ARCHIVES OF ACOUSTICS
15, 3-4, 463-476 (1990)

LOW-CYCLE FATIGUE INVESTIGATION BY ACOUSTIC EMISSION METHOD

J. SIEDLACZEK**, S. PILECKI*, F. DUŠEK***

* Institute of Fundamental Technological Research, Polish Academy of Sciences
(00-049 Warsaw, Świętokrzyska 21)
** High Pressure Research Center, Polish Academy of Sciences
(01-142 Warsaw, Sokołowska 21)
*** Institute of Physical Metallurgy, Czechoslovak Academy of Sciences
(616-62 Brno, Žižkova 22)

The results of the measurements of acoustic emission (AE) count rate are presented during low-cycle fatigue of the variously heat treated 45HNMFA structural steel, which can be used for the production of high-pressure chambers. The experimental technique is described briefly. The most important result of this investigation is the occurrence of three stages of the AE activity during the low-cycle fatigue. These dependencies can be applied in monitoring of the service life (safe exploitation period) of high-pressure chambers and/or other studied objects.

W artykule omówione są wyniki pomiarów gęstości zliczeń emisji akustycznej występującej podczas nisko cyklowego zmęczenia stali konstrukcyjnej 45HNMFA, używanej do wytwarzania komór wysokociśnieniowych. Krótko naświetlono przebieg prac doświadczalnych. Najważniejszym wynikiem badań jest stwierdzenie występowania trzech stadiów nasilenia emisji akustycznej w procesie niskocyklowego zmęczenia. Zależności te mogą być wykorzystane podczas monitorowania rozwoju uszkodzeń (oceny bezpiecznego czasu użytkowania) komór ciśnieniowych oraz/lub innych obiektów technicznych.

1. Introduction

When investigating the properties of materials in the region of low-cycle (high loading amplitudes) fatigue, they are supported by the records of hysteresis loops arisen due to elastic-plastic deformations during particular loading cycles. The area delimitate by the loop is proportional to the energy dissipated by the material during this loading cycle [1]. From the practical point of view, the purpose of the investigation at low-cycle loading is as follows:

a) determining the service life of a specimen or a machine part at the given loading level;

b) estimating the allowable load for the given number of cycles to failure.

The problems in question are the accuracy we are able to apply in defining this and the certainly how we can put the obtained results into practice. It is difficult to answer these questions in an exhaustive way. It is a very serious problem, for when dimensioning (the calculation) of constructions working at the low number of cycles to failure we can reach either by the influence of necessary scattering or by an inaccurate estimation of the limiting deformation (or stress) value, the close neighborhood of the fracture curve, so that a possible failure of the structure can appear.

Such a case occurs in high-pressure chamber [2] working in conditions of low-cycle loading. The fatigue computations [7] based on the presumptions of Lamé do not give satisfactory results, because the problem is being solved in the region of elastic deformations (strains) and the calculated allowed loading is then (at the security coefficient $n = 1$) up to 4 times lower than that used for dimensioning the high-pressure chamber for laboratory practice. In this situation, a complicated system of protections from possible consequences of a breakdown of the high-pressure chamber must be used. These systems, however, do not protect the materials and equipments inside the chamber or in its close neighborhood. This practice does not enable to make full use of the material for high-pressure chamber rationally, either.

That is why an attempt has been made to include the acoustic emission (AE) method in the research of low-cycle fatigue of the 45HNMFA steel used for the production of high pressure chambers. It was expected that the AE activity, as well as the area of hysteresis loop, would be proportional to the energy dissipated by the material during one loading cycle. Besides, it was supposed that the AE activity in samples would be similar to that in working pressure chambers made of the same material. This would give a possibility to use the AE as a crack detection method for parts serving in the region of low-cycle fatigue — in our case, a possibility of the estimation of safe service life of the high-pressure chambers.

In the present paper, the results of AE measurements on the samples of variously heat treated 45HNMFA steel during low-cycle fatigue transient tensile loading are brought up.

