ - – number of AE signals in a range 350-2000 kHz)

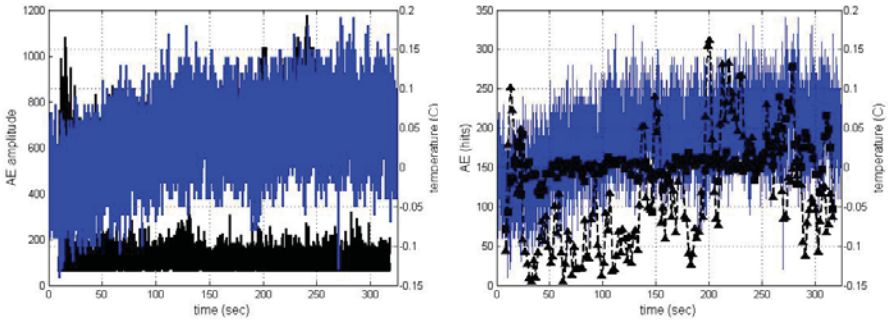


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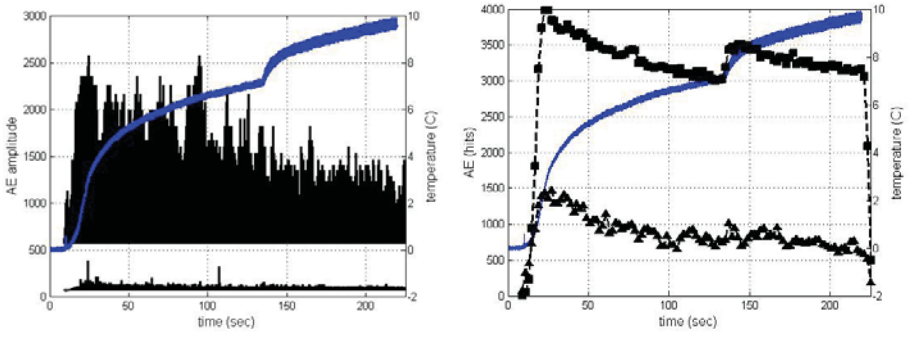
Fig. 6. Specimen temperature increase (a continuous line), AE amplitudes (a) and total number of AE signals (b) versus time at amplitude of pressure 75 MPa. (■ – number of AE signals in a range 50-400 kHz, ▲ - – number of AE signals in a range 350-2000 kHz)



a) b)

Fig. 7. Specimen temperature increase (a continuous line), AE amplitudes (a) and total number of AE signals (b) versus time at amplitude of pressure 125 MPa. (■ – number of AE signals in a range 50-400 kHz, ▲ - – number of AE signals in a range 350-2000 kHz)

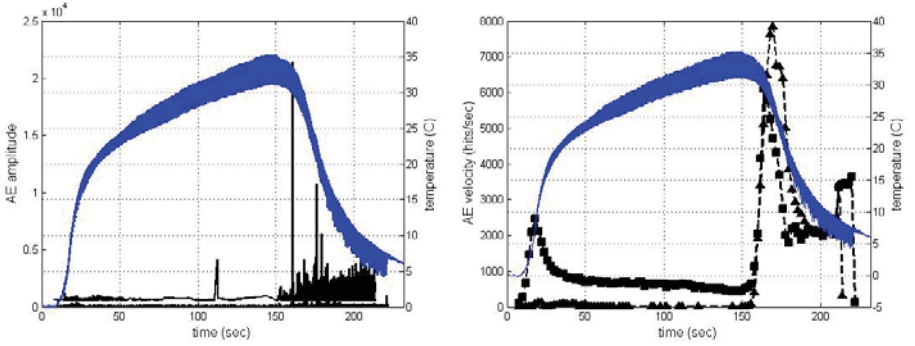


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Fig. 8. Specimen temperature increase (a continuous line), AE amplitudes (a) and total number of AE signals (b) versus time at amplitude of pressure 137 MPa. (■ – number of AE signals in a range 50-400 kHz, ▲ - – number of AE signals in a range 350-2000 kHz)

The relaxation is accompanied by decrease of heat dissipation and increasing of heat exchange between specimen, environment and clutches. The analysis of AE data shows that process of cyclic loading is accompanied reduction of the rate of defects generation (AE rate) and the sizes of individual defects (AE amplitudes). The conclusion about decreasing of the defect sizes has been made on the basis of the analysis of the form of registered signals. The form of signals did not change during loading step that support the conclusion about unalterable mechanism of defect evolution. Emergence of a fatigue crack changes the character of process. Speed of heating of the sample drops at sharp growth of speed and AE amplitudes (fig. 8).

Experimental results (effect of grain size on dissipation ability of metals)

Recent discoveries of the unique properties of fine grain materials (unusual mechanisms of deformation, anomalies of conductivity, magnetic and optical properties) have given an impetus to a new scientific direction – nanotechnology. Physical and mechanical properties of solid nano- and mesostructural media offer unique possibilities for electronics, medicine, various technical applications, for instance in the field of aero-space technologies.

At present time, two general approaches to the development of the materials are considered. The first approach, the so-called «bottom-up approach», involves compaction of the nano-size powders (ultra disperse powders can be obtained by gas condensation in the inertial atmosphere or by plasma-chemical method, aerosol and chemical synthesis, and also by grinding of powders in a spherical mill, etc.). Some of these methods have been successfully used for creation of the material and serve as a basis for studying the structure and properties in the nanocrystalline state. At the same time the specimen size is no appropriate for mechanical testing.

