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Monitoring of Fracture of Welded Joints in Hazardous Facilities by Acoustic Emission under Static and Cyclic Loadings

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Abstract

Background/Objectives: Acoustic emission under static and fatigue failure of steel welded joints 9MnSi5 in a zone of thermal influence is investigated at temperatures of 296 K and 233 K. **Methods/Statistical Analysis:** Flat samples with a welded seam, weakened by a notch in the Zone of Thermal Influence (ZTI), were made for static and cyclic tests of steel 9MnSi5 monoaxial stretching. Type of welded connection: end-to-end, double-sided with full pen of chamfers (C255 type). Stress risers in tension were manufactured by a sparkerrosion wire-cutting machine Sodick AG400L LN2W with high precision of positioning and repeatability of the shape of notches. All static and dynamic tests were carried out by servohydraulic machine Instron 8802. **Findings:** The received results show that origin and development of fatigue cracks are significantly easier at positive temperatures, than at negative. This fact testifies that origin of fatigue cracks on real objects, most likely, happens during the summer period, and their sudden development (break down) – in winter. That means that the low temperature of operation is not the defining factor for catastrophic failure. This fact should be born in mind in the analysis of AE registered by monitoring systems during the summer and winter period in case of controlling objects working in the conditions of cyclic loadings. **Applications/Improvements:** It is shown that at all types of tests; the range of AE-signals is shifted towards lower frequencies as the moment of failure approaches. Criteria parameters based on the signal wave form and its power spectral density are suggested with the aim of using them in automatic monitoring systems.

Keywords: Acoustic Emission, AE Energy, Crack formation, Hazardous Facilities, Loading Signals, Plastic Deformation

1. Introduction

Society and environment are exposed to the risk connected with potential accidents because of destruction of equipment when operating any industrial equipment. Therefore development and operation of production dictates vital importance of advancing development of means ensuring protection and prevention of accidents on hazardous production facilities for the purpose of decrease in risk and size of catastrophic consequences of the specified accidents. The most dangerous objects are: pressure vessels, storage of ammonia and oil products, main oil and gas pipelines, chemical equipment, ammonia refrigeration units and many others.

Use of intellectual systems of monitoring prevention and forecast of accidents is one of ways of safety of industrial facilities. The unique method of nondestructive control allowing to estimate defects on degree of their danger to construction operation is an Acoustic Emission method (AE)[1,2]. Nowadays a steady tendency of transition of control methods from periodic to continuous (monitoring) is observed around the world[3,4]. However, there are no standards or techniques so far, in which criteria for an assessment of degree of danger of controlled object in real time on the basis of data recording of AE would be accurately designated.

Steel 9MnSi5 belongs to number of the most widespread materials for making bearing elements of dangerous

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objects, and the weakest link of such objects are welded joints. There is an additional problem connected with the phenomenon of low-temperature embrittlement of metal when operating refrigeration units, storages of ammonia, and any equipment operated in the conditions of low temperatures. However information on AE during fracture of welded joints of these designs is practically absent in references, and there aren't any researches devoted to AE at fracture in the Zone of Thermal Influence (ZTI). In this regard, the purpose of carrying out the real research is establishment of communication of behavior of the AE parameters with degradation of welded connections at their static and fatigue loading in the conditions of the room and lowered temperatures. As a result of work it was supposed: (1) to determine consistent patterns and distinctive features in behavior of AE at static and fatigue failure of material; and also (2) to develop recommendations to monitoring AE-systems about registration of parameters of signals of AE, the most sensitive to metal degradation processes.

2. Materials and Methods

Flat samples with a welded seam, weakened by a notch in the Zone of Thermal Influence (ZTI), were made for static and cyclic tests of steel 9MnSi5 monoaxial stretching. This notch guarantees localization of deformation and fracture exactly at that point. Type of welded connection: end-to-end, double-sided with full pen of chamfers (C25[5] type). This type of connection is basic when assembling shell structures, such as vessel equipment of chemical, petrochemical and oil processing productions. The form of the concentrator of tension in the weakening point of section is a wedge with top radius of 0,16 mm. Appearance of the made samples is presented in Figure 1.