2. Experimental details

The experimental study of AE during the low-cycle fatigue was carried out on the samples of the 45HNMFA steel produced by Polish industry. Its chemical composition is given in Table 1.

From this material, 12 test specimens were made according to Fig. 1. Then they were divided into three groups, heat treated (quenched and tempered) to three

Table 1. Chemical composition of 45HNMFA steel (in weight %)

C	Mn	Si	Cr	Ni	Mo	V	S	P	Fe
0.45	0.50	0.30	1.00	1.70	0.25	0.15	0.027	0.026	Rest

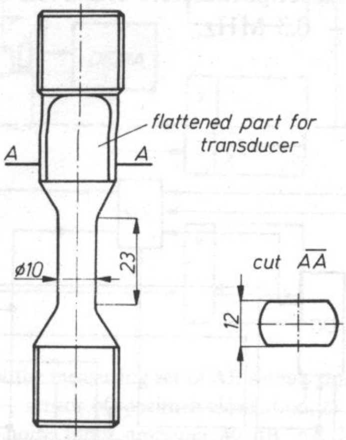

FIG. 1. Dimensions and form of test specimens

different Rockwell hardnesses – 30, 40 and 50 HRC and marked: 0, 1 and 2, respectively. Thus, each specimen has double number: the first figure is the number of the group, and the second – is the number of the specimen inside this group, e.g. 03, 21 etc. Conventional mechanical properties after the heat treatment are presented in Table 2.

Table 2. Mechanical properties of 45HNMFA steel

Rockwell Hardness	σ_{ys}	σ_u	A_5	Necking
HRC	MPa	MPa	%	%
30	975	1050	17	44
40	1375	1585	12	34
50	1500	1875	10	32

The loading of specimens in the low-cycle fatigue region was performed with the testing machine Zwick 20T. The specimens were loaded by variable force with triangle-waveform from zero up to the constant maximum amplitude, determined according to the value of total plastic deformation, chosen before. The crossbar shift rate of the testing machine was chosen to 2 mm/min.

The AE was measured by the analyzer AE 10–UFM CSAV (Fig. 2), developed in the Institute of Physical Metallurgy of the Czechoslovak Academy of Sciences in Brno [3]. This analyzer has been constructed as a ten-channel device with amplitude levels firmly set up. The frequency range of linear circuits is 30 kHz … 2 MHz. The dynamic range of this amplitude analyzer is 40 dB, and therefore the separation of individual channel is 4 dB. The set parameters of the AE analyzer were: amplification 70 dB and band pass 0.1 – 0.3 MHz.