The second approach, originally proposed by V.M. Segal and developed by R.Z. Valiev [6], is widely known as the “top-down approach”. According to this technique, the formation of fine grain material is by grinding of the initial microstructure up to a nano-size scale under intensive plastic deformation (IPD). The IPD methods provide refinement of the grain structure in various metallic materials, however, the character of grain structure (size and shape of grains, types of grain size, phase structure, etc.) depends on the processing conditions, phase structure and initial microstructure of materials. IPD processing leads to the formation of ultra fine grains separated by nonequilibrium grain boundaries. This state is characterized by generation of high density lattice defects and grain boundary defects with long-range correlation properties. The size of the specimen prepared by IPD is bigger that size of specimens made by «bottom-up approach». In our

experiments we have specimens size enough for cyclic testing and energy dissipation monitoring, but to small to connect with our AE gages.

Figure 9 presents the results of experiments with titanium specimens. The polycrystalline titanium shows nonlinear two-step growth of heat dissipation. According to the used technique the point of crossing of straight lines in figure 9 determines the value of the EL for the coarse-grained titanium (the average stress is 80 MPa, the maximal stress is 145 MPa).

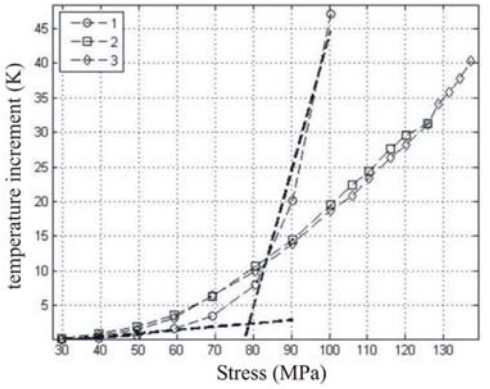

Fig. 9. Mean temperature increment of titanium samples in coarse-grained (curve 1) and nanocrystalline states (curves 2,3) versus mean stress; dashed lines determine approximately the value of EL (the stress corresponding to the knee point).

Experiment with the coarse-grained titanium was stopped before failure in the case when the sample temperature overran a working range of the camera with exposition 1100 μsec (75 ^{o}C). The results of infra-red scanning show that cyclic loading of nanocrystaline titanium is accompanied by a qualitative change in the mechanisms of dissipation. At small stress amplitudes the average temperature of the sample with a fine grain structure insignificantly exceeds the temperature of the coarse-grained titanium sample. At the stress of about the EL the picture qualitatively changes. For the stress higher than the EL of the coarse-grained titanium the increment of temperature in the nanocrystalline sample is much less than in the samples in a polycrystalline state. A linear dependence of the temperature growth rate on the average stress was observed for all fatigue histories of nanocrystalline samples.

The temperature of samples is stabilized approximately after 20000 cycles which reflects the ability of the samples with submicrocrystalline structure to form an equilibrium defect system (probably grain boundary defects) and qualitatively confirms the theoretical result about the formation of defect "lattice", whose characteristic size (density of dislocation) homogeneously increases with increase in the average stress. Fine grain specimens experienced brittle failure, which occurred at the stress amplitude 35 % - 40 % higher than in titanium samples in an ordinary polycrystalline state.

Summary

As a result of the work the energy dissipation and mesodefect evolution processes in metals under cyclic loading have been studied. Step-by-step loading with increasing of stress amplitude allowed us to define a threshold of the AE generation and heat dissipation. It is shown, that the AE generation caused by defects initiation starts at small stress amplitude. The rate 100-150 hits/sec doesn't leads to tangible temperature difference of the specimen. At stress amplitude corresponding

to EL the rate of defect initiation is equals about 300-400 hits/sec and temperature increase is about 0.4 ^{o}C.

The analysis of AE data coupled with observation of temperature evolution allows us to study the process of a material accommodation to applied loading. At high stress amplitude (higher then EL) the moment of loading application is accompanied by multiple formation of defects (1000 and more impulses/sec) and intensive heat dissipation. The thermodynamic balance of the specimen with environment is reached due to both increase of heat exchange power and decrease of mesodefect generation rate.

Transition to process of fatigue crack initiation is spontaneous. The moment of fatigue crack initiation is accompanied by localization of energy dissipation and essential growth both qualitative and quantity characteristics of AE signals. Growth of AE activity is accompanied by change of resonant frequency of the specimen and directly connected with crack growth. The analysis of quantitative characteristics of AE data and temperature kinetics does not allow us to determine the invariant precursors of failure.

It is also show that the initial defect density influences on dissipation activity of metals. The high defect density was obtained by intensive plastic deformation (equals channel pressing). Intensive plastic deformation of metals leads to the formation of fine-grained nonequilibrium structures containing high density lattice and grain boundary defects with long range elastic stress fields. This circumstance allows us to consider nanostructural state of materials as metastable. As a result the plastic and/or cyclic deformation of these materials is accompanied by anomalies of energy dissipation and absorption. The analysis of the experimental data confirms the conclusion about the qualitative difference in the energy dissipation and failure mechanisms of polycrystalline and nanocrystalline titanium. The dependence of "intensity" of the energy dissipation on the average stress is well approximated by the line for different samples of nanocrystalline titanium. This qualitatively differs from a behavior of the material in coarse-grained polycrystalline state. In the material with a fine grain the EL cannot be treated as stress value the achievement of which leads to a qualitative change in the mechanisms of structural relaxation characterized by multi-scale character of the final stage of deformation. The growth of the average temperature of the nanocrystalline sample, and, hence, the integrated capacity of heat sources caused by material structure evolution is directly proportional to the quantity of energy (a square of the stress amplitude), spent on deformation of a sample for all investigated values of the applied stress. This fact characterizes the ability of a submicrocrystalline material to use effectively the structural (configuration) channel of energy absorption, involving in this process all nanocrystalline volume.

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