Stress risers in tension were manufactured by a spark-errosion wire-cutting machine Sodick AG400L LN2W with high precision of positioning and repeatability of the shape of notches. The sample passed superficial polishing on insignificant depth for an exception of emergence of AE signals connected with flaking and fracture in grips of products of corrosion, cinder, etc. pollution of a surface after production of concentrators of tension. Overall dimensions of samples: the total length of 200 mm, length of working part of 40 mm, section between concentrators of voltage of 6x8 mm^2.

All static and dynamic tests were carried out by servo-hydraulic machine Instron 8802. Static tests for uniaxial stretching were carried out in accordance with GOST 1497-84 with a speed of loading of 4,5 mm/min. Tests for fatigue in accord with monoaxial constant signs scheme were carried out according to ASTM E647-00[6] in a verification mode of the applied stretching force changing under the sinusoidal law in the range of 1800 ÷ 18000 N i.e. with coefficient of asymmetry of a cycle R = 0,1, with a constant frequency of 10 Hz. Static and cyclic tests were carried out at room (296 K) and lowered (233 K) temperatures which were provided with the climatic chamber

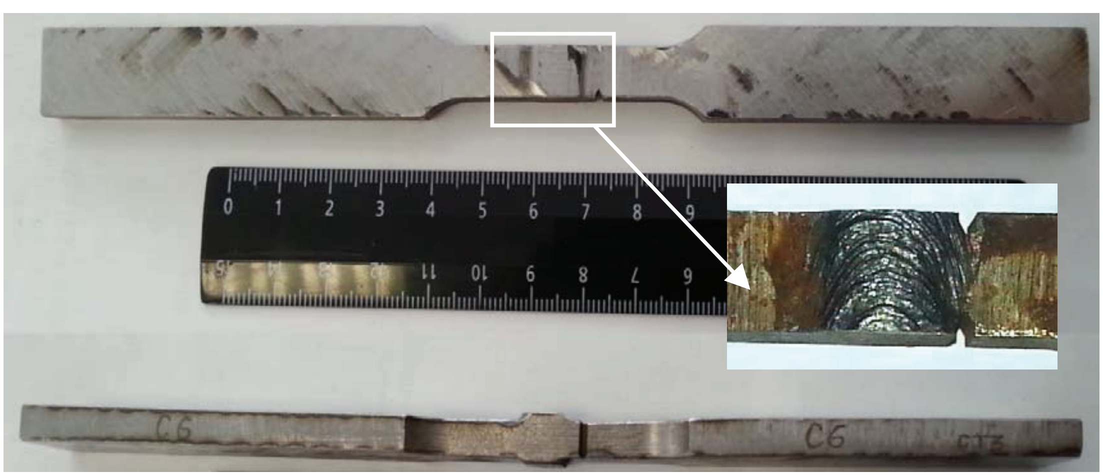

Figure 1. Appearance of samples for static and dynamic tests (the big fragment before removal of a layer of cinder and rust is shown in a window)

Instron SFT3119. Cooling of samples in the climatic camera was carried out by evaporation of the liquid nitrogen from the back of the camera. Temperature during preparation and during tests was regulated by the camera controller in accord with three thermocouples installed in various parts of the camera and one thermocouple installed directly on the sample.

Acoustic Emission (AE) was registered using a PCI2 board by PAC. AE from a sample was measured by a piezoelectric MSAE-1300WBC transducer, which was clamped on a sample through the acoustic media. The AE signal arriving from the transducer was amplified by means of low-noise preliminary amplifier MSAE-FA010 by 60db. The received signal went through the band-pass filter with a frequency range of 150÷1200 kHz. The measured key parameters were energy (E) and median frequency (Fm – frequency dividing area under a curve of spectral density in two equal parts). The analysis of signals of AE was carried out with application of the original software package.

Samples were washed out in alcohol and dried after tests for passivation of processes of corrosion in breaking points. Research of breaks surfaces was conducted by means of a three-dimensional microscope Zeiss Stemi 2000.