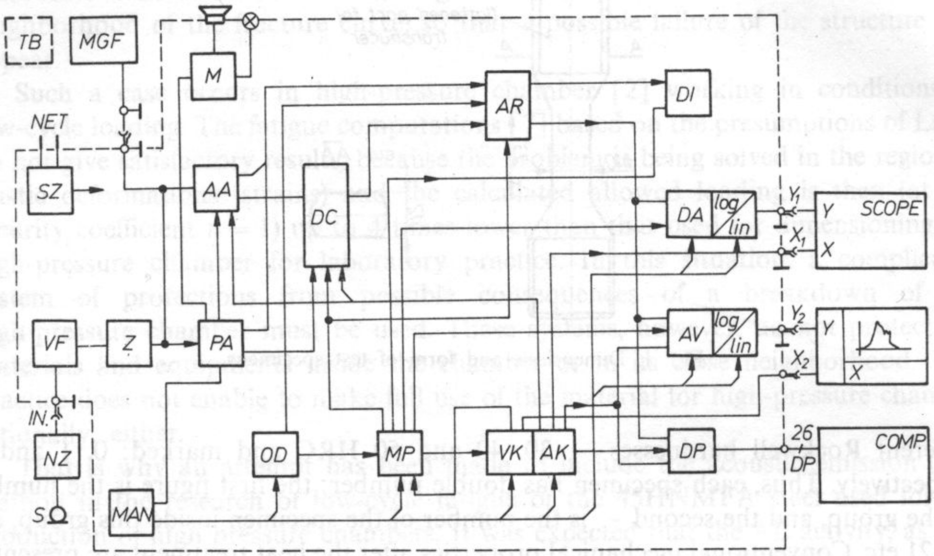

FIG. 2. Block diagram of the AE 10 Analyzer: *NZ* – low-noise input amplifier, *VF* – electronic filters, *Z* – linear amplifier, *PA* – threshold analyzer, *AA* – ten-channels amplitude analyzer, *DC* – counter, *OD* – control and pilot circuits, MP – multiplexer control, *VK* – channel choice modulus, *DA* – *D*/*A* converter, M – acoustic and optical monitor, *SZ* – power supply unit

Besides, AE signals caused by oscillations of the testing machine Zwick were checked, when arranging the measuring set according to Fig. 3, by the AE analyzer DEMA–10 RMS, developed in the Experimental Department TECHPAN attached to the Institute of Fundamental Technological Research of the Polish Academy of Sciences, Warsaw. It was found that no foreign interfering AE signals input into the specimen test result.

To measure AE signals, a suitable probe was chosen from the set products of the Polish firm UNIPAN, Warsaw. The estimation of frequency characteristics by means of a spark calibrator were carried out in the Institute of Physical Metallurgy, Czechoslovak Academy of Sciences [4]. The frequency characteristic is given in Fig. 4.

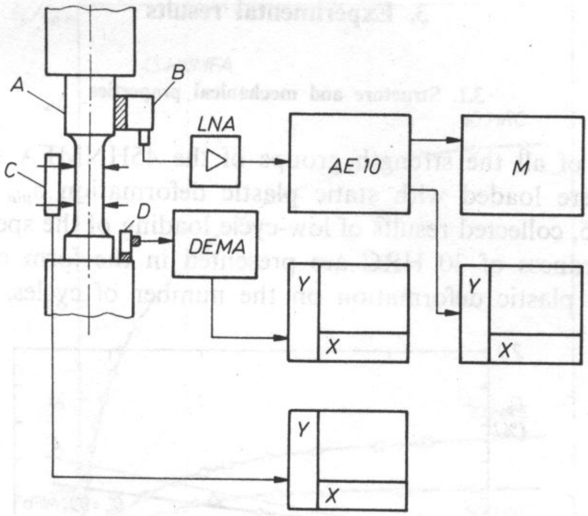

FIG. 3. Diagram of arrangement of the measuring set of AE signals during low-cycle fatigue tests. *A* — test specimen, *B* — AE transducer, *C* — sensor of specimen elongation, *D* — acoustic transducer pickup of test machine vibration, *LNA* — low-noise input amplifier 40 dB, AE 10 — a Czechoslovak AE analyzer, *M* — monitor, DEMA — a Polish AE analyzer, *XY* — coordinate recorder

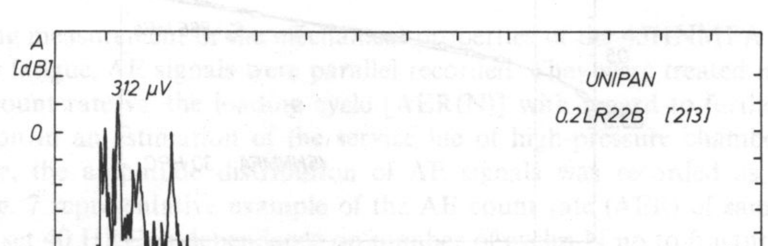

FIG. 4. Frequency characteristic of the acoustic emission transducer UNIPAN — 0.2LR22B, No. 213

3. Experimental results

3.1. Structure and mechanical properties

The samples of all the strength groups of the 45HNMFA steel – see Table 2 – initially were loaded with static plastic deformation $\varepsilon_{pin} = 0.310$; 0.800 or 1.345%. In Fig. 5, collected results of low-cycle loading of the specimens No. 01, 02 and 03 with hardness of 30 HRC are presented in the form of dependencies of cumulative total plastic deformation on the number of cycles.

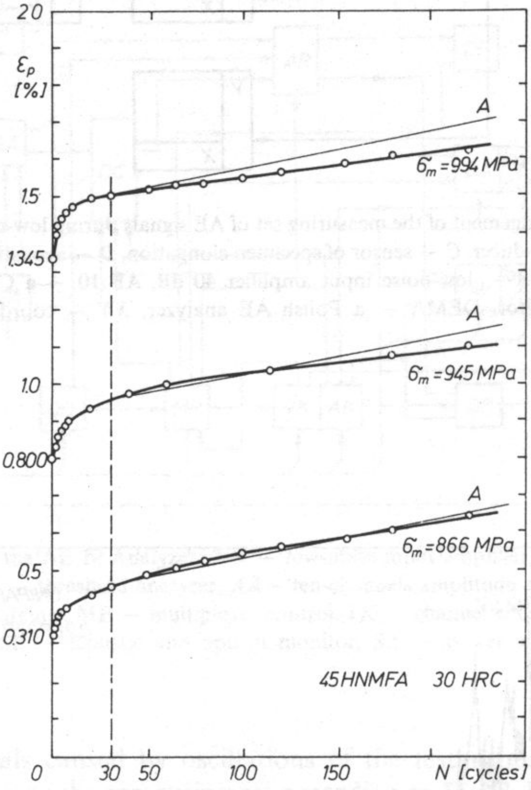

FIG. 5. Plastic deformation ε_p vs. the number of cycles N in the low-cycle fatigue in dependence on the different degree of initial static deformation

Similar results were obtained also in both other sets of specimens. To compare the average results of all three strength sets of steel, the deformation values in dependence on the number of cycles were recalculated on the dimensionless relative quantity given by the ratio of the final plastic deformation ε_p to the initial one ε_{pin}. That made it possible to show all the curves of deformation vs. number of cycles from the beginning of rectangular coordinate system – see Fig. 6.

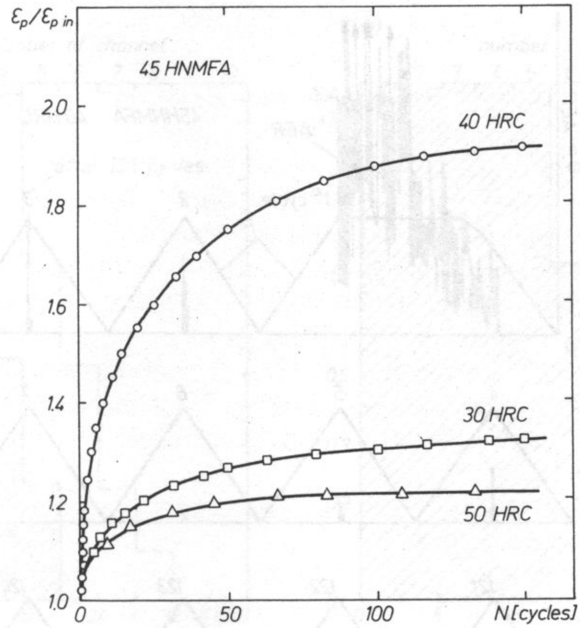

FIG. 6. Normalized courses of plastic deformation $\varepsilon_p/\varepsilon_{pin}$ for all three strength sets of the 45HNMFA material during low-cycle fatigue

3.2. Acoustic emission

During measurement of the mechanical properties of the 45HNMFA steel in the low-cycle fatigue, AE signals were parallel recorded. They were treated in a form of the AE count rate vs. the loading cycle [AER(N)] with regard to further practical application in an estimation of the service life of high-pressure chambers. At this procedure, the amplitude distribution of AE signals was recorded as well.