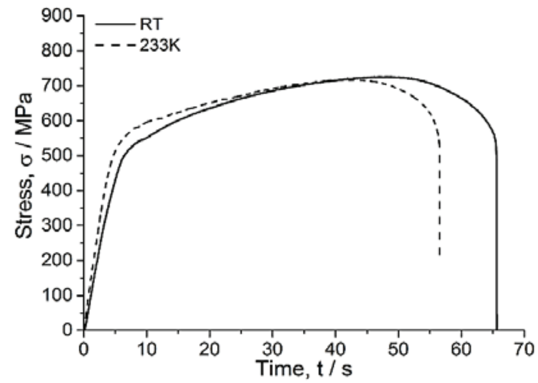

Figure 2. Charts of stretching of samples with tension concentrator in HAZ of welded connection at room (continuous line) and lowered (dash line) temperatures

Table 1. Characteristics of durability and fatigue

Test temperature, K (C°)	Flow limit, MPa (±5 MPa)	Strength, MPa (±5 MPa)	Quantity of cycles before fracture (±2200 cycles)
296 (+23)	550	720	20900
233 (-40)	605	710	26900

3. Results of Tests and Discussion

Figure 2 presents charts of test of samples for monoaxial stretching at room (296 K) and lowered (233 K) temperatures in coordinates tension (σ) – time (t). Certain mechanical characteristics are provided in the Table 1. Fracture of samples happened in the sections of HAZ of welding (Figure 3) set by concentrators of tension.

As could be expected, fall of temperature leads to a little increase of strength properties (flow limit) and decrease of plastic properties (time before fracture). The surface of breaks of the samples tested at room and negative temperature is shown in Figure 3. Breaks of samples both at room (Figure 3a), and at negative temperature (Figure 3b) are viscous as evidenced by the surface relief with existence of level differences. The most part of the central part of the break is occupied by the area formed under the influence of separation tension. Micro relief of breaks of the samples tested at negative temperature is less developed than tested at room temperature. It proves more fragile nature of fracture.

It is known that endurance limit value, as a rule, increases at test fall of temperature[7,8]. The task of definition of endurance limit wasn't set in this work, however the increase in average of cyclic loadings before fracture at fall of temperature of tests approximately by 1,3 times is observed by results of tests (table).

Fracture of samples at fatigue tests also always happened in HAZ of welding. The surface of breaks of samples tested for fatigue at room and negative temperature is shown in Figure 3c, d. Breaks of samples both at room (Figure 3c), and negative temperature (Figure 3D) are viscous as evidenced by the surface relief with existence of level differences. Photos demonstrate that cracks arose on concentrators of tension and developed deep into sample with break down in the middle part under the influence of separation tension. The microrelief of breaks of the samples tested at negative temperature is less developed, than of the ones tested at room temperature. It proves more fragile nature of fracture. However there are no visible signs of uneven development of fatigue cracks on a surface of cracks formation. It proves viscous mechanism of development of cracks by means of connection of