In Fig. 7 representative example of the AE count rate (AER) of sample No. 11 from the set 40 HRC in dependence on number of cycles N up to fracture is shown.

The cumulative amplitude distribution in the sum ΣAE after the first loading cycle, when the dislocation structure has been formed, is shown in Fig. 8a. By a dashed line, the amplitude distribution in the ΣAE after 136 cycles has been given here. In Fig. 8b amplitude distribution in the ΣAE after 206 cycles is presented, when fracture of specimen No. 11 occurred.

In Fig. 9, there are shown representing examples of AER(N) measurements in several cycles with differently modified loading courses on the specimen No. 03 from the set with 30 HRC.

The results with the same character, even though quantitatively different, were obtained, too, on all other samples in all the hardness sets.

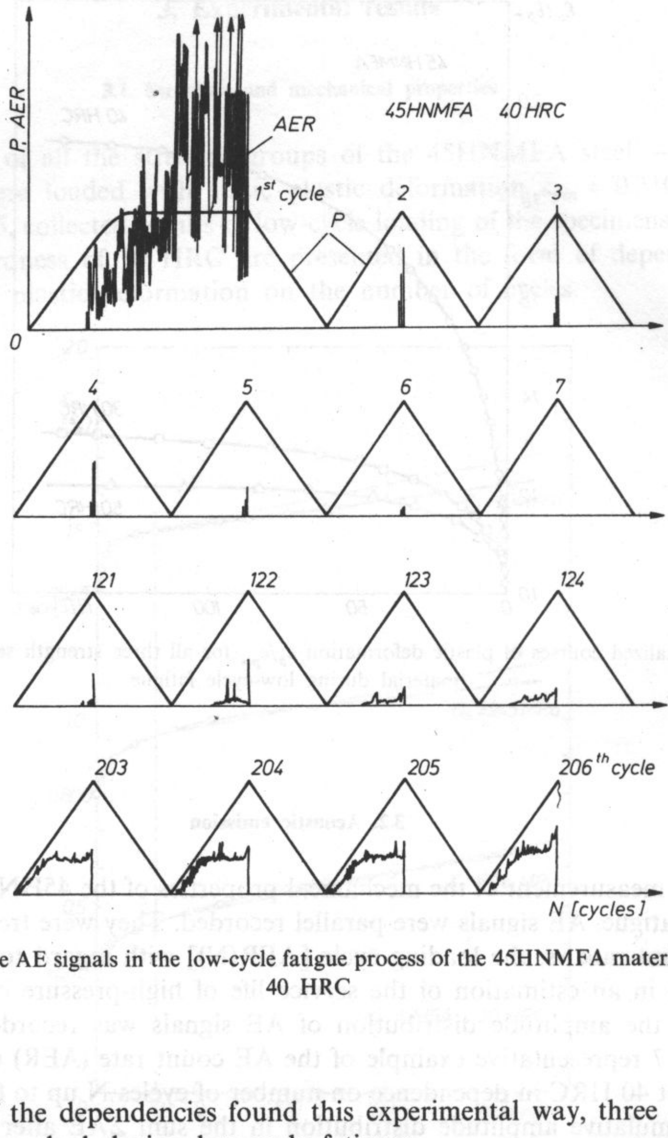

FIG. 7. Activity of the AE signals in the low-cycle fatigue process of the 45HNMFA material, hardness of 40 HRC

By means of the dependencies found this experimental way, three AE activity regions can be marked during low-cycle fatigue:

a) high AE activity in the first cycle (with aftereffects by slight "showers" of AE signals in some few following cycles) bound with forming of a dislocation structure during plastic deformation, i.e. new dislocation generation and displacement;

b) extinguishment of AE signals from several initial cycles up to ca a half of the number of cycles to the failure of the specimen;

c) rise of a new AE activity starting from about half of the number of cycles to the failure. Now the first AE signals occur by maximum loading only (see Fig. 7), then they take place by lower and lower one, and up to the failure. The amplitudes of AE signals increase step-by-step as well.

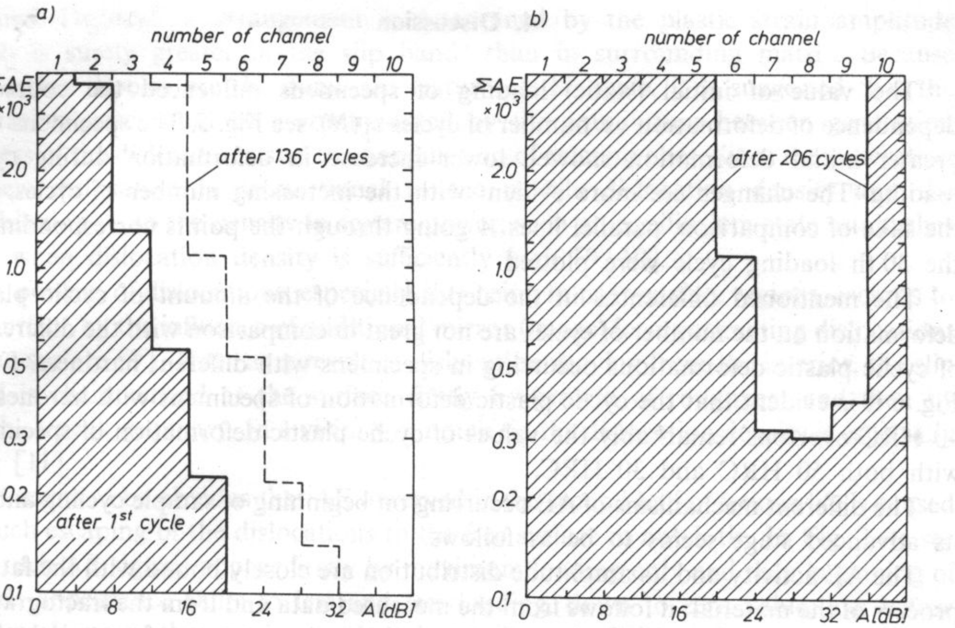

FIG. 8. Amplitude distribution of the AE signals during cyclic loading of the specimen with hardness of 40 HRC

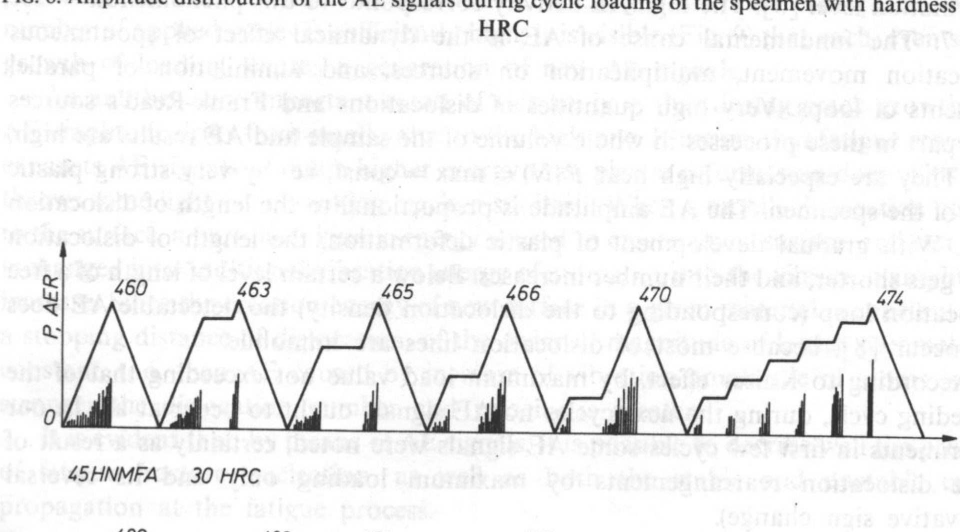

FIG. 9. AE activity in dependence on various modifications of loading courses in the specimen with hardness of 30 HRC