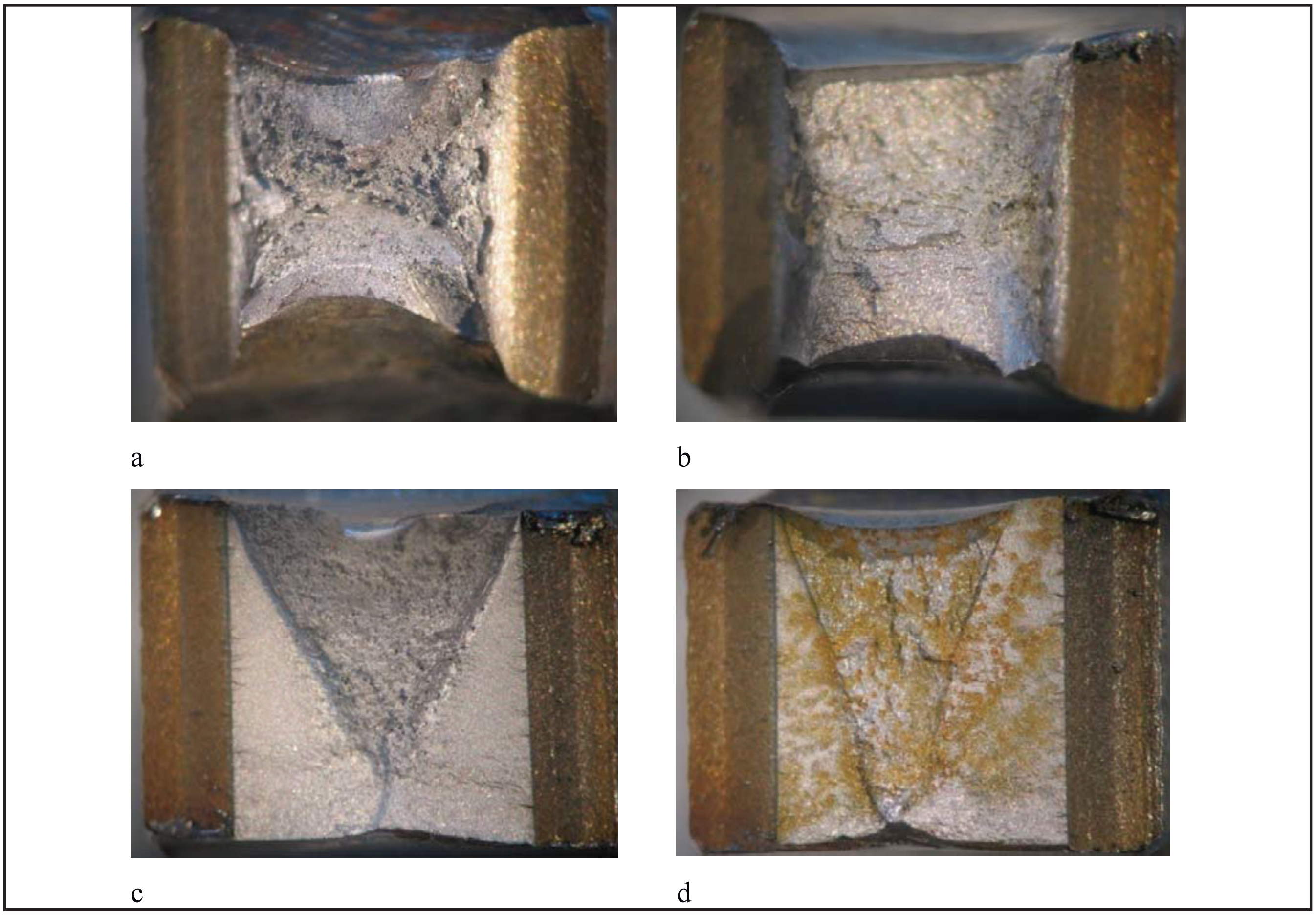

Figure 3. Appearance of a surface of breaks of samples in HAZ after static (a, b) and cyclic (*c, d*) tests at room (and, c) and 233K (*b, d*) temperatures.

deformed areas ahead of the crack, both at room, and at lowered temperatures of tests.

The typical charts of AE energy synchronized with charts of samples stretching tested at different temperatures are given in Figure 4.

As it can be seen, the behavior of AE at room and lowered temperatures strongly differs in spite of the fact that the general plasticity changes slightly. A noticeable peak of energy of AE is observed at both temperatures of test at an early stage of deformation, which is characteristic for the majority of metals and alloys with FCC and BCC lattice and, as a rule, is associated with sources of dislocation nature. Nature of behavior of median frequency which increases in quasi-elastic area of deformations in parallel with increase in level of the enclosed tension unambiguously testifies the same, and gradually falls after flow limit, reaching constant value before fracture (it isn't provided on Figure 4).

The peak of energy of AE is obviously expressed only at room temperature on the hardening area. AE has a pulse character on this area of loading that, as a rule is associated with the beginning of break down. Fracture processes at low temperature (below 0 ^{o}C) begin already near the yield point and therefore the higher AE peak and rare impulses of AE during the hardening stage is observed at under these conditions.

The behaviour of AE energy E synchronized with curves of cyclic loading of the studied samples tested at different temperatures are given in Figures 5 and 6 (some increases in various time of long tests on 2 cycles of loading are made in drawings for descriptive reasons).