4. Discussion

The value of initial (static) loading of specimens influenced the course of dependence of deformation vs. number of cycles $\varepsilon_p(N)$, see Fig. 5. The specimens with greater initial deformation showed lower increase in deformation during cyclic loading. The changes are more evident with the increasing number of cycles. For the sake of comparison, parallel lines A going through the points corresponding to the 30 th loading cycle were plotted.

The mentioned differences in the dependence of the amount of cyclic plastic deformation on the number of cycles are not great in comparison with the differences of cyclic plastic deformations occurring in specimens with different hardness. From Fig. 6 it is evident that the cyclic plastic deformation of specimens with hardness of 40 HRC overtops remarkably the values of cyclic plastic deformation of specimens with both 50 HRC and 30 HRC.

The different mechanisms of AE occurring on beginning of sample cycling and on its advanced stage seems to be as follows.

The AE activity and its amplitude distribution are closely bound with the fatigue process of the material; it follows from the measured data and from the fractographic analysis. In the first loading cycle, a complete dislocation structure forms at the high deformation level [5]. The high AE activity corresponds to this phenomenon – see Fig. 7. The fundamental cause of AE is the dynamical effect of spontaneous dislocation movement, multiplication on sources, and annihilation of parallel segments of loops. Very high quantities of dislocations and Frank-Read's sources take part in these processes in whole volume of the sample and AE results are high, too. They are especially high near $P(N) = \max = \text{const}$, i.e. by very strong plastic flow of the specimen. The AE amplitude is proportional to the length of dislocation loop. With gradual development of plastic deformation, the length of dislocation loop gets shorter, and their number increases. Below a certain level of length of a free dislocation loop (corresponding to the dislocation density) the detectable AE does not occur [8], because most of dislocation lines are immobile.

According to Kaiser effect, by maximum load value not exceeding that of the preceding cycle, during the next cycles no AE signals ought to occur at all. In our experiments in first few cycles some AE signals were noted, certainly as a result of some dislocation rearrangements by maximum loading only and its reversal (derivative sign change).

During many following load cycles no AE signals appear because ground dislocation structure was formed in the course of first cycle, especially by quite great plastic strain (see Fig.7). In the subsequent cycles, dislocation density reaches its saturation state which does not enable greater movement of dislocation and their multiplications; Frank-Read's sources do not work.

After saturation stage reaching (what is usually complete for most materials after 20 to 50% of their life to failure), inhomogeneous plastic strains in the form of slip bands occur. These bands do not begin their development until after saturation is reached. Dislocation arrangement is determined by the plastic strain amplitude which is surely greater in the slip bands than in surrounding matrix. Because dislocation dipoles are the dominant feature of this state, it is suggested that the saturation state could be accommodated by the equilibrium between generation process of the dislocations and the annihilation of existing ones. Since the generation of new dislocation is proportional to the mobile dislocation density and the annihilation – to the density in square power, such an equilibrium state establishes only when dislocation density is sufficiently high [9, 10].

A portion of dislocations, especially this being in near-surface regions, escapes to the surface by the influence of additional mirror (image) forces attracting dislocations to the surface [9]. Thus, as a result of dislocation moving from the interior, the slip band is characterized at the surface, firstly by growth of roughness and then by notch – peak geometry. In a vicinity of notch tip the dislocation density is especially high [11].

It seems to be obvious that AE observed in the second half of fatique life is caused by such escaping of the dislocations to the free surface in notch tip. In Fig. 7 we see that such AE signals appear firstly by maximum loading only and then beginning of signals appearance shifts to less and less loading, down to zero value, just before fracture. It means that crack growth makes the escape of dislocations more and more plentiful and thus essential acceleration of crack growth must take place. When number of applied cycles is sufficiently high, it is visible (Fig. 9) that each, even small growth of loading, causes a generation of new AE signals.