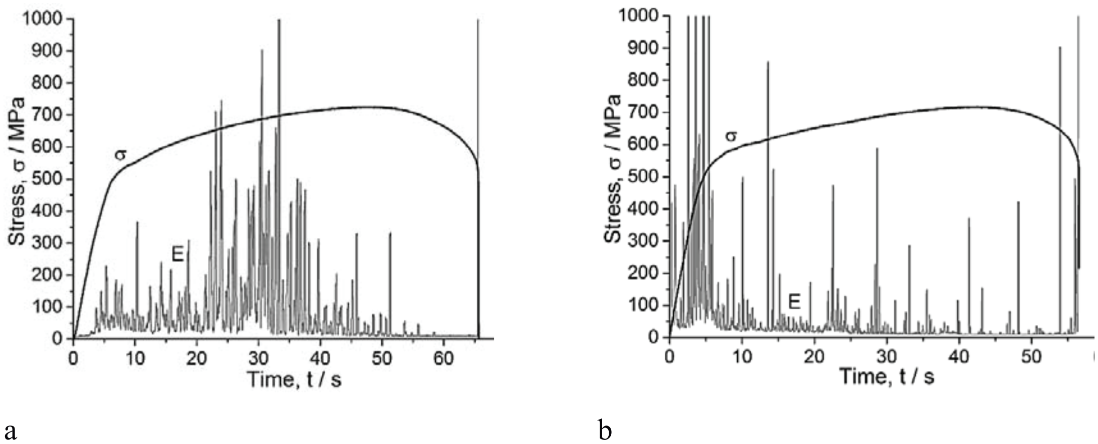

Figure 4. The energy of AE (E) synchronized with the chart of stretching (σ) of sample in HAZ welding at room temperature (a) and at a temperature of 233 of K (b).

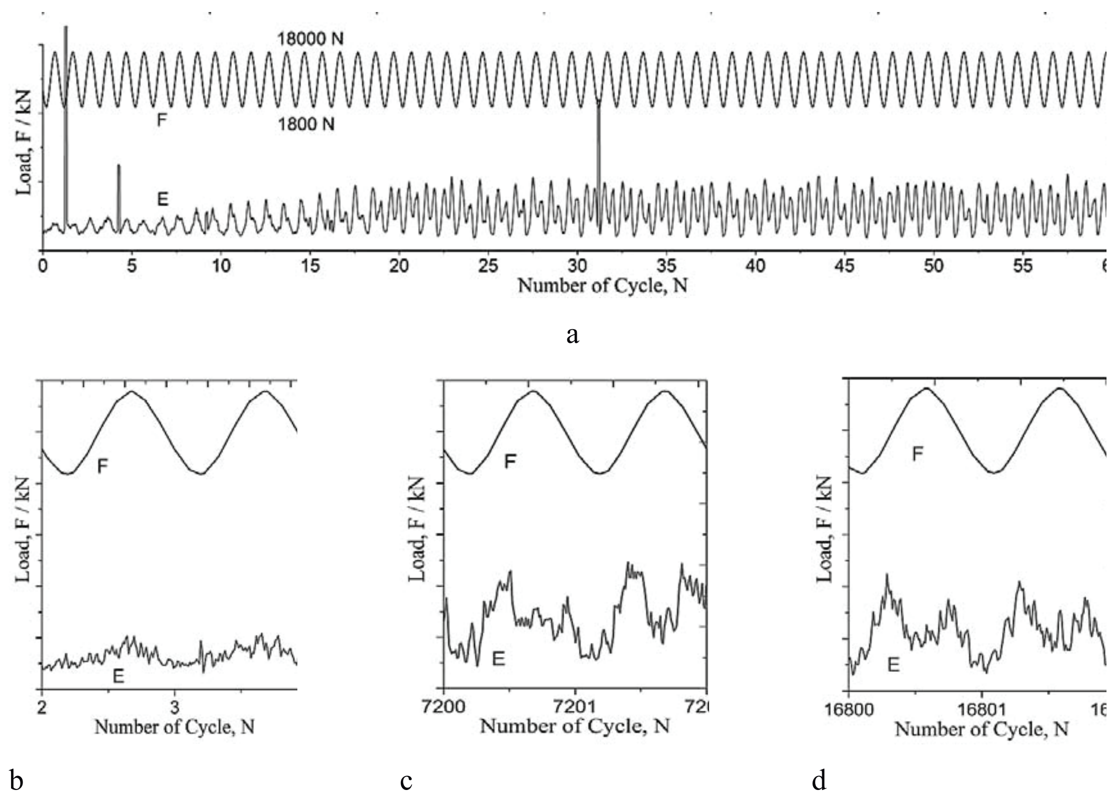

Figure 5. Energy of AE (E) synchronized with cycles of fatigue loading (F) at room temperature, where: a – a general view at the initial stage of test, b, c and d – specification of record AE on 2 cycles at the beginning, middle of test and before fracture in HAZ respectively.

The general tendency of change of AE revealed at fatigue tests of steel 9MnSi5 at room and negative temperatures is identical and consists in the following: acoustic emission is mainly created by signals of continuous kind which general level changes synchronously with a cycle of loading and in general increases approaching the moment of fracture (AE trend). A single peak is divided into two since the 20th cycle observed on

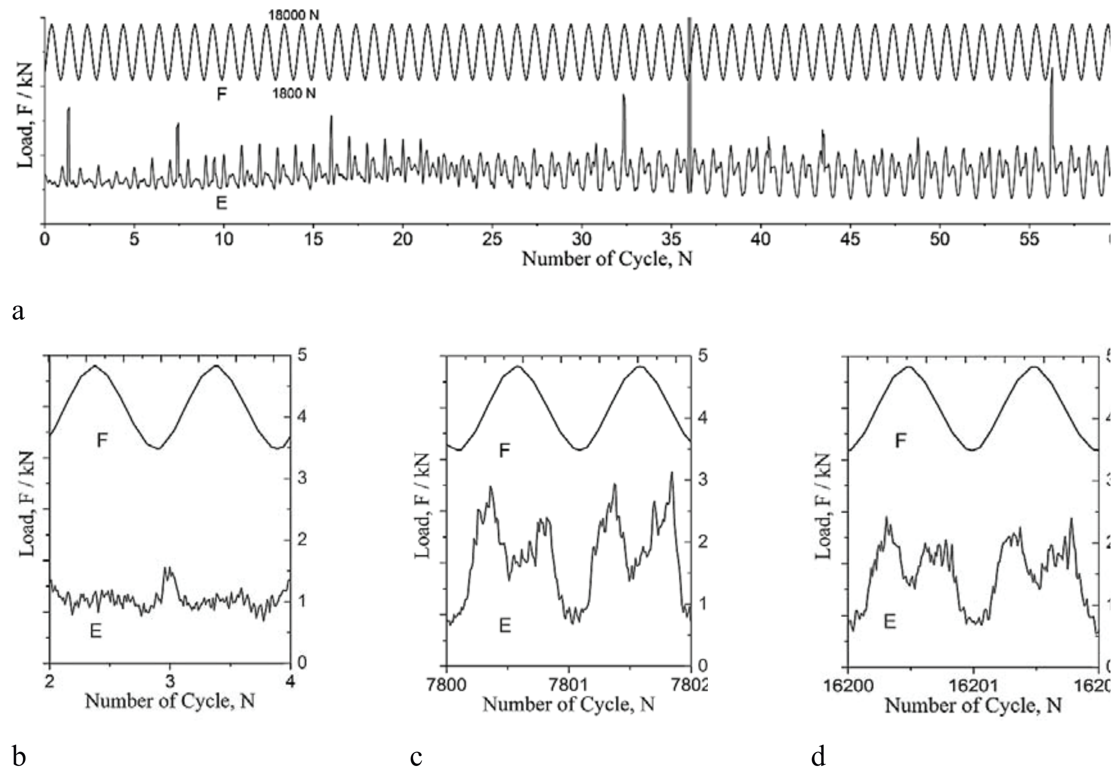

Figure 6. Energy of AE (E) synchronized with cycles of fatigue loading (F) at a temperature of 233K, where: *a* – a general view at the initial stage of test, *b, c* and *d* – specification of record AE on 2 cycles at the beginning, middle of test and before fracture in HAZ respectively.