An another very important result of this study is that during crack growth the AE amplitude drifts from small value to the high one. It means that fatigue cracking exhausts AE signals of much higher energy than plastic deformation does. This fact throws some light on a cracking mechanism itself. When a mobile dislocation comes to the surface, a part of its kinetic energy is used to create a new surface, and rest of it is changed into additional vibration energy of atoms, i.e. into the vibration amplitude increase. Since the creation energy of new surface in a given material is constant and a stopping distance of dislocation, of the order of magnitude of lattice parameter is constant, too, then AE caused by increase of vibration amplitude of atoms is the stronger the dislocation number and velocity is greater.

It is evident that, by means of AE signals, it is possible to decribe well the process of fatigue fracture nucleation, as well as both the stable and unstable crack propagation at the fatigue process.

5. Conclusions

The data on mechanical and structure characteristics of the 45HNMFA steel in the low-cycle fatigue region will be applied in the construction of service-safe high pressure chambers.

The most important results of these experiments is a repeated occurrence of increasing AE activity in the second half of life period of the material, see Figs. 7, 9, with increasing amplitude value of AE signals, see Figs. 8a, b. This information allows to use the AE method to estimate the safe service life of devices working in the fatigue conditions. What concerns the AE signals, it is evidently possible to describe the dependence of exploiting use [6] of a monitored object which consists of three stages:

I. hardening connected with the high AE activity;
II. dislocation density saturation characterized by extinguishment of AE activity;
III. development of crack whit corresponds to the increasing AE activity with increasing amplitude of the AE signals up to failure.

References

[1] W. SZCZEPIŃSKI et al, *Experimental methods in solid state mechanics*, (in Polish) PWN, Warsaw (1984).

[2] *UNIPRESS. Prospect of the LC liquid cells. Information* Leaflet of High Pressure Research Center, Warsaw (1986).

[3] F. DUŠEK et al., *The acoustic emission analyzer AE* 10. Patent. Author's Certificate No. 231236, Prague, 1984.

[4] F. DUŠEK, and C. SEIDL, *Acoustic emission transducers calibration.* Proc. of Summer School of Defectoscopy, (in Czech) Stary Smokovec, 1987, pp. 92–97.

[5] F. DUŠEK, M. KOTOUL, and C. SEIDL, *Acoustic emission.* Research Report of the Czechoslovak Academy of Sciences, (in Czech) Brno (1987).

[6] M. HOUSSNY-EMAN and M. N. BASSIM, *Study of the effect of heat treatment on low-cycle fatigue* in AISI 4340 *steel by acoustic emission*, Mater. Sci. Eng. **64**, No. 1, pp. 79–83 (1983).

[7] J. SIEDLACZEK, *Acoustic emission in the high pressure vessel testing* (in Polish), XII KKBN (NDT-Conference) Rydzyna (1983).

[8] J. SIEDLACZEK, *Acoustic emission of metals and alloys in plastic deformation and fatigue* (in Polish), Ph. D. Thesis, IFTR PAS, Warsaw (1987).

[9] S. PILECKI, *Dislocation – diffusion mechanism of fatigue crack formation*, Fourth International Conference on Fracture, Waterloo, Canada, 2, pp. 687–692 (1977).

[10] S. PILECKI, *Proliferation, diffusion and vanishing of dislocations in the course of process of metal fatigue*, Bull. L'Acad. Polon. des Sci., Ser. Sci. Techn. **17**, pp. 489–496 (1969).

[11] T. YOKOBORI, K. SATO, and Y. YAMAGUCHI, *X-ray micro beam studies on plastic zone at the tip of fatigue crack.* Rep. Res. Inst. Strength and Fracture of Materials, Tokohu Univer., Vol. **6**, No. 2, pp. 49–67 (1970).

Received on March 3, 1989