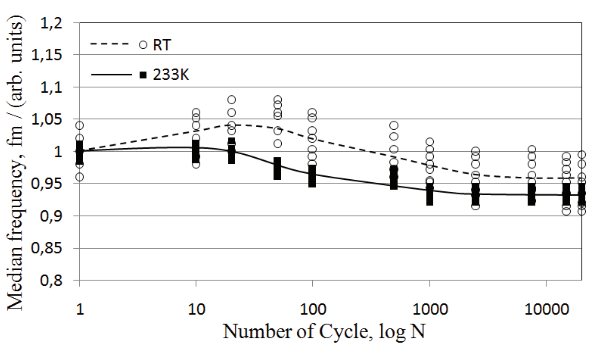

Figure 7. An example of change of rated median frequency of AE signals, in conditions of fatigue tests of samples at room temperature and at 233 K.

the chart of energy on each cycle of loadings. The general level of energy of AE at lowered test temperature is slightly higher than at room, but thus acoustic radiation is more stationary (compare, for example, Figure 6d with 5d).

Obviously distinguishable periodic pulse signals of AE connected with jumps of a crack for a loading cycle aren't revealed in these results, for example, AE noted in works on studying at fatigue tests[8]. This can be connected with the viscous mechanism of formation and development of cracks when development of fatigue cracks occurs not intermittently as at brittle fracture, but by the mechanism of rather slow association of the deformed areas ahead of the crack. Lack of pulse signals from a crack complicates identification of "useful" signals by amplitude methods; however it is essentially possible to do on function of spectral density.

The last finding is based on the experimental fact that the average level of median frequency continuously decreases during all types of tests (static, cyclic, different temperatures) approaching the moment of fracture. As an example, data on change of the median frequency of signals of AE, rated for the beginning of tests received at fatigue tests of samples at room temperature and at 233 K are given in Figure 7.

4. Conclusions

1) It is shown that AE registered during fracture of welded joints of steel 9MnSi5, widely used in petrochemical equipment, reflects change of fracture processes.
2) Nature of change of AE at fracture of welded joints in conditions of static loading has the following distinctive features:
   - There are two peaks of AE at room temperature, the first one - early stage of deformation, the second one- segment of hardening. AE at an early stage is expressed by the continuous and pulse signals coming with a big frequency. AE is mainly pulse on segment of hardening;
   - There is one peak of AE at a negative temperature only at an early stage of deformation. AE is also expressed by continuous and pulse signals;
   - Shift of function of spectral density in area of low frequencies is observed at both temperatures of tests with increase in the general deformation.
3) Nature of change of AE at fracture of welded joints in the conditions of variable loading has the following distinctive features:
   - AE is mainly created by signals of a continuous form;
   - The AE general level (AE trend) increases when fracture is approaching;
   - The AE level changes synchronously with a loading cycle, thus there is one peak of AE on each cycle on the first cycles of loading, and then there are two peaks.
4) Plastic deformation and crack formation in the conditions of variable loading signals of AE have a continuous form and are distinguishable only by function of spectral density. Thus, it must be kept in mind that the frequency analysis also has to be surely involved in algorithms of allocation of AE signal out of the noise level of monitoring systems. This approach is more labor-consuming in calculations and demands use of powerful equipment, but allows allocation and analysis of AE, both pulse, and continuous form.
5) Wave form of a signal at continuous or quasicontinuous record of input signal and spectral density function are criteria parameters for monitoring systems. It is possible to use the parameter of median frequency or equivalent frequency parameter in the simplified versions.
6) The received results show that origin and development of fatigue cracks are significantly easier at positive temperatures, than at negative. This fact testifies that origin of fatigue cracks on real objects, most likely, happens during the summer period, and their sudden development (break down) – in winter. That means that the low temperature of operation is not the defining factor for catastrophic failure. This fact should be born in mind in the analysis of AE registered by monitoring systems during the summer and winter period in case of controlling objects working in the conditions of cyclic loadings.

5. Acknowledgement